

A model of the French residential demand for heating energy to evaluate the impact of policy instruments

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Abstract

The residential building sector features both a high share of final energy consumption and large technical potentials for energy savings. Proactive action is thus necessary but has failed so far because of market and behavioural failures, justifying the implementation of public policies. In France, the ambitious target of reducing residential energy consumption by 38% in 2020 compared to 2008 has been set and associated policy instruments are being designed.

We develop a model of the French residential sector to assess the ability of the proposed policy mix to reach this objective and its economic cost. Focused on the demand for space heating, the model builds on energy performance classes to describe new constructions and retrofitting of existing buildings. We attempt to overcome traditional modelling limitations in the residential sector by describing explicitly investment and consumption behaviours on the demand side and endogenous retrofitting dynamics on the supply side. The model therefore includes the following innovative features: a clear distinction between energy efficiency (i.e. investment decisions in energy efficient technologies like heating systems and insulation) and sufficiency (i.e. the absolute level of energy consumed for a given service), allowing for rebound effect estimation; gaps from the perfect rationality and information hypothesis in representing decision maker's heterogeneity (in particular between landlords and tenants) and incomplete information on energy efficient goods; an endogenous retrofitting rate resulting from countervailing effects on the potential for energy savings by natural exhaustion on the one hand and deepening through technology learning on the other hand. The model is connected to the hybrid model IMACLIM-R and energy prices are thus endogenous.

The business as usual scenario shows that in 2020, energy demand for space heating is likely to decrease by 16% while other uses increase significantly, which makes the national target very unlikely to be reached. A sensitivity analysis on energy prices and decision maker's heterogeneity parameters exhibits a variation range of +/- 5%. Policies are then simulated, CO₂ and end-use energy taxes, subsidies on efficient retrofitting and regulations on both new constructions and retrofitting. Although leading all to effective energy savings compared to the business as usual scenario, they are not equal in terms of cost-effectiveness: taxes are by far the more cost-effective, with virtuous effects on both efficiency and sufficiency; building codes entail a high degree of effectiveness in new constructions but a much smaller one in retrofitting; subsidies generate a marked net social cost but may have positive short term effects on consumer information and technology learning in combination to other policies. But on the whole, none of the policies evaluated allows reaching the 2020 target, which makes new radical ones necessary.

Keywords

French policy, energy efficiency, energy sufficiency, consumer heterogeneity, retrofitting dynamics

JEL codes

H23, Q47, Q48, R21

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1. Introduction

Among end-use energy consuming sectors, residential buildings encompass the highest technological and behavioural potentials to reduce the energy demand and thus cut CO₂ emissions (Levine et al., 2007). However, chronic underinvestment in energy efficiency is observed and it is generally assumed that despite their long-term profitability, energy efficiency investments in the residential sector are hurdled by a set of “barriers” like imperfect information or split incentives (Sorrell et al, 2004; Gillingham et al, 2009) that justify the implementation of public policies (Goulder et al, 2008). In France that question was central to the *Grenelle de l’environnement* process, a collective consultation held in 2007 and aimed at giving a new orientation to the French environmental policy for the next decades. This resulted in 2008 in a law² setting the target of reducing energy consumption in the residential sector by 38% in 2020 compared to 2008. Policy instruments designed to meet this target are being defined in another forthcoming law. The magnitude of this target, considered as ambitious by many stakeholders, is difficult to evaluate since neither the energy savings potential nor the *ex ante* impact of policy instruments about to be implemented have been estimated. Therefore, there are social needs for prospective technical-economic studies on the *Grenelle de l’environnement* impacts in the residential building sector and this is our goal to meet them.

