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Reducing the Energy Burden of the Poor and Greenhouse Gas Emissions: Can We Kill Two Birds with One Stone?

Dorothée Charlier - Anna Risch - Claire Salmon

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Reducing the Energy Burden of the Poor and Greenhouse Gas Emissions: Can We Kill Two Birds with One Stone?

Dorothée Charlier,[1] Anna Risch,[2] and Claire Salmon[3]

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Abstract
In this article, we assess current public policies, designed to reduce greenhouse gas (GHG) emissions, lower energy consumption, and fight the "energy burden" in the long term, so that it might offer relevant policy recommendations. We develop an existing partial equilibrium model to take into consideration key determinants of excessive energy burden. This analysis reveals that public policies are not sufficient to reach the ambitious objectives for reducing energy consumption and GHG emissions in France. Moreover, the decreases that might occur disguise significant social disparities across households. The joint implementation of multiple instruments leads to interactions that diminish overall policy outcomes. Overall, current public policies produce estimated free-riding rates of 75%. Energy efficiency measures are thus insufficient; governments need to focus more on monetary poverty as a cause of low renovation rates and consider subsidies of renovation costs as a potential solution.

Keywords: energy burden; public policies; bottom-up simulation; energy consumption; GHG emissions
JEL codes: Q41, Q48, Q58, C21, C61

[1] dorothee.charlier@umontpellier.fr ; UFR Science Economique, site Richter, rue Raymond Dugrand, CS 79606, 34960 Montpellier Cedex 2, phone +33434432476.
[2] anna.risch@univ-savoie.fr ; IAE Savoie Mont-Blanc, IREGE, 4 chemin de Bellevue, 74940 Annecy le vieux
[3] claire.salmon@univ-savoie.fr; IAE Savoie Mont-Blanc, IREGE, 4 chemin de Bellevue, 74940 Annecy le vieux

1. Introduction

In many European countries, the "energy burden" has become an urgent problem (Brunner *et al*., 2012), requiring attention from policy makers (Dubois, 2012; Moore, 2012). The energy burden refers broadly to the burden placed on household incomes by the cost of energy,[i] calculated as the ratio of energy expenditures to household income. Recent studies estimate that the energy burden affects 150 million people in the European Union alone (Bird *et al*., 2010). These households often live in poorly insulated housing but are unable to improve the energy efficiency of their homes. The over-consumption of energy, together with thermal under-comfort, leads to massive energy waste and significant environmental consequences over time (see Figures A1–A3 in Appendix A). To address the energy burden, energy over-consumption, and greenhouse gas (GHG) emissions, European countries have initiated several policy instruments. Our research objective is to establish a general understanding of the consequences of these public policies on the joint effect on energy burden and GHG emissions, especially among poor citizens, and give policy recommendations. An adequate policy measure should let a decrease of GHG emissions but would be also a solution to decrease other public expenditures to help low income households in the future. We are aware of only a few studies that deal with the joint impact of public policy on GHG emissions and energy burden using a bottom-up simulation model. In conducting such an assessment, we extend existing literature.

A thorough assessment of the public policies on energy efficiency investments with a simulation model must ideally be based on data encompassing a broad scope of variables. This would include a set of predetermined variables (regardless of the type of investment opportunity) reflecting the socioeconomic characteristics of households, housing tenure, income quintile, dwelling type, energy-relevant equipment features and quality, as well as energy expenditure.

Another set of variables would concern potential energy efficiency (EE) investment opportunities (options): the list of technical opportunities and, for each option, the cost, equipment quality, energy savings in physical units, as well as expected energy prices for computing expected savings on energy expenditures. Finally, there would be a set of financial variables, including the constraint capacity for investing, the amount spent and the access to capital. Unfortunately, very few simulation models let us to perform assessment considering all these parameters. In France, we can find Res-IRF, a bottom–up module of the French building stock (Giraudet *et al*., 2011), to the general equilibrium model IMACLIM-R (Crassous *et al*., 2006; Sassi *et al*., 2010). However, in these models, simulations are not focus on joint impact on energy burden and GHG emissions. The household's capacity constraint is also unconsidered. In this paper, we demonstrate a procedure for extending an existing simulation model (Charlier and Risch, 2012). Comparing to the initial model, we distinguish households by income quintile in order to take into account all the parameters aforementioned above according to the income level of the households, and we consider the key determinants of energy burden. This allows obtaining simulations according to the type of dwelling as well as the household's profile. We combine the technological explicitness typically found in bottom–up models[ii] with the economic mechanisms typically found in top–down models (Hourcade, 2006). Thus, we can determine who suffers most from increased energy costs and benefits most from residential energy efficiency improvements. The model also lets us to assess the public cost as well as the magnitude of free-riding. This extension is the key original feature of our approach and constitutes a value added to the literature. The model is calibrated with French data but simulations with other European dataset are feasible in the future. We obtain that current public policies allow inducing households to undertake EE investments, but (i) they are not sufficient to reach the ambitious objectives for reducing energy consumption and GHG emissions in France[iii] and (ii) disguise significant social disparities across households.

In turn, we define which policy instruments might be the most effective for achieving both social and environmental objectives simultaneously (Druckman and Jackson, 2010). Substantial literature analyzes the effect of public policies on the French households' energy consumption and GHG emissions (Charlier and Risch, 2012; Giraudet *et al*., 2011; Mauroux, 2012; Nauleau, 2014) and acknowledges that some households make energy-saving investments, but others free-ride on their efforts. Moreover, the joint implementation of multiple instruments can lead to interactions that augment or diminish overall policy outcomes (Bennear and Stavins, 2007). Vona and Patriarca (2011) also show that an excessive inequality between households harms the development of environmental technologies especially in rich countries using a dynamic model. Empirical assessments of the joint impact of current environmental policies on the energy burden and GHG emissions are relatively rare, even though the energy burden is an important indicator in any consideration of the social implications of an energy policy. For example, one recent estimate suggests that fuel poverty affects between 9% and 20% of French households (Legendre and Ricci, 2015). This situation cannot be attributed solely to insufficient household income. High energy costs and the poor energy efficiency of a significant portion of available residences increase the prevalence of fuel poverty and excessive energy burdens (Brunner *et al*., 2012; Santin, 2011). The situation is thus suboptimal, both socially and environmentally. Büch and Schnepf (2013) examine whether the association between emissions and household characteristics varies for different types of emissions. They show that distributional implications of mitigation policies that aim to create financial dis/incentives are likely to differ across income groups.

For policy makers concerned about the need to offer energy assistance to vulnerable populations, a key consideration is the impact of any actions they take on energy burden (Bouzarovski *et al*., 2012). Public policies to overcome energy burden are expensive and potentially not sustainable. For example, in 2010 the United Kingdom provided 4.2 billion euros worth of winter fuel and cold weather payments to residents, while the United States offered the equivalent of 1.8 billion euros and Ireland provided 0.3 billion euros (Heffner and Campbell, 2011). To achieve more efficient energy policies while also determining their effects on populations, governments need to take a closer look at low-income households in particular, to identify differences in their energy use and energy burden, compared with other segments of the population (Castaneda *et al*., 2005; Dubois, 2012; Morestin *et al*., 2009). Housing policies that support disadvantaged families rarely account for the economic challenges associated with energy use and utility consumption though. In France, between 2005 and 2010, more than 5 million main residences benefitted from tax credits that encouraged them to undertake energy-saving renovations, at a significant total public cost of 12 billion euro over this five-year period (Clerc *et al*., 2010). An additional 10 billion euro has been dedicated to the Energy Transition Law. Yet, in 2014, one-fifth of French households struggled to pay their energy bills (ONPE, 2014). Thus, we need to assess policies and consider innovative policies with regard to their ability to relieve low-income households of energy burdens in the long term (Hernàndez and Bird, 2010).

In Section 2, we introduce existing French public policies. We then assess their effectiveness, according to their joint impact on GHG emissions and the energy burden in the long run. Specifically, we develop an existing partial equilibrium model according to these results (Charlier and Risch, 2012) in Section 3. In Section 4, we outline the results, before we conclude and suggest some policy recommendations in Section 5.

2. Description of residential energy policies

We note several measures proposed and adopted during French environmental roundtables, broadly known as "Grenelle de l'environnement" under the "Grenelle 2" law and the "Energy Transition Law" (project of law, 06-18-2014). Some measures feature short-term actions to lighten the energy burden of the most vulnerable households, such as social energy tariffs or bonuses. They do not seek to reduce energy consumption or GHG emissions. Social energy tariffs assist very low income households that use electricity or gas as their main fuel. When households use gas as their main fuel for heating, this measure can reduce their annual bills by 22€–156€, depending on their income threshold. (Note that the cost of a kWh of energy for a residence using gas as its main fuel is around 0.0543 euros.) If they use electricity, the tariffs reduce annual bills by 71€–140€ (the cost of electricity equals 0.1467 euros/kwh). A new energy transition project instead would provide a "chèque énergie" (or bonus) to help households pay their energy bills, though the amount of these bonuses has not been defined yet.

Other measures seek long-term impacts on energy consumption, GHG emissions, and the energy burden through improvements to houses' insulation quality. There exist three principal financial supports: (1) a tax credit, such that some of the renovation expenses may be deducted from income taxes; (2) a zero-rate bank loan to homeowners who make several renovations or energy-saving investments, and since 2014, this loan may combined with the tax credit; (3) subsidies, according to household incomes (including "ANAH" and "live better" subsidies) Table B-1 provides summary descriptions of these public policies in appendix B.