The reason for that gap is that most models have failed so far to catch the endogenous complex dynamics occurring in the residential building sector. In a recent paper, Swan et al review top-down and bottom-up techniques that have been used in this field to date (Swan et al, 2009). The authors figure out that due to its focus on historical responses, the former is best suited for forecasting energy supply whereas the latter is best suited for energy efficiency improvements analysis thanks to its behavioural and technological detail. In addition to these limitations, intrinsic to these modelling methods regardless of the end-use sector, the residential sector faces a specific lack of knowledge on its presumably fundamental drivers that make the use of technical-economic models even more difficult:

- Energy consumption is the resulting product of *energy efficiency* (the amount of energy per unit of energy service) and *energy sufficiency* (the amount of energy service). This distinction is crucial for the analysis of the rebound effect, i.e. when energy efficiency improvements are followed by a decrease in absolute energy consumption to a lesser extent (or even increase) because of a sufficiency relaxation (due to increased rate of capital utilization, increased load, etc.). Although theoretically formalised and empirically estimated in the residential sector (Sorrell et al, 2009), the representation of the rebound effect in prospective models is rarely satisfying. More precisely, bottom-up models fail to take account of sufficiency feedbacks, whereas top-down models merge them with efficiency improvements together in price and income elasticities of the energy demand.
- The core determinants of energy efficiency investments are subject to debate since the early 1970s. Several concepts have been investigated to explain or to model consumer underinvestment in energy efficiency like high implicit discount rates (Train, 1985), split incentives between landlords and tenants (IEA, 2007) or option values (Ansar et al, 2009). These multiple market and behavioural failures are united under the broad notion of “barriers to energy efficiency”. They are well documented and some of them

² Loi n° 2009-967 du 3 août 2009 de programmation relative à la mise en œuvre du Grenelle de l’environnement (1), Article 5

have been empirically quantified (Sorrell et al, 2004). Nevertheless, stylized representations are still missing and this prevents their implementation in prospective models, where the discount rate settlement remains the common way to take account of them. Progress towards a better representation of the barriers has been made in CIMS model (Jaccard and Dennis, 2006), as we will see later.

- Lastly, as discussed by some authors (Laitner et al, 2004; Fischer, 2005), much emphasis has been given to the determinants of energy demand while letting aside considerations on the supply of energy conservation technologies. This is of prior interest in the field of environmental policies, where countervailing effects are expected. For instance, subsidies to innovative technologies may induce a demand increase not necessarily followed by a decrease of their price to consumer, since manufacturers or retailers may incorporate it as a rent in their margin. A broader view of the market for energy conservation technologies, with demand being set in balance to supply, is needed. In particular, the renovation rate, which is most of the time an exogenous feature, should be represented endogenously.

To help policy-makers evaluate the targets and means following the *Grenelle de l'environnement*, we develop a model of the French residential sector attempting to overcome these hurdles. We build on architecture in line and connected to the French version of IMACLIM-R, a model developed for five years at CIRED to investigate energy and environmental issues occurring in a “second best world” characterized by suboptimality, inertia, disequilibrium and uncertainty. A computable general equilibrium framework is recursively linked to sectoral sub models where technologies are explicitly described. At each annual time step, the static equilibrium determines new production capacities and the level of their utilization. This distinction between production and production capacity allows for analysing suboptimality. IMACLIM-R can thus be considered as a hybrid model, combining behavioural realism, technological explicitness and macroeconomic feedback (Crassous et al, 2006).

Our model is designed as a submodel of IMACLIM-R. It focuses currently on space heating uses, which represent 66% of the French residential energy consumption. The thermal performance of each dwelling is given by an energy class assumed to represent both the quality of the envelope and the efficiency of the space heating system. We model the improvement of this performance through the construction of new buildings and the retrofitting of existing ones. Other uses are modelled more roughly with price and income elasticities. The model is calibrated on the 2007 stock of main residences in metropolitan France, which covers 84% of the overall stock and 95% of the residential final energy consumption. In this paper, we focus on energy conservation and not detail fuel substitution. However, fuel switch between commercial energy carriers, mainly electricity, natural gas and domestic oil is made possible in our model. In the current version of the model, wood energy is not treated because of the difficulty to accommodate the various technical options and to derive a unique price of wood.