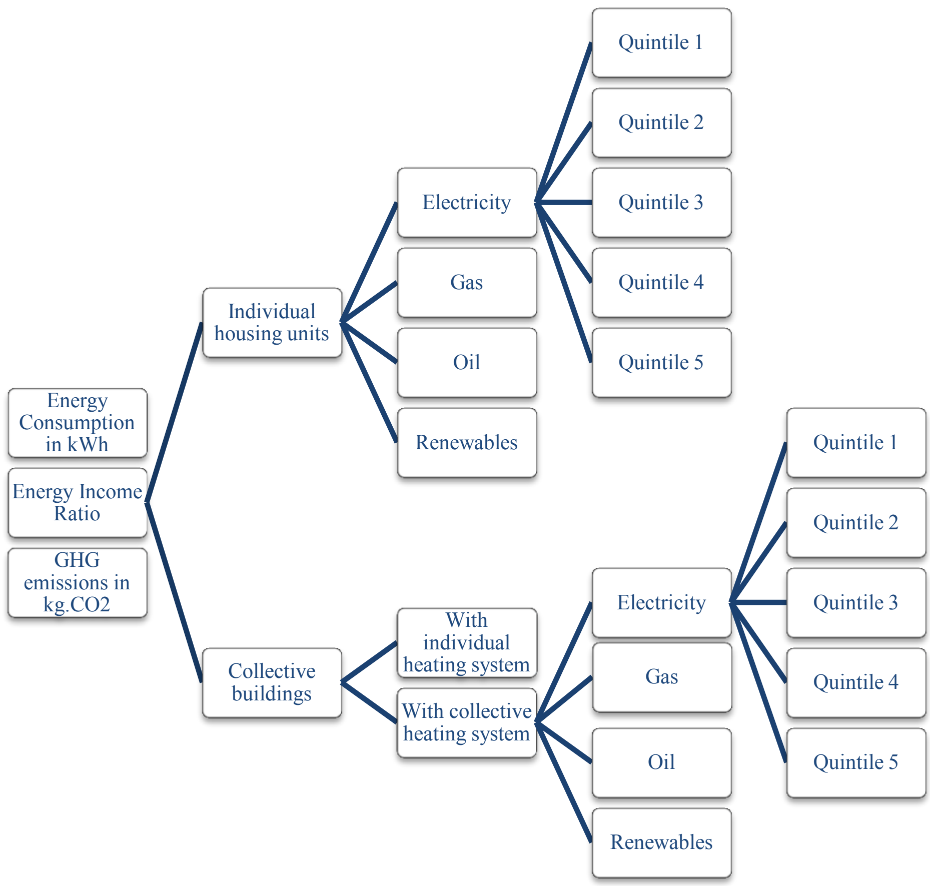
3. Public policy evaluations: Bottom-up model

We use a bottom-up method in a partial equilibrium framework. This model is an extension of the one presented by Charlier and Risch (2012). This extension aimed at take into account the energy burden. In a first time, we used the *2006 Enquête Logement*, a disaggregated, household-level survey data set provided by INSEE[iv], to study the factors that cause households to suffer excessive energy burdens. This statistical analysis shows that three main factors emerge to explain a high energy burden: low income, poor energy efficiency in the housing, and high energy expenditures (statistics are presented in appendix C). In a second time, we develop and calibrate the bottom-up model on the basis of these results. We included income quintiles in the model and therefore extent the 2012 version of the model taking into account the decision of households, and their GHG emissions according to their income level. This new feature has an impact on all equations of the model (obsolescence of the housing stock, renovation decision, and dynamics of the housing stock...). We present the model in this section. A full list of the variables is available in Appendix D.

3.1 Model structure

Energy consumption, GHG emissions, and the energy income ratio reflect three main uses: heating and hot water, lighting, and appliances. We also consider 60 types of dwellings, reflecting the range of housing available in France. These 60 types differ, depending on the type of housing (collective or individual), main fuel source for heating and hot water (electricity, gas, oil, or renewable), and the type of heating in flats (individual, for just one dwelling; or collective, which is common for the whole building). We also distinguish households living in each type of dwelling, according to their income quintile. Thus, in this new version of the model, there are 60 dwelling categories instead of 12 in the old one. An example of the model structure is in Figure 1.

Figure 1: Dwelling categories in the model



For each type of dwelling *i*, we estimate the evolution of energy consumption, energy income ratios, and GHG emissions. Our analysis is based on final energy consumption which it refers to energy that is supplied to the consumer for all final energy uses such as heating, cooling and lighting. The average energy consumption in kWh/m^2 in year t (EC_t) is the sum of energy consumption for each end-use j (EC_{END_USEt}): heating and hot water (H_t), lighting (L_t), and appliances (A_t). Thus,

$$EC_t = \sum_{j=1}^{3} EC_{END\_USE_{jt}} \ , \qquad [1]$$

where $EC_{END\_USE_t} = H_t + L_t + A_t$. [2]

Each end-use then is a sum of the energy consumption by households in each income quintile q living in the 60 types of representative dwellings i. The total energy consumption related to heating and hot water (H_t), appliances (A_t), or lighting (L_t) is the sum of energy consumption for a representative dwelling (H_{qit}, A_{qit}, and L_{qit}, respectively) multiplied by the stock of dwellings in this category (S_{qit}). The methodology is the same for GHG emissions, except that we estimate them in kg.$_{CO2}$. Therefore,

$$H_t = \sum_{i=1}^{12} \sum_{q=1}^{5} H_{qit} S_{qit} \ . \qquad [3]$$

$$A_t = \sum_{i=1}^{12} \sum_{q=1}^{5} A_{qit} S_{qit} \ . \qquad [4]$$

$$L_t = \sum_{i=1}^{12} \sum_{q=1}^{5} L_{qit} S_{qit} \ . \qquad [5]$$

We can determine, for each category of dwelling i, the energy expenditures in year t (EE_{it}) and the energy income ratio (EIC_{it}) using energy prices (P_{it}). The introduction of this energy income ratio variable is one of the main extensions represented by this model. As detailed in appendix C, the energy income ratio depends on households' characteristics, particularly their occupancy status and income quintile q. To determine it (EIC_{qit}), we divide energy expenditures in year t (EE_{qit}) for each household according to its income quintile q living in a dwelling category i by the disposable income (Y_{qit}), or

$$EIC_{qit} = \frac{EE_{qit}}{Y_{qit}} \ , \qquad [6]$$

where $EE_{qit} = EC_{qit} P_{it}$. [7]

The model construction involves two steps. First, we build the dynamic of the housing stock. The model is dynamic, because the weight of the representative dwelling in the total housing stock is affected by the evolution in the number and characteristics of households, as well as by any energy efficiency renovations. This dynamic is particularly affected by evolution of income growth and population structure. Second, we assess energy consumption, GHG emissions, and the energy income ratio.

3.2 Dynamic housing stock

Regarding the evolution in the number of households and/or their characteristics, we have five categories of households (single, couple without children, couple with children, single-parent family, and others), characterized by their propensity to live in a defined type of housing i (collective or individual and with a determined heating system; Figure 1). This population is assumed to be exogenous and determines housing needs, or the stock of housing in category i and year t divided across each household's income quintile q (S_{qit}). Each year, some exogenous part of the housing stock (D_{qit}) is demolished. New construction (NC_{qit}) corresponds to the need for new housing, or:

$$NC_{qit} = S_{qit} - S_{qit-1} + D_{qit} \quad . \qquad [8]$$

The structure of the household and the way it changes over time both affect the structure of housing stock (i.e., number of dwellings in each representative category i). Any changes in the population structure affects the repartition in income quintile and in consequences the energy expenditures. To estimate housing demand through 2050, we use predictive scenarios for the evolution of the population and household structures, as provided by INSEE (see Appendix E table E-2).

With regard to the age of the housing stock, the model contains a key variable linked to obsolescence. The dynamics of housing stock and energy efficiency renovations depend on and affect the obsolescence of the housing stock. We calculate—for each year *t*, each category *i*, and each household income quintile *q*—an age of the housing stock (or obsolescence), according to new construction, demolitions, and energy efficiency renovations. New buildings are less than one year of age; the age of demolished housing at time *t* is the average age of housing stock from the previous year. All renovations of type *r* in time *t* in each category *i* for each income quintile *q* are taken into account (R_{qrit}). The calculation for renovations is developed next. Here, we consider AGE_{qit} as a proxy for housing thermal quality; this endogenous variable reflects renovations in previous years. Renovations reduce AGE_{qit} by bringing new blood into the housing stock. We calculate the modernization effect produced by renovated housing by calculating the number of kilowatts per hour saved after a renovation ($AGER_{qit-1}$). Therefore,

$$AGE_{qit} = \frac{(1+AGE_{qit-1})\times S_{qit-1}+NC_{qit}-D_{qit}\times AGE_{qit-1}+\sum_1^r R_{qrit}\times AGER_{qit-1}}{(S_{qit-1}+NC_{qit}-D_{qit}+\sum_1^r R_{qrit})} \quad [9]$$

Now, the obsolescence of the housing stock is directly affected by households' income. It is possible to distinguish which type of dwelling is negatively affected by a low rate of renovation due to the incapacity to invest by low income quintile. It is also possible to demonstrate the obsolescence of the housing stock according to income quintile.

3.3 Drivers of energy conservation

For the energy efficiency renovations, we consider five types of renovation (glazing insulation, wall insulation, roof insulation, equipment for heating and hot water, and replacement of fuel by renewable energy) for individual dwellings, as well as an additional type for collective dwellings (individualization of heating systems). The renovations might be combined. We thus obtain 23 possible combinations in the individual sector and 35 in the collective one. Each kind of renovation (R_{qrit}) would decrease energy consumption and energy expenditures by heating systems (H_{qit}) and GHG emissions. To estimate the number of renovations (R_{qrit}), we compute the probability that a household invests in a renovation to improve energy efficiency (PI_{qrit}) and conduct a cost–benefit analysis. The probability that a household invests in an energy efficiency renovation (PI_{qrit}) depends on the cost–benefit analysis, which reflects the comparison of the discounted energy savings for renovation (NPV_{qrit}) with its total cost (C_{qrit}), and the household's financial constraint (FC_{qit}). In consequence, renovations are the result of household's decision according to its financial constraint and potential EE investment opportunities at each period. In the model, the dynamics of renovation is based on the cost-benefit analysis which depends largely on the financial constraint of the household. With new improvements and extensions, it is now possible to distinguish each combination of renovations according to each dwelling category (and therefore, each households quintile). For each category, a representative households make the decision to renovate or not according to its financial capacity. Therefore,

$$PI_{qrit} = f\{FC_{qit}, NPV_{qrit}, C_{qrit}\}. \quad [10]$$

The energy savings (kWh$_{pe}$/m /year) (G_{qrit}) equations are linear functions of the age of the housing (AGE_{qit}). It is cheaper to save one kilowatt hour when the housing unit has never been renovated. The older the housing stock, the larger the number and impact of possible renovations. Once a dwelling has been renovated, the age of the housing stock diminishes. It is not possible for a housing unit to be renovated in two consecutive years. Therefore, before calculating energy savings in euros, we convert primary energy into final energy.[v] To avoid comparing *annual* energy savings in euros with *one-shot* total costs, we discount the expected benefit to obtain a net present value:

$$NPV_{qrit} = \sum_{t=1}^{\mathrm{T}} \frac{G_{qrit}}{(1+\phi)^{T}} \ , \qquad [11]$$

where Φ is the market long-term interest rate, and T is the average life of the equipment (obtained from ADEME, *Agence De l'Environnement et de la Maitrise de l'Energie*).

The cost of renovation (C_{qrit}) depends on the price of the renovation per square meter and potential public policies.[vi] Now, in this version of the model, the cost benefit analysis, consider social energy tariffs and bonuses. Bonuses can be distributed to help low income households to pay their energy bill or as an additional income. They can also be given to finance energy efficiency renovation. These different types of bonus have different impact on the evolution of energy consumption, GHG emissions and energy burden. All costs and all benefits are calculated each year. Thus, an investment that is not profitable today may become so over time, due to obsolescence in housing stock.

The financial constraint (FC_{qit}) is determined each year according to the category of dwelling and households' characterictics (occupancy status and income quintile); it represents the maximum amount in euros that households can invest in a home renovation. This part is very important in the model since the household's decision is based on its financial capicity to undertake energy saving renovation (with and without capital access). Thus, this financial constraint depends on income quintile, occupancy status, disposable income, saving rate, share of savings devoted to energy efficiency investments, and borrowing power. To align with prior literature, we assume it is more difficult for a household with debts and low income to invest in an energy efficiency renovation. Taking into account income quintile let us to identify what households have capital access. We can also compare the cost of renovation and the borrowing capacity for each quintile.

Thus, we take more than just the building characteristics into account. Households' characteristics also determine decisions to invest in energy-saving systems. To obtain this financial constraint, we first multiply the saving rate and the share of the saving rate devoted to energy efficiency investments with the disposable income. In turn, we add the debt ratio.

Finally, the probability (PI_{qrit}) of undertaking energy-saving renovations is calculated each year, for each combination of renovations, according to households' income quintile. The probability value ranges between 0 (i.e., the household does not renovate) and 1. First, we compare the cost of renovation with the household's financial constraint. If a household cannot afford the renovation, the probability equals 0. Second, if the probability differs from 0, we calculate the length of time required to obtain a positive return on investment. Third, depending on the duration, we assign a value to the probability; it decreases over time. To set this probability, we account for the average length of occupancy (5.2 years, with a margin up to 7 years) and occupancy status. If the household owns the home, the renovation probability is higher. Tenants have less incentive to make energy efficiency investments, because they do not stay long enough in the dwelling to secure a return on their investment. Meanwhile, renovations increase the value of the dwelling for homeowners. Therefore, if $FC_{qit} < C_{qrit}$ or $FC_{qit} > C_{qrit} > NPV_{qrit}$, we set $PI_{qrit} = 0$. If instead $FC_{qit} > C_{qrit} < NPV_{qrit}$, we assume $0 < PI_{qrit} \leq 1$.

In each year, households first consider the most interesting energy efficiency renovation in terms of energy savings. If they cannot afford it, they look at the second most interesting renovation, and this procedure takes place 23 times for individual housing units and 35 times for collective buildings. Finally, we can compute the number of renovations for each combination, such that

$$R_{qit} = \sum_{r=1}^{r} R_{qrit} \quad , \qquad [12]$$

where $R_{qrit} = PI_{qrit} S_{qit}$. [13]

3.4 Energy consumption and GHG emissions

Next, we determine energy consumption due to heating and hot water systems as follows:

$$H_{qit} = \frac{H_{qit-1}(S_{qit} - R_{qit}) + NC_{qit} \times HC_{qit} + \sum_1^r Hr_{qrit} \times R_{qrit}}{S_{qit}} , \quad [14]$$

where HC_{qit} is energy consumption for new construction (taking into account the thermal regulation[vii]), and Hr_{qrit} is energy consumption for each type of renovation, calculated as:

$$\mathrm{Hr_{qrit}} = \mathrm{H_{qrit-1}} - \mathrm{G_{qrit}} \ . \quad [15]$$

Consumption for each renovated dwelling of type *r*, according to income quintile *q* (H_{qrit}), is the difference between the average consumption in the previous year (H_{qrit-1}) and the energy savings provided by the renovation (G_{qrit}).

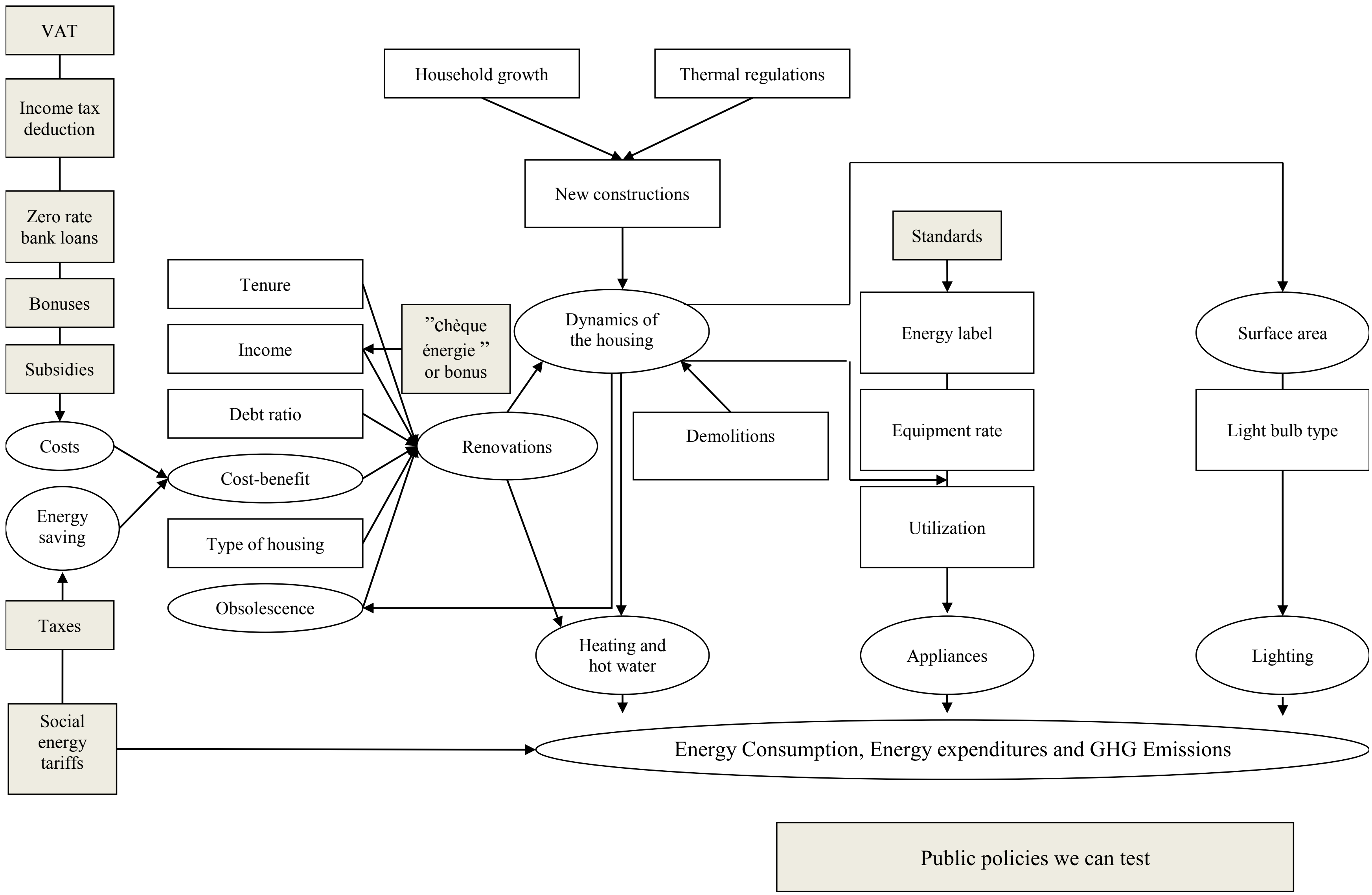
Energy consumption and GHG emssions due to appliances are based on the same assumptions detailed by Charlier and Risch (2012). The electricity consumption of appliances is the sum of the consumption of each dwelling in kWh_{pe}/m^2/year, taking into account appliance categories. We determine average consumption for each device in kWh_{pe}/m^2/year from the energy label (from A+ for those that consume the least energy to D for the largest energy consumers).

For lighting, we consider three possible kinds of light bulbs: halogen, standard, and energy saving. To calculate energy consumption from lighting in kWh_{pe}/m^2/year, we weight consumption of each type. The number of light bulbs depends on the surface area. Thus, it is possible to identify for each household's category the weight of each end-use consumption in total consumption. The weight of heating expenditures should be probably more important for low income households as the time which reinforce inequalities between individuals.

3.5 Calibration

To sum-up, there is a dynamic in the model particularly as regards household decision. Each year, a household decides whether to renovate given its occupancy status, the expected profitability of investment, financial constraint and its borrowing capacity. Every decision of the household has an impact on the dynamics of renovation and thus the obsolescence of the housing stock. A decision taken in year t, will have repercussions in t + 1. Thus, many of the equations in the model are endogenous and only few parameters are exogenous. The exogenous parameters are calibrated with 2006 data from: (i) *INSEE, l'enquête logement 2006,* (ii) the Ministry of Ecology, Sustainable Development and Energy and (iii) Energy Performance Diagnosis.[viii] The energy prices depend on evolution scenarios provided by International Energy Agency. Between 2006 and 2012, we adapt the value of main parameters according to the financial crisis. To ensure the quality of calibration, we compare our results with data provided in 2012 by PHEBUS[ix] database. Our results are consistent. According to the latter, energy consumption is 274 kWh_{pe}/m and we obtain 283.6 kWh_{pe}/m . Parameters values used for calibration are summarized in appendix E in Table E-1, E-2 and E-3. The model is summarized in the framework in Figure 2. The endogenous variable are in ovals; the public policies that we test are in shaded in grey.

Figure 2: The proposed model



4. Results and policy implications

One of our objectives is to estimate the impact of public policies on the energy burden, as well as on GHG emissions and energy consumption. To judge their effectiveness, we use three criteria. First, we assess the extent to which these policies facilitate achievement of the *Grenelle targets* (average energy consumption of 50 kWh_{ep}/m^2 by 2050 in the residential sector, GHG emissions reduced by 75% compared with the 1990 level). To reduce GHG emissions by 75% in the residential sector, the maximum amount of CO_2 that this sector can emit in 2050 is 13.75 million tons. The share of energy consumption due to renewables should be 30% in 2030.

Second, we analyze the impact of public policies on the average energy income ratio by income quintile, to determine if the energy burden for households diminishes over time. Usually, an energy poor household is one with a ratio greater than 10% (EPEE, 2007, 2011). Accordingly, we set the objective of an energy income ratio inferior to 10%.

Third, we study the cost of the measures for the government. We calculate the cost of each policy and divide it by the GHG emissions saved due to this policy measure. To estimate the cost to the government, we compare two scenarios: when no policy is implemented, and when a selected policy that we wish to examine is implemented. Therefore, we account for the impact and cost of one policy at a time.

4.1 Results with current public policies

To compare the results, we consider a reference scenario in which public policies in 2050 are the same as in 2014 (e.g., tax credit at a constant rate during the entire period, zero-rate bank loan, subsidy, VAT with a reduced rate of 5.5% instead of 19.6%, social energy tariffs for gas and electricity). The results obtained from the reference scenario indicate that low-income households (quintiles 1 and 2) have a higher energy income ratio over the period (14% and 7%, respectively, versus 2% for quintile 5 in 2006) and generate more GHG emissions in 2050 (Figures 3–5). With current policies, the energy income ratio decreases slightly over time for all income quintiles.