The model is run until 2030 with two purposes. First, to build a reference scenario aimed at evaluating the French current situation towards the recently adopted national objective of a 38% energy consumption reduction in existing dwellings in 2020. This scenario, subject to a sensitivity analysis on energy prices and key parameters, shows that the expected reductions for space heating consumption are 16% +/- 5% in 2020. Second, we use the model to evaluate the impact on energy demand and on key economic variables of various policy instruments

already implemented or in project: CO₂ and final energy taxes, thermal regulations and subsidies. Our conclusions are that the most cost-effective instrument in terms of heating energy savings, actually the energy tax, reduces the consumption by an additional 9% compared to the reference scenario (-16%), which is still far from the national reduction target (-38%). In terms of cost-effectiveness, regulations and subsidies are ranked second and third, respectively. The paper is organised as follows. Section 2 details the model architecture, Section 3 details data and calibration process, Section 4 provides an evaluation of policy instruments impact and Section 5 concludes.

2. The model

To progress towards behavioural realism on the demand side, the model has to incorporate the main “barriers to energy efficiency”. The dispersion and heterogeneity of decision makers is assumed to be a relevant barrier, as well as imperfect information. Therefore, we represent consumer’s choice regarding energy efficiency as a basic investment decision, withdrawing from the perfect rationality assumption by imperfect information and decision maker’s heterogeneity. On the supply side, we represent explicitly the energy savings potential and the retrofitting endogenous dynamics resulting from the countervailing effects of potential exhaustion and technology learning. To be eventually connected to IMACLIM-R France, the model is built on recursive architecture, with an annual time step.

2.1. General heating demand

For each dwelling and given the energy carrier (electricity, natural gas or domestic fuel), the final energy demand for space heating use E_{fin} is the following product of three variables:

$$E_{fin} = S \frac{E_{conv}}{S} \frac{E_{fin}}{E_{conv}} \quad (1)$$

Where S represents the dwelling’s area in square meters, the conventional unitary consumption E_{conv}/S is a proxy for thermal efficiency of the dwelling and the ratio between conventional and final unitary consumption E_{fin}/E_{conv} represents a “service factor” or utilization rate of the thermal capacity. Sections 2.2 to 2.4 detail the dynamic evolutions of these variables, while Section 2.5 details the complex retrofit dynamics and Section 2.6 details the connection of the submodel to IMACLIM-R France.

2.2. Building stock dynamics

This point is very similar to other models (e.g. Satori et al, 2009). The evolution of S results from both the retrofitting of the buildings existing at the calibration step (referred to as the *pre-2007 stock*) and the construction of new buildings (the cumulated stock of buildings constructed after 2007 is referred to as the *post-2007 stock*). Both stocks are disaggregated into single and collective dwellings on the one hand, into occupying and non-occupying landlords³ on the other hand, which leads on the whole to four types of agents. The respective shares of the four types differ in the pre-2007 and post-2007 stock but are assumed to be constant over time for each stock. The progressive penetration of the post-2007 stock into the

³ As we will see later, this distinction is used to tackle the so-called “landlord-tenant dilemma”. Nevertheless, we take the point of view of the investor, which is most of the time the landlord and therefore rather use occupying and non-occupying terminology. Actually when we consider one dwelling, we implicitly consider the non-occupying landlord when we refer to the investor and the tenant when we refer to the energy consumer.

overall stock leads however to a slight evolution of the aggregated shares, in line with trends observed during the last decades⁴.

As showed by Equation 2, the annual building needs in square meters are the product of the total population L as projected by INSEE (Robert-Bobée, 2006), the inverse of the average inhabitants per household L/H , decreasing with the overall population, and the average area per household S/H , increasing with disposable income (given as an input by IMACLIM-R). The number of square meters increases thus faster than the population. This discrepancy is however reduced by a decrease towards a saturation level of population growth and decreasing income-elasticities driving the evolution of L/H and S/H , respectively.

$$S = L \frac{H}{L} \frac{S}{H} \quad (2)$$

Pre and post-2007 stocks are characterized by very different quantitative and qualitative dynamics and are considered separately. Each year, new constructions are the sum of requirements to meet the projected needs plus reconstruction needs. Actually, some buildings of the pre-2007 stock are getting out of the stock, mainly by pure destruction, and rebuilt. Like Sartori et al (2009), we make the important assumption that the worst energy classes get out first.

2.3. Energy efficiency investment decision

For each dwelling, improvements in energy efficiency (represented by the conventional unitary consumption E_{conv}/S in Equation 1) result from investments in a package of retrofitting actions like insulation, heating system replacement or double glazing windows. Given the very large set of technical solutions, we use a limited number of efficiency levels corresponding to the energy classes prescribed by the thermal regulation and the “energy performance diagnosis”⁵ (EPD) for new and existing buildings, respectively. This allows us to use a discrete choice framework to model the investment decision, all the options available being compared regarding their life cycle cost. Discrete choice models have been used in the field of residential consumption for a long time, especially for the energy carrier system choice, and we build on the progress towards more behavioural realism made recently by CIMS modellers with the use of Equation 3 (Jaccard et al., 2006). Under this logit functional form, the largest market share ($MS_{i,j,t}$ for class i and fuel j , at time t) is allocated to the lowest life cycle cost ($LCC_{i,j,t}$) option. This dynamics is controlled by the ν parameter, assumed to represent the heterogeneity of consumer preferences. A high value of ν leads to a 100% market share for the least life cycle cost option, thus reflecting a homogenous preference of consumers towards the best available technology. Conversely, with a value of zero, every option will get the same market share regardless of cost.

⁴ The share of individual and collective dwellings is relatively constant and the share of dwellings occupied by landlords compared to tenants increases by 0.4%/yr (MEEDDM, 2009)

⁵ The French EPD defines classes ranging from G to A, in energy and carbon terms but we only represent the energy class for two reasons. First, since energy is actually paid by consumer, we assume that the consumer is more sensitive to it and make his financial choice on that information rather on the carbon information. Second, due to the generally assumed low carbon content of energy in France, all policy objectives in the field of residential consumption are formulated in terms of kWh saved rather than tons of CO₂.

$$MS_{i,j,t} = \frac{LCC_{i,j,t}^{-\nu}}{\sum_k LCC_{k,j,t}^{-\nu}} \quad (3)$$

$$LCC_{i,j,t} = CINV_{i,j,t} + ConRef_i P ener_{j,t} \frac{1 - (1 + r_a)^{-l}}{r_a} \quad (4)$$

As stated in Equation 4, the life cycle cost calculation takes only into account the investment cost of each option ($CINV_{i,j,t}$, time-dependent because of technology learning, see below Eq.6) and the energy expenditure under the conventional consumption of the class ($ConRef_i$), cumulated and discounted over the theoretical lifetime of the underlying capital (with lifetime l and discount rate r_a for each actor a). We make the assumption of myopic expectation of the energy price ($P ener_{j,t}$), i.e. consumers use the current energy price for life cycle cost calculation. Maintenance costs are not included here, nor intangible costs⁶. In addition to the preferences heterogeneity parameter ν , we use different discount rates to reflect the heterogeneous investment behaviour between four type of agents who face unequal incentives to invest in energy efficiency: occupying (O) and non-occupying (N) landlords in individual (I) and collective (C) dwellings. The split incentive between landlords and tenants, also referred to as the “landlord-tenant dilemma” is well known (IEA, 2007): a non-occupying landlord has no incentive to make investments that are mainly unrecoverable because the following savings on the energy bill profit to the occupying tenant. Therefore, we assume that non-occupying landlords have higher profitability requirements than occupying ones, and thus higher discount rates. Moreover, we assume that occupants in single dwellings are generally more responsible for their own energy consumption than in collective ones, for practical (single versus collective boiler) or technical reasons (heat transfers may occur between adjacent dwellings in collective buildings). In single dwellings, occupants have more control over their energy consumption and are thus more likely to invest in energy efficiency (with lower discount rates) than in collective dwellings. To summarize, we have a gradient of increasing discount rates from the occupying landlord in single dwelling (OI) to the non-occupying in collective ones (NC). The way ν and r_a parameters are set is detailed in Section 3.