Figure 3: Evolution of the energy income ratio in the reference scenario

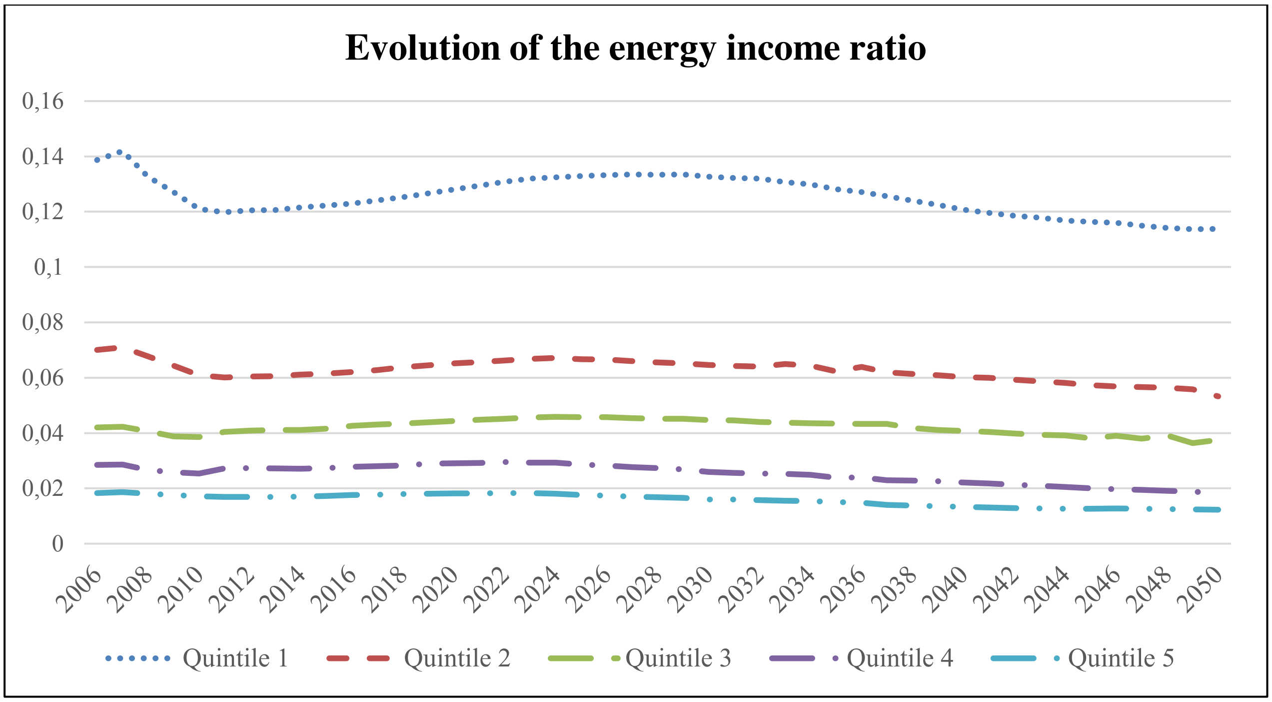


Figure 4: Evolution of GHG emissions by income quintile

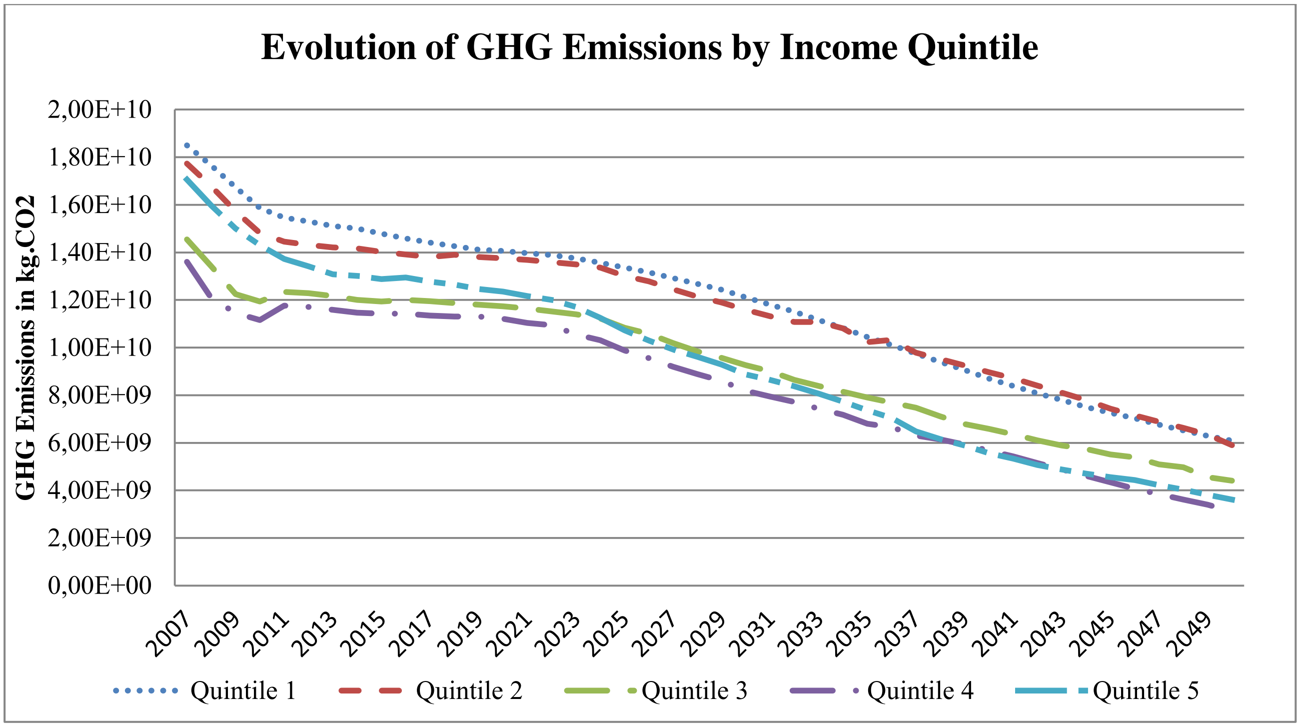
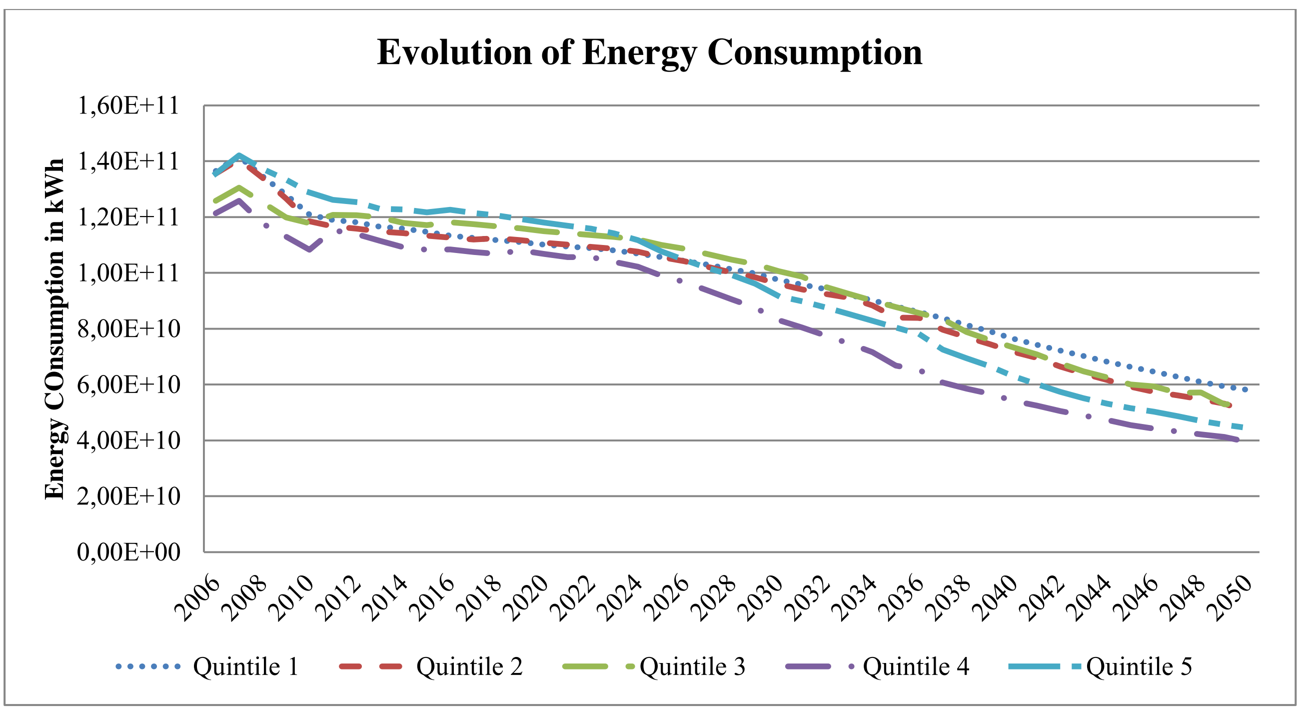


Figure 5: Evolution of energy consumption



We detail the results in Table 1. Public policies help decrease the energy consumption, GHG emissions, and energy income ratio. In a scenario without public policies, GHG emissions, energy consumption, and the overall energy income ratio are higher among all households by 2050. On average then, public policies lead to decreases of 58.08% for energy consumption, 64.80% in GHG emissions, and 11.82% for the energy income ratio.

These results indicate that only the energy consumption goal would be reached (recall that the objective is a 50% decrease). Yet they also hide some large disparities across households. The decrease in energy consumption is mitigated in low-income households (around 50%) compared with wealthier households (almost 64%). Likewise, GHG emissions decrease more slowly for low-income households. Their energy income ratio even increases in the middle of the period. The poorest households are more affected by energy expenditures and more vulnerable to energy costs. They live in more energy consuming dwellings and undertake fewer energy-saving renovations than wealthy households. Therefore, current public policies are not sufficient to help low income households or to achieve existing targets.

Without public policy, GHG emissions and energy consumption still decrease, but to a much lesser extent (respectively, 46.56% and 37.19%). These outcomes result from the dynamics of housing stock and thermal regulations on new constructions. However, the energy income ratio increases by 20.26%, and households are more vulnerable to changes in the cost of energy.