For new buildings, the discrete investment choice holds for *efficiency levels*. Prior to construction, each agent faces three options for the energy carrier and three options for the thermal performance of the dwelling: 2005 thermal regulation level (labelled RT05 with consumption levels ranging from 250 to 120 kWh/m²/y of primary energy), low consumption building (labelled BBC for *Bâtiment basse consommation* and consuming 50 kWh/m²/y of primary energy) and “passive” building (labelled BEPOS for *Bâtiment à énergie positive*). Differently for existing dwellings, the discrete choice holds for *transitions* from the current energy class to upper energy classes (from over 450 kWh/m²/y, labelled “G” to below 50 kWh/m²/y, labelled “A”, in primary energy). For example, a dwelling labelled D can be

⁶ Intangible costs are used in CIMS to reflect the fact that a market share calculation based only on financial cost may not reflect the observed market shares (Jaccard et al, 2006). For instance in France, double glazing window is the most commonly undertaken measure but not the most efficient, since such a calculation would have led to select insulation as the most cost-effective (Laurent et al, 2009). In CIMS, intangible costs they are derived from empirical surveys. Since such data are not available in France, it was not possible to implement them in spite of their accuracy in this field.

retrofitted to reach class C, B or A. This leads on the whole to 21 possible transitions (126 when taking into account fuel switch possibilities).

One could argue that the much aggregated EPD representation simplifies the technological reality, since different retrofit packages can lead to the same energy class transition, at different cost. Nevertheless, the implementation of this tool is recommended in the EU by the Energy Performance of Buildings Directive and where it has already been done, some studies show that end-users are becoming sensitive to this label (ADEME, 2008, in France; Shorrock et al, 2007, in the UK; Maes et al, 2007, in Belgium). Moreover, it is also used in other models (Sartori et al, 2009; WBCSD, 2009). Therefore we consider that the energy class is a good trade-off between description accuracy and technological realism, but it requires a considerable work of data aggregation, as we will see in Section 3.

2.4. Energy consumption behaviour

Another suggested limitation about the EPD is that relying on energy classes prevents from considering effective discrepancies with the assumptions made on the equipment utilization rate or the indoor comfort requirement during the conventional consumption settlement (Laurent et al, 2009). To overcome this problem, we use a service factor to parameterize the consumption behaviour. This is actually the ratio between the unitary *final* consumption and the unitary *conventional* consumption calculated by an engineering thermal model (E_{fin}/E_{conv} in Equation 1). Adapted from Haas et al (1998), this ratio is assumed to be a decreasing function of the annual energy expenditure, as illustrated on a stylized way on Figure 1. The energy expenditure being the product of the conventional consumption at current energy prices, both changes in energy prices or improvements of the capital structure's efficiency can induce changes in behaviour, with opposite trends.