Table 1: Effects of current public policies

	Millions of Tons of kWh	Evolution Compared to 2014	Millions of Tons of CO_2	Evolution Compared to 2014	Energy Income Ratio (%)	Evolution Compared to 2014
2014 reference scenario						
All households	***585.7***		***65.7***		***5.33***	
Income Quintile 1	*116.6*	-	*15.0*	-	*12.05*	-
Income Quintile 2	*114.8*		*14.2*		*6.05*	
Income Quintile 3	*119.9*		*12.4*		*4.11*	
Income Quintile 4	*111.5*		*11.5*		*2.71*	
Income Quintile 5	*122.9*		*13.0*		*1.70*	
Situation in 2050						
Objective by 2050	*292.5*	*-50% (compared to 2014)*	*13.75 (level compared to 1990)*	*-79%*	*<10% for all income quintiles*	
Reference scenario: 2050 if policies remain unchanged from 2014						
All households	**245.5**	**-58,08%**	**23.1***	**-64.80%**	**4.70**	**-11.82%**
Income Quintile 1	58.1	-50,17%	6.1	-59.33%	11.38	-5.56%
Income Quintile 2	50.3	-56.18%	5.9	-58.45%	5.32	-12.07%
Income Quintile 3	53.2	-55.63%	4.4	-64.52%	3.75	-8.76%
Income Quintile 4	39.4	-64.66%	3.1	-73.04%	1.81	-33.21%
Income Quintile 5	44.4	-63.87%	3.6	-72.31%	1.23	-27.65%
No policy: situation in 2050 without any public policy compared with 2014						
All households	**367.88**	**-37.19%**	**35.11**	**-46.56%**	**6.41**	**20.26%**
Income Quintile 1	89.2	-27.40%	10.0	-33.33%	16.68	38.42%
Income Quintile 2	74.2	-35.37%	8.32	-41.41%	6.82	12.73%
Income Quintile 3	72.8	-39.28%	6.31	-49.11%	4.40	7.06%
Income Quintile 4	58.3	-47.71%	4.82	-58.09%	2.52	-7.01%
Income Quintile 5	73.3	-40.36%	5.77	-55.81%	1.61	-5.29%

Note: In the reference situations, the current policies remain unchanged from 2014 until 2050, including a VAT with a reduced rate of 5.5%, tax credit, zero-rate bank loan, social energy tariffs, and a subsidy. Households can receive several forms of financial support at the same time.

*With current policies, we used simulations to predict 23.1 millions of tons of GHG emissions in 2050, representing a decrease of 64.8% instead of the objective of -79%.

The most efficient measure is the tax credit (Table 2). It leads to an important decrease in the energy income ratio (almost 22%), energy consumption, and GHG emissions (more than 31%). However, when we also account for the public costs, the subsidy is the most efficient method. The cost of the tax credit reaches 462.87 euros per ton of CO_2, compared with 15 euros for the subsidy. This result is not surprising; a subsidy is the only measure that focuses specifically on low-income households living in less energy efficient dwellings. It aims to induce the households with the lowest income to renovate, and these households also have the highest energy income ratio. After the renovation, they live in more energy-efficient buildings, so they can decrease their emissions and energy expenditures. The tax credit invokes a greater decrease of GHG emissions but at a higher public cost. It includes all households but induces changes mainly by households with high incomes (and high income tax).

Social energy tariffs have a slight impact on the energy burden, because energy prices are increasing faster than income. The energy income ratio decreases by 0.16% with this measure alone.

We also test the new social measure, the "chèque énergie" or bonus, suggested by the Energy Transition Law project. To the reference scenario, we add a bonus of 1350 euros for households that belong to the first quintile, to help them to pay their energy bills. This amount is one-fifth the average expenditures for energy-saving renovations, which has been estimated at €6410 (and 50% of renovations have a cost below €5000; ADEME, 2011). With this addition, the energy income ratio decreases, but not enough to move beyond the 10% ratio for households in the first income quintile (Tables 2 and 3). Nor are the objectives for GHG emissions reached. The only objectives achieved are those related to energy consumption. This additional measure is not sufficient to reach the French objectives, and the public cost is very high, at 811.66 euros per ton of CO_2 saved. Measures that seek to induce households to undertake energy-efficient renovations (e.g., tax credit, subsidy) thus are more efficient than social measures (e.g., social energy tariff, bonus), for decreasing both the energy burden and the environmental footprint.

Regardless of the scenario (reference scenario or with bonus), the 30% objectives for the share of renewable energy for 2030 are not reached (i.e., 26% of total energy consumption). With regard to GHG emissions and energy consumption, this result hides some large disparities across households. Only wealthier households invest in renewables. Thus, another recommendation emerges from these results: Governments must ensure social equity in implementing their public policies. Members of quintile 3 (middle class) are not necessarily able to finance renovations in renewable energy and are not targeted by policy makers, because the subsidies focus only on lower income households. They may become a vulnerable population in the long run too.

Table 2: Comparison of policies

	Tax Credit	Zero-Rate Bank Loan	Subsidy	Social Energy Tariff	Bonus	All Policies Together
Evolution of average energy income ratio in 2050 (%) compared with a scenario without policy						
All households	-21.98%	-8.46%	-6.91%	-0.16%	-4.29%	-26.70%
Income Quintile 1	-22.54%	-8.59%	-13.82%	-0.31%	-8.66%	-31.78%
Income Quintile 2	-22.41%	-9.01%	/	/	/	-22.02%
Income Quintile 3	-14.50%	-5.80%	/	/	/	-14.61%
Income Quintile 4	-28.82%	-25.97%	/	/	/	-28.41%
Income Quintile 5	-23.95%	-16.36%	/	/	/	-24.12%
CO_2 saved in 2050 (%) compared with a scenario without policy						
All households	-31.17%	-21.47%	-3.87%	0.00%	-2.73%	-34.16%
Income Quintile 1	-29.43%	-16.61%	-15.59%	0.00%	-10.69%	-40.26%
Income Quintile 2	-15.15%	-18.82%	/	/	/	-32.08%
Income Quintile 3	-28.27%	-20.02%	/	/	/	-31.17%
Income Quintile 4	-35.54%	-27.66%	/	/	/	-39.40%
Income Quintile 5	-36.29%	-30.15%	/	/	/	-38.83%
Energy consumption saved in 2050 (%) compared with a scenario without policy						
All households	-31.81%	-26.05%	-1.88%	0.00%	-1.23%	-35.36%
Income Quintile 1	-28.84%	-25.75%	-8.71%	0.00%	-5.74%	-37.28%
Income Quintile 2	-32.23%	-24.54%	/	/	/	-33.47%
Income Quintile 3	-26.80%	-14.13%	/	/	/	-29.50%
Income Quintile 4	-32.62%	-31.59%	/	/	/	-34.56%
Income Quintile 5	-39.33%	-35.38%	/	/	/	-41.41%
Public cost						
Public cost in € / tCO_2 saved	462.87	493.25	15.00	No effect on CO_2	811.66	-
Total energy saving (in euros) by all households in Quintile 1 for each euro spent by the government	0.49**	0.27	21.20	No effect on energy consumption	0.32	-

Notes: With a tax credit only, the energy income ratio in 2050 is 21.98% lower than in a scenario without policy. For each 1 euro spent by the government as a tax credit, the total energy saving is 0.49 euro for all quintile 1 households.

Comparing the number of renovations conducted without any public policy against the number with public policies, according to income quintile, we can assess the number of free-riders (i.e., households that would have made energy efficiency investments even in the absence of public policy). Therefore, the effectiveness of the public policy is an important issue, and free-riding undermines it. Recent estimates of the extent of this form of free-riding range from 50% to 92% (Grösche and Vance, 2009; Malm, 1996). Using French data, Risch (2014) predicts that 79% of households that received a tax credit would have performed the renovation without the subsidy. Nauleau (2014) estimates that the average proportion of free-riders has varied between 40% and 85% since 2006. Our results indicate that 74.6% of households free-ride when all policy measures are taken together. We also identify different results according to the quintile. The share of free-riders reaches 88.8% for households in the fifth quintile (cf. 24.8% for households in the first quintile). That is, free-riding is greater among the wealthiest households; it also varies with the type of policy measure. The tax credit invokes the most free riders, followed by the zero-rate bank loans (which targets mainly wealthy households). Moreover, the joint implementation of multiple instruments leads to interactions that diminish overall policy outcomes (Bennear and Stavins, 2007). Same households can benefit from different policies and would have renovated without them.

Table 3: Comparison of the reference scenario with bonus of €1350 for low-income households

	Millions of Tons of kWh	Evolution Compared to 2014	Millions of Tons of CO_2	Evolution Compared to 2014	Energy Income Ratio (%)	Evolution Compared to 2014
Situation in 2014						
All households	***585.7***		***65.7***		***5.33***	
Income Quintile 1	*116.6*	-	*15.0*	-	*12.05*	-
Income Quintile 2	*114.8*		*14.2*		*6.05*	
Income Quintile 3	*119.9*		*12.4*		*4.11*	
Income Quintile 4	*111.5*		*11.5*		*2.71*	
Income Quintile 5	*122.9*		*13.0*		*1.70*	
Situation in 2050						
Objective by 2050	*292.5*	*-50% (compared to 2014)*	*13.75 (level compared to 1990)*	*-79%*	*<10% for all income quintiles*	
Reference Scenario and bonus from 2014: situation in 2050, compared to 2014 (reference scenario)						
All households	**238.0**	**-59.36%**	**24.5**	**-62.71%**	**4.47**	**-16.14%**
Income Quintile 1	56.0	-51.97%	5.81	-61.27%	10.77	-10.62%
Income Quintile 2	49.4	-56.97%	5.03	-64.58%	5.16	-14.71%
Income Quintile 3	51.5	-57.05%	5.32	-57.10%	3.57	-13.14%
Income Quintile 4	38.2	-65.74%	3.94	-65.74%	1.71	-36.90%
Income Quintile 5	42.9	-65.09%	4.44	-65.85%	1.16	-31.76%
Notes: Public cost: €811.66 / tCO_2 saved. Total energy saving (in euros) by all households in quintile 1: 0.32 euro/euro spend by the government						

4.2 Results obtained with new public policies

If the objectives cannot be achieved with current policies (cf. energy consumption), we might propose two additional measures: subsidies on renewable energies or bonuses for households belonging to first quintile, as well as carbon taxes.

4.2.1 Subsidies for renewables energies and bonus for households belonging to first quintile

One solution might be to trigger investments in renewable energies, which would decrease GHG emissions due to fossil fuels and energy costs (which produce the high energy income ratio). We start by testing the effect of increasing the tax credit to 50% of the deduction rate for the adoption of renewable energy from 2014, beyond the current policy. In addition, we test a bonus of 2000 euros in 2014 (increasing at the rate of inflation) for all households that invest in renewable energies. None of these measures achieves the objectives though, because they do not encourage sufficient investment in renewable energies. Introducing a tax credit can have important effects initially, but over time, only the wealthier households renovate. The total number of renovations (and the impact on GHG emissions) over the entire period thus does not differ much from the reference scenario. We would realize GHG savings faster but without reaching the objectives. We reach the same conclusion when we test the bonus.

Another solution would be to introduce measures for households that belong to the first income quintiles. Because low-income households are those that emit the most, this approach might help decrease inequalities among households. Accordingly, we simulate the effect of bonuses for households in the first quintile and all energy-saving renovations, in addition to current policies. We test different amounts of bonuses, increasing at the inflation rate. A bonus of €4000 is needed to reach an average energy income ratio below 10% for households in the first income quintile. To achieve the GHG emission objective, the bonus must be at least €5500 (Figure 6). This amount is huge, considering that half of all renovations cost less than €5000 (ADEME, 2011). We estimate that the public cost of this bonus would be 755,93 euros per tons of CO_2 saved.

We also extend this bonus to households in income quintiles 2 and 3. A bonus of €4000 could reach the energy burden objective; a bonus of €4500 would be needed to achieve the desired environmental footprint too (Figure 7). These amounts are approximately equivalent to the cost of a renovation, which constitutes a huge problem in terms of public costs. Here, the public cost is 1416,68 euros per ton of CO_2 saved.

Figure 6: Bonus for households in the first income quintile

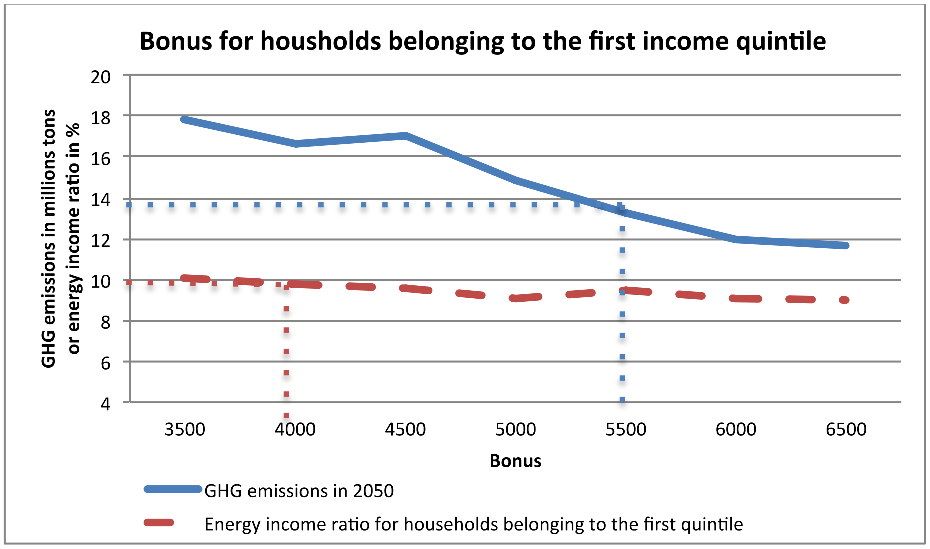
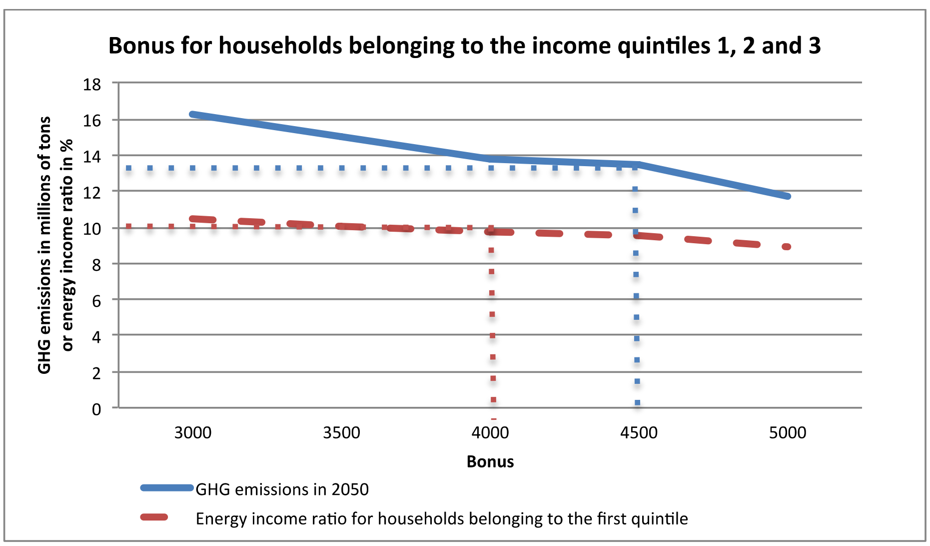


Figure 7: Bonus for households in income quintiles 1, 2, and 3



4.2.2 Carbon tax

We also test the effect of a carbon tax, to assess its impact on GHG emissions and energy consumption. A carbon tax of 32 euros would apply to dwellings with bad energy labels (i.e., E, F, and G). This tax is not enough to decrease the energy income ratio for households in the first quintile, but it triggers energy efficiency investments. To avoid another form of inequality though, the taxes should be paid by landlords in communal residences, because the poorest households often live in less insulated dwellings and are mainly tenants. For example, Bräanlund and Nordström (2002) in Sweden show that the CO2 tax has regional distribution effects, in the sense that household living in sparsely populated areas carry a larger share of the tax burden. Moreover, these results demand careful interpretation: The model is in partial equilibrium, and it is not possible to simulate a carbon tax that affects the whole economy or every aspect of people's lives.

Therefore, it might be appropriate to fight fuel poverty not with another energy efficiency measure but by introducing new measures to fight monetary poverty. Although the redistributive effects of the measures can be considered (carbon tax to finance subsidy for example), measures to encourage energy renovation does not seem the most appropriate. We must focus on poor households and therefore on measures to fight monetary poverty.

4.3 Sensitivity analysis

The results from the sensitivity analysis all refer to the year 2050, as we summarize in Table E-4 in appendix. Energy prices are key explanatory variables for the energy burden: A huge increase in energy prices causes important decreases in energy consumption and GHG emissions, and energy efficiency renovations become more attractive.

An interesting finding also emerges from the renovation prices, in that the results are very sensitive to this parameter. Lowering renovation prices leads to the achievement of France’s objectives, without modifying the policy mix. Therefore, the government might find ways to set renovation costs, such as by introducing a ceiling price. Most companies account for the subsidies allowed by the government in calculating renovation costs (Risch, 2014). This result is reinforced when we consider interest on bank loan. Despite a huge decrease of interest rates, the energy consumption stay higher. This result is especially for low income, even if the access to capital is facilitated. Although we only tested measures dedicated to the demand side, in line with the dominant perception that the low rate of energy efficiency investment is a demand problem, our results suggest that the supply side may be a potential path to energy efficiency renovations.

The results also are sensitive to the income growth parameter. If the income growth rate is high (around 4%), all households escape fuel poverty, even those in first income quintile. If the French economic context is less optimistic (e.g., rising unemployment rate), an income decrease could have serious consequences in terms of the energy burden and GHG emissions. This would be the case during the financial crisis. Thus, policies dedicated to monetary poverty problems seem more appropriate than policies to trigger energy efficiency investments. When the discount parameter decreases, energy-saving renovations increase, because the net discounted profits are higher. The level of energy consumption, GHG emissions, and the energy income ratio all are decreasing functions of the discount rate.

Then, if all households become homeowners, the energy income ratio or energy burden would decrease. Encouraging ownership may be meaningful for diminishing energy consumption, GHG emissions, and the energy burden, because homeowners generally are more willing to make energy-efficient renovations than are renters. The renovation rate is very low among tenants.

Finally, results are obtained in a partial equilibrium framework. It would be interesting in future researches to analyze the same decision in a general equilibrium setting.

5. Conclusion and policy recommendations

The objective of this article was to establish a general understanding of the energy burden, as a proxy for fuel poverty, and thereby help policy makers make decisions. Accordingly, this research sought to assess current public policies aimed at reducing GHG emissions, lowering energy consumption, and alleviating the energy burden in the long term, as well as to provide some policy recommendations. As an original contribution, this study reveals who suffers the most from an increase of energy costs, as well as who benefits most from residential energy efficiency improvements using a bottom-up approach. Although the model was calibrated with French data, other simulations with other European dataset are feasible in the future. Through our efforts to gain a general understanding of the impact of French public policy on these indicators, we determine that existing public policies (e.g., tax credit, zero-rate bank loan, subsidies, social energy tariff) are not sufficient to reach the social objectives for fuel poverty alleviation and normative environmental targets. Moreover, a global decrease in GHG emissions or energy consumption tends to hide large disparities among households, according to their level of income. Households in the first income quintile will not renovate their homes, and their energy income ratio will remain higher than 10% in 2050, with current policies. Moreover, these policies represent a high public cost, with free-riding estimated to reach 75% over the period. Moreover, the joint implementation of multiple instruments leads to interactions that diminish overall policy outcomes. Energy efficiency measures must focus on low-income households, and the government should address monetary poverty, which is largely responsible for the low rate of renovation. An adequate policy measure should let a decrease of GHG emissions but would be also a solution to decrease other public expenditures to help low income households in the future. In consequence, fuel poverty and inefficiency in the residential sector is mainly due to monetary issue. The government would do better to invest the money of these policies in action against poverty instead of investing them in favor of energy efficiency, especially when we consider free-riding. Although the redistributive effects of the measures can be considered (carbon tax to finance subsidy for example), measures to encourage energy renovation are not appropriated. We must focus on poor households and therefore on measures to fight monetary poverty. Finally, the low rate of energy-efficient renovations mainly has been treated as a demand-side issue. But the cost of renovation is so high mainly because building professionals integrate the amount of public policies allocated by the government into their costs. Thus, monitoring renovation costs could be a solution that might induce more households to renovate.