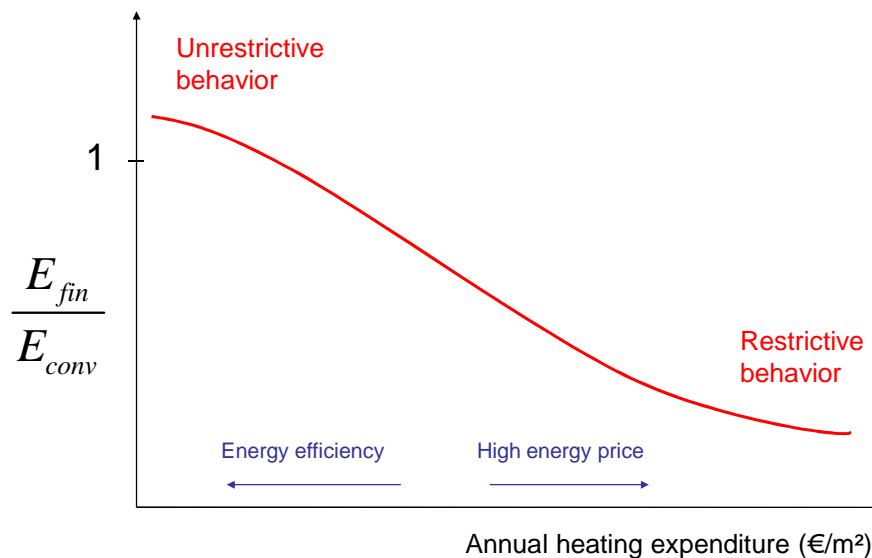


Figure 1: Consumption behaviour curve

This logistic behavioural curve allows us to take account implicitly of comfort requirements, which are generally explicitly labelled in other models of space heating demand through heating degree days. Moreover, it allows us to separate sufficiency from efficiency dynamics

and thus to simulate the rebound effect due to behaviour shifts towards less restriction. We will see in Section 3 how this curve was calibrated.

2.5. Retrofitting endogenous dynamics

The most challenging issue in modelling residential energy consumption is probably to catch the endogenous retrofit dynamics. Retrofit decisions have been studied in many fields (e.g. seismic structures, Camillo et al, 2003) but specific studies are lacking in the field of residential buildings. Other models generally use age-dependent functions for capital stock retiring (Koopmans et al, 2001; Mau et al, 2009). We have identified four effects likely to influence the renovation rate and worthwhile to incorporate in our model:

- (i) *Technology learning*: this represents the production cost decline of a technology consequently to its progressive penetration in the market, following an “experience curve”. This is due to processes like economies of scale, learning by doing and technological innovation (Weiss et al, 2009). Although a well-tried technique in modelling of energy supply technologies, experience curves have been rarely applied to energy demand technologies (Laitner et al, 2004). Recently, useful experience curves have been provided for key technologies like insulation (Jakob et al, 2004) and condensing boilers (Weiss et al, 2009).
- (ii) *Demand surge inflation (DSI)*: this refers to the increase in retrofit costs consecutive to a demand surge, a process modelled by Hallegatte (2009) in the aftermath of 2004 and 2005 Hurricanes in Florida. Such a demand surge may occur when new policies are implemented and is likely to be followed by inflation of retrofit aggregate prices. The process underlying is a sudden disequilibrium between supply and demand followed by rationing incorporated by professionals as rents into their margin.
- (iii) *Energy savings potential exhaustion/ deepening*: given the irreversibility of major retrofit investments like insulation, energy efficiency improvements lead to an exhaustion of the savings potential. The number of annual retrofits is thus expected to decrease with the cumulated number of retrofits. Conversely, a policy lowering the price of technologies also increases the net present value (NPV) of the retrofit project. When a negative NPV becomes positive, such a policy turns a non-profitable investment into a profitable one, thus deepening the overall energy savings potential.
- (iv) *Consumer information improvement*: one of the most important barriers to energy efficiency is the lack of consumer information about the virtuous attributes of energy efficient technologies. Information is assumed to increase with the diffusion of the technologies under patterns that are largely unknown. CIMS modellers implemented recently an analogous “neighbour effect” in their model⁷ (Axsen et al, 2009; Mau et al, 2009).

⁷ The neighbour effect is supposed to represent increased penetration of technologies through imitation among consumers. It is modelled in CIMS as decreasing intangible costs with increasing market shares (Mau et al, 2008).