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Appendix A. Energy Burden in European Countries (Source: Wand, 2013)

Figure A1: Percentage of households unable to afford to keep their home adequately warm

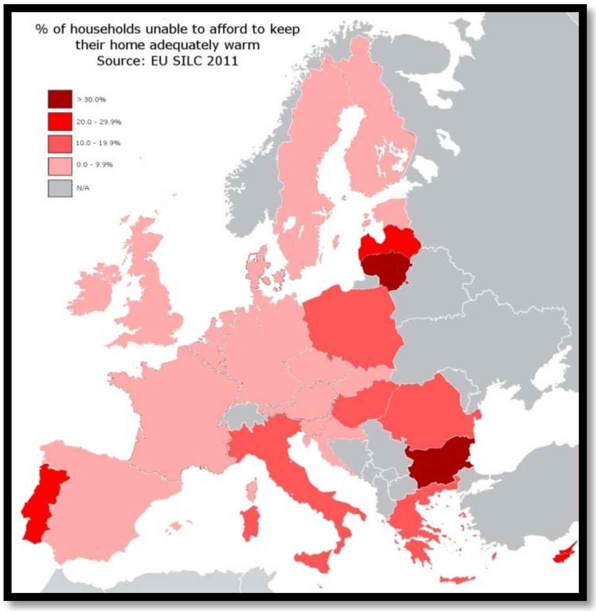


Figure A2: Percentage of households in arrears on utility bills

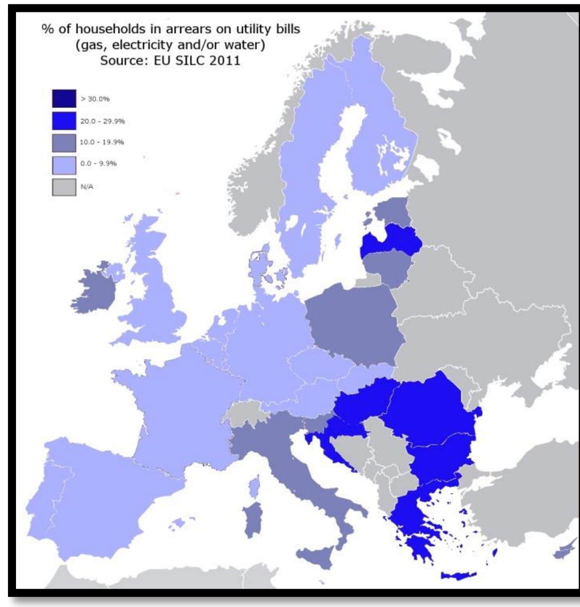
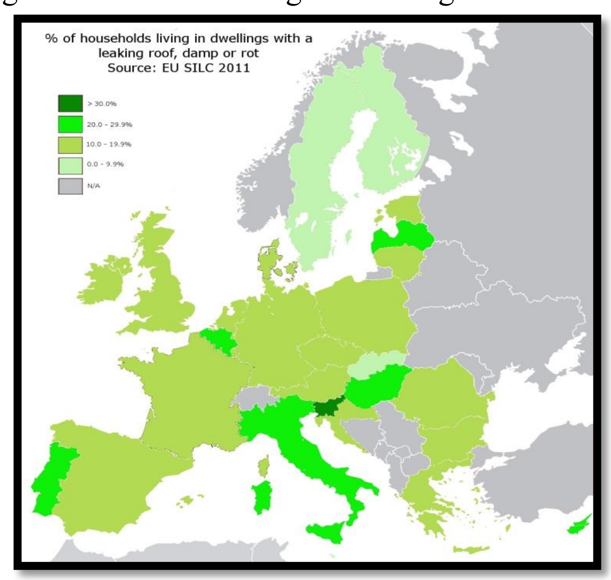


Figure A3: Percentage of households living in dwellings with a leaking roof, damp or rot



Appendix B. Public policies

Table B-1: Public policies

Measure	Description	Rate and/or Amount
To improve energy efficiency of the buildings		
Tax credit	Some of the expenses of energy-saving renovations can be deducted from the household's income tax (or refunded if the household pays no income tax). The credit applies only to specific renovations, and the expenses deducted are limited, depending on household characteristics.	30%
VAT reduction	A reduction of the indirect tax, based on consumption	5.5% (instead of 19.6%)
Zero-rate bank loan	No interest bank loans for homeowers who make several renovations or important energy-saving investments. The amount of the loan depends on the renovation. It is possible to combine it with the tax credit for several renovations.	
ANAH Subsidy	A subsidy depending on household income (mainly focused on first income quintile households). It is possible to combine it with the tax credit and zero-rate bank loan.	50% of renovation expenses for very low income households and 35% for low income households.
"Live better" subsidy	Complement to the ANAH subsidy. The same households are eligible.	3000€, with a possible increase in the share of the local community up to 500 €
To help low income households pay their energy bill		
"Chèque énergie"	For very low-income households, a bonus or check to help them pay their energy bills. This measure, still to be tested, may reduce energy bills or increase income.	The threshold have not been set yet. Several amounts are possible.
Social energy tariffs	Tariffs for very low income households that use electricity or gas as their main fuel.	For gas, tariffs reduce the bill between 22€ and 156€. For electricity, tariffs reduce the bill between 71€ and 140€.

Notes: To receive these financial assistances, households must hire professionnal renovators. If they perform the renovations themselves, they may not receive subsidies, tax credits, or zero bank loans.

Appendix C. Main factors explaining energy burden

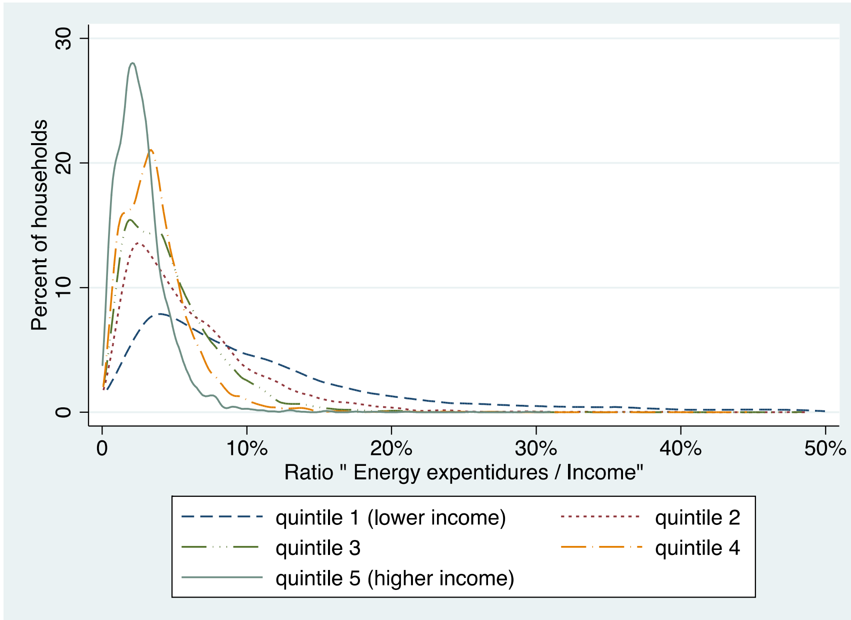
We use the *2006 enquête logement* from INSEE to study the key determinants of energy burden. This is a disaggregated households-level survey data set, which give information on 36, 955 households, including their socio-demographic characteristics (e.g., income, number of persons, occupancy status, education level) and housing characteristics (e.g., type of dwelling: individual or collective, size, year of construction, type of energy used, effective energy expenditures, double glazing, quality of roof and walls). When we exclude any partial observations, we retain a final sample of 22,938 households. To study their energy burden, we calculate their *energy income ratio* (i.e. the ratio energy expenditures on income) (EPEE, 2007, 2011). On average, the households in the database spend 6.4% of their income for household energy uses (excluding transportation uses), in line with previous studies (De Quero, 2009). We note that 15.8% of households in our sample spend more than 10% of their income on energy expenditures, many of which are low income households (i.e., 49.22% of households in the first income quintile display an energy income ratio greater than 10%, compared with 1.16% of households in the fifth income quintile). The energy burden thus correlates with income, as Table C-1 and Figure C-1 confirm.

Table C-1: Energy income ratio by household characteristics

	Energy Income Ratio	Percentage of Households with Ratio > 10%
Quintile 1 (lowest income)	14.24 %	49.22 %
Quintile 2	6.62 %	20.24 %
Quintile 3	5.18 %	9.30 %
Quintile 4	4.11 %	3.34 %
Quintile 5 (highest income)	2.8 %	1.16 %
Owners	6.79 %	17.66 %
Tenants	5.85 %	13.19 %

Source: INSEE, 2006 Enquete logement, Final sample

Figure C-1: Distribution of the energy expenditures/income ratio by income quintile



Source: INSEE, 2006 Enquete logement, Final sample

According to prior literature (Davis, 2010; Mahapatra and Gustavsson, 2008; Meier and Rehdanz, 2010; Mendelson, 1977), households' characteristics, beyond income, have impacts on their energy expenditures and energy burden. Owners' energy burden also is slightly higher than tenants' (by one percentage point), which may stem from the characteristics of the building. Whereas 77% of tenants live in collective buildings, 78% of owners live in individual housings. The energy burden is more substantial for individual housing (Table C-I), which tends to be bigger (117 m^2 on average, versus 70 m^2 for collective buildings).

Moreover, poorly insulated housing, unsuitable heating systems, and defective insulation (windows, roof structures, walls) are crucial determinants of the high energy income ratio, according to the *European energy burden and energy efficiency group* (2006) and as confirmed by the table below (Table C-2).

Table C-2: Energy income ratio by building characteristics

	Energy Income Ratio	Percentage of households with Ratios > 10%
Collective buildings with collective heating	3.46 %	5.28 %
Collective buildings with individual heating	6.69 %	14.82 %
Individual housing	7.70 %	21.17 %
Surface area below 50 m^2	5.23 %	10.97 %
Surface area between 50 and 75 m^2	5.94 %	14.31 %
Surface area between 75 and 100 m^2	6.25 %	15.88 %
Surface area between 100 and 150 m^2	6.87 %	16.38 %
Surface area above 150 m^2	7.55 %	21.26 %
Heating with electricity	5.85 %	11.81 %
Heating with gas	5.77 %	12.08 %
Heating with oil	7.73 %	24.03 %
Heating with wood or charcoal	7.60 %	19.45 %
Year of construction before 1975	6.84 %	18.07 %
Year of construction after 1975	5.45 %	10.93 %
Without double glazing	6.90 %	19.32 %
With double glazing	6.15 %	14.06 %
Moisture in the dwelling	6.79 %	18.17 %
No moisture in the dwelling	6.30 %	15.24 %
Cold problem in the dwelling	6.60 %	17.11 %
- related to poor insulation	6.63 %	17.51 %
- related to the cost of heating	10.05 %	38.58 %
No cold problem	6.34 %	15.62 %

Source: INSEE, 2006 Enquete logement, Final sample

Appendix D. List of variables

Variables	Description
i	Index for the type of dwelling
q	Index for the type of income quintile
t	Index for the time period
r	Index for the type of renovation
EC	Energy consumption (total)
EC_{END_USEt}	Energy consumption for each end-use
H	Heating (consumption, GHG emissions, or energy income ratio)
Lt	Lighting (consumption, GHG emissions, or energy income ratio)
At	Appliances (consumption, GHG emissions, or energy income ratio)
S	Surface area
EE	Energy expenditures
EIC	Energy income ratio
P	Energy prices
Y	Disposable income
NC	New construction
D	Demolitions
R	Renovations
AGE	Age of the housing stock (obsolescence)
AGER	Age of the housing stock (obsolescence) after a renovation
PI	Probability to invest
NPV	Net present value
C	Renovation cost
FC	Financial constraint
G	Energy savings
Φ	Market long-term interest
T	Average life of equipment

Appendix E. Calibration of the simulation model

Table E-1 : Sources of data and assumptions

Parameters	Sources of data and assumptions
Housing Stock	A function of demographic evolution taking into account jointly households composition and income evolution. New constructions are a function of demolitions and renovations. Thermal regulations are considered. The probability to live in a specific category is a function of occupancy status, income quintile as well as the number of persons in the household.
Demolition	A constant share of the housing stock. In 2006, data come from Ministry of Ecology, Sustainable Development and Energy (website: http://www.developpement-durable.gouv.fr/).
Renovations	Depending on obsolescence of dwelling and cost-benefits analysis. Renovations are a function of households' decision according to their financial constraint.
Energy Consumption related to heating and hot water	Depending on energy consumption of new constructions (based on thermal regulations), demolitions and renovations (energy consumption are obtained using PROMODUL software for 2006 and the data are available from the authors upon request. In this software, energy consumption can be calculated using 3CL method to estimate energy consumption and GHG emissions in France, and it is used to label the dwellings. This computation method is described by a French decree in November 2006). Results are controlled in 2012 with PHEBUS database for energy consumption.
Cost Benefit analysis	Depending on: -household financial constraint (data come from INSEE). The decision is endogenous and depends on households' financial constraint. -prices of renovations (from ADEME) -energy savings
Energy savings	Energy savings in kWh and kg_{CO2} are linear functions of AGE_{it}. These functions were constructed using PROMODUL software. Energy savings in euros through the renovation depend on: -energy prices (projection of IEA) and social energy tariff. -average life of equipment (ADEME) Possibility to modify during the period these parameters in case of crisis, change policies or important innovation.
Energy Consumption related to appliances	Depending on: -repartition in energy label (ADEME) -utilization and equipment rate (INSEE)
Energy Consumption related to lighting	Depending on: -the number and the kind of lights bulbs (data from ADEME) -surface area (from INSEE in 2006 and then the surface area for new construction is increasing by 0.46% per year. This figure is based on the twenty previous years trend)
Energy Burden	Depending on: -Energy expenditures (evolution of energy prices and social energy tariff) -renovations -Income (depending on economic growth)

Table E-2: Main values of parameters used for calibration

Parameters	2006	Annual change	Sources
Number of dwellings	26,049,046	Depending on number of households	Ministry of Ecology, Sustainable Development and Energy
Number of new constructions	0.84% of the total housing stock	Endogenous	Ministry of Ecology, Sustainable Development and Energy
Demolition rate	0.05%	Constant of the period	INSEE
Energy consumption for new dwelling	110 kWh/m /year	110 until 2013, 50 kWh/m /year until 2030, 10 kWh/m /year after.	Thermal regulations, Ministry of Ecology, Sustainable Development and Energy
Surface area (in square meter)	65 in collective buildings and 110 in individual housing	Surface area for new construction is increasing by 0.46% per year	*INSEE*
Average area per new built dwelling	66 m in collective buildings and 110 in individual housing	0.46% per year	*INSEE, projection of past trend*
AGE	60	Endogenous	*INSEE, l'enquête logement 2006*
Energy prices (euros/kWh/m)			
Gas	0.0529	5.23%	Ministry of Ecology,
Fuel	0.0651	5.22%	Sustainable Development
Electricity	0.091	3.2%	and Energy
			Projection between 2006
Social energy tariffs	22€ for gas	5.23%	et 2013
	156€ for electricity	3.2%	
Interest rate of bank loan for renovation works	6.12%	Constant over the period	*INSEE*
Inflation rate	2%	2%	*OECD*
Discounting rate	2.98%	Constant over the period	
Average cost of renovations (in euros by square meter)			
double glazing	27.6	2%	*ADEME*
wall insulation	15.31	2%	*ADEME*
roof insulation	10.72	2%	*ADEME*
changing heating system	35.88	2%	*ADEME*
renewable energy	106.42	2%	*ADEME*
Rate of income growth		1.98%	*INSEE*
Homeowner share	57.2%	Constant over the period	*INSEE, l'enquête logement 2006*

Table E-3: Main values of income parameters used for calibration

	Individual housing units		Collective buildings	
	Homeowners	Tenants	Homeowners	Tenants
Electricity				
Quintile 1	9568	7892	9242	8481
Quintile 2	17867	17370	17900	17385
Quintile 3	27049	26514	26791	26245
Quintile 4	37426	36705	37526	37519
Quintile 5	67817	64618	65790	58614
Gas				
Quintile 1	9109	8690	9247	8727
Quintile 2	17880	17411	17817	17276
Quintile 3	27053	26449	26878	26207
Quintile 4	37664	36726	37503	36825
Quintile 5	68579	64618	69174	65774
Oil				
Quintile 1	9858	8695	9517	8733
Quintile 2	17826	17335	17554	17453
Quintile 3	26507	26762	26638	25875
Quintile 4	37168	37226	36887	36750
Quintile 5	69380	60856	65895	63194
Renewables				
Quintile 1	7679	11036	7772	9693
Quintile 2	17677	15265	17791	16887
Quintile 3	26228	25608	27719	25214
Quintile 4	36833	37842	38610	35980
Quintile 5	62533	64282	75961	56178

Source: Enquête logement 2006, INSEE

Table E-4: Sensitivity analysis

	Low Scenario	**Reference Scenario**	**High Scenario**
Inflation rate	**1%**	**2%**	**3%**
Energy consumption	248.2	245.5	243.5
GHG emissions	23.4	23.1	22.8
Energy Income ratio	4.78	4.70	4.65
Discounting rate	**1.5%**	**2.98%**	**4%**
Energy consumption	243.7	245.5	251.1
GHG emissions	23.1	23.1	23.2
Energy Income ratio	4.70	4.70	4.71
Anticipated increase in domestic prices			
Renovation prices	**-1pp**	**2%**	**+1pp**
Energy consumption	196.1	245.5	468.15
GHG emissions	14.61	23.1	45.9
Energy Income ratio	3.63	4.70	7.72
Gas	**-1pp**	**5.23%**	**+1pp**
Energy consumption	283.1	245.5	230.5
GHG emissions	29.0	23.1	21.7
Energy Income ratio	5.12	4.70	4.52
Oil	**-1pp**	**5.22%**	**+1pp**
Energy consumption	289.5	245.5	232.8
GHG emissions	31.40	23.1	19.32
Energy Income ratio	5.45	4.70	4.46
Electricity	**-1pp**	**3.2%**	**+1pp**
Energy consumption	380.44	245.5	233.3
GHG emissions	30.8	23.1	21.8
Energy Income ratio	4.70	4.70	4.70
Income growth rate	**1%**	**1.98%**	**3%**
Energy consumption	277.01	245.5	239.8
GHG emissions	26.6	23.1	22.4
Energy Income ratio	8.57	4.70	4.65
Demolition rate	**0.1%**	**0.5%**	**1%**
Energy consumption	245.4	245.5	242.3
GHG emissions	23.1	23.1	22.7
Energy Income ratio	4.7	4.70	4.63
Interest rate of bank loan	**2%**	6.12%	
Energy consumption	**223.3**	245.5	
GHG emissions	**16.75**	23.1	
Energy Income ratio	**4.49**	4.70	
Homeowner share		**52.7%**	**100%**
Energy consumption		245.5	225.3
GHG emissions		23.1	18.3
Energy Income ratio		4.70	4.1

[i] The energy burden generally is measured as the ratio of energy expenditures to household income (Hills, 2011, 2012; Palmer *et al*., 2008). Among other indicators (see Legendre and Ricci, 2015), an excessive energy burden represents a proxy of fuel poverty, which leads households to suffer thermal discomfort. Households that cannot sustain an adequate level of warmth and comfort at a reasonable cost confront a situation of fuel poverty (Boardman, 1991, 2004; Lewis, 1982; ONPE, 2014). For this study, an energy burden exists when the energy income ratio is greater than 10%, in line with common definitions of fuel poverty (European Fuel Poverty and Energy Efficiency, 2006; Hills, 2011).

[ii] The major attributes of bottom up approach is the determination of typical end-use energy contribution and the inclusion of socioeconomic using billing data from a survey sample of households (see Swan and Ugursal (2009) for a precise review of this techniques).

[iii] We consider environmental objectives set by the Grenelle Act, which is divided by 4 GHG emissions by 2050, compared to their 1990 level. For the social objective, a household is in fuel poverty situation if energy expenditures represent more than 10% of its total income. We set the objective to be lower than this limit.

[iv] This survey gives information about 36,955 households, including their socio-demographic characteristics (e.g., income, number of persons, occupancy status, education level) and housing characteristics (e.g., type of dwelling: individual or collective, size, year of construction, type of energy used, effective energy expenditures, double glazing, quality of roof and walls). When we exclude any partial observations, we retain a final sample of 22,938 households.

[v] For electricity, it is necessary to produce 2.58kWh/m ^{2}/year of primary energy to obtain 1 kWh/m ^{2}/year of final energy.

[vi] Similar to Charlier and Risch (2012), we assume households may incur two types of loans: a conventional bank loan and a zero-rate bank loan. They also can receive a tax credit, a subsidy, a bonus, and a benefit from reduced VAT rates (see Table B-I in appendix). In addition, if a household decides to make the renovations itself, to save the cost of hiring a company to do the work, the household will not receive assistance (subsidies, VAT reduction, income tax deduction, or zero-rate bank loan). The percentage of households choosing to do the renovation work themselves differs for each type of renovation and varies over time, according to the ratio between the total cost of a measure including the cost of hired labor and the cost without hired labor. The share of households engaging in renovations on their own increases with the cost of hired labor.

[vii] To ensure the thermal quality of new buildings, various thermal regulations have been implemented. In France, the first thermal regulation was set in 1974, and since then, they have grown more stringent, up to the most recent regulation established in 2012.

[viii] The energy performance diagnosis is a document that provides an estimate of energy consumption and greenhouse gas emissions of a dwelling. It is part of the technical diagnostics record, as well as asbestos diagnostics, termites, lead and status of indoor facilities for electricity and gas. This diagnosis has been mandatory since 1 November 2006 in case of sale of a dwelling and since 1 July 2007 for leasing. The display of the energy performance of real estate in the real estate agencies has been mandatory since 1 January 2011.

[ix] The PHEBUS (Housing Performance survey, Equipment, needs and uses of energy) database is a new time survey. This new punctual survey consists of two parts made separately, a face to face with the occupants of the home about their energy consumption expenditures and their energy consumption attitude, and an energy performance diagnosis of the housing. The survey aims to provide information about the energy performance of the housing stock, allowing for analysis according to the households' characteristics, households' appliances, as well as their energy use and their energy consumption. The survey was conducted from April to October 2013. The Operation Manager of the survey are: Ministry of Ecology, Sustainable Development and Energy (MEDDE); General Commission for Sustainable Development (CGDD); Service Observation and Statistics (SOeS); Under direction of the housing and construction statistics; Under the direction of energy statistics