⊕ ⊖ : evolution given an *increase* of the starting variable

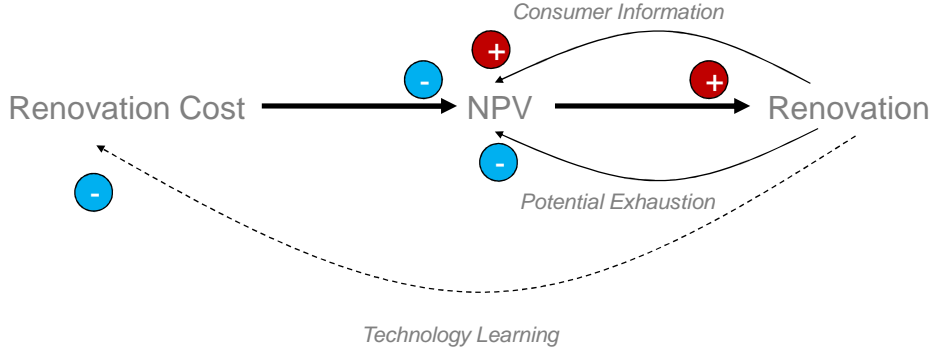


Figure 2: The renovation dynamic system

We incorporate all these countervailing effects into a complex framework, as illustrated by Figure 2. The basic retrofit decision is ruled by the following equation:

$$NPV_i = CENER_i - \sum_{k>i} MS_k LCC_k \quad (5)$$

For each departure energy class i , the retrofit decision is driven by the NPV of the “retrofit versus status quo” investment project, that compares the cumulated energy expenditure of the current situation i ($CENER_i$) to the average retrofit cost, i.e. the sum of life cycle cost weighted by market share (as calculated in Equation 3) over all retrofit options towards upper energy class k , $k>i$. If the resulting NPV is negative, no retrofit occurs; if positive, the higher the NPV the larger the number of retrofits. The sum of all positive NPVs over the whole pre-2007 building stock possible transitions (given the departure energy class, the energy carrier and the type of decision-maker) represents the initial potential for energy savings. A ratio of retrofitted dwellings per unit of positive NPV is calibrated in 2007 to allow converting in the next steps positive NPV units into a *theoretical* number of retrofits. Under this framework, the energy savings potential is endogenously exhausted, since every dwelling shifting towards an upper energy class will have a lower NPV compared to even upper options at the next time step.

This process may be modified by the four identified effects at different steps, with various feedbacks of the renovation rate: (i) Technology learning is a long term, supply side effect inducing a negative feedback on retrofit costs ($CINV$) as showed in Equation 6, where the learning rate LR corresponds to the cost decrease amount relative to a doubling of the cumulative experience, approximated by building stocks ($Stock$) for each energy class; (ii) DSI is a short term, both supply and demand side effect, inducing a positive feedback on renovation costs; we will not take it into account here to keep consistency with the mid to long time scale of the effects represented; (iii) the potential deepening is a mid-term (of the same

order of magnitude as the lifetime of the policy), supply side effect, inducing a negative feedback on the potential, regardless of cost; (iv) consumer information is a long term, demand side effect inducing a positive feedback on the potential, regardless of cost. Because of imperfect information, the *effective* renovation rate differs from the *theoretical* one but this discrepancy is reduced with increasing information. We postulated for that evolution a basic cumulative process, the information index increasing straightforwardly with the cumulated number of retrofits.

$$CINV_t = CINV_0 \left(\frac{Stock_t}{Stock_0} \right)^{\frac{\log(1-LR)}{\log 2}} \tag{6}$$

2.6. Macroeconomic feedback

The resulting demand for space heating energy is a submodel of the IMACLIM-R France hybrid model. Useful documentation on IMACLIM-R can be found in (Crassous et al, 2006). IMACLIM-R disposable income and energy prices are inputs of the submodel, which in turn outputs new energy demand for space heating and demand for investment. The population scenario is exogenous for both IMACLIM-R and the submodel. To keep consistency on the overall residential consumption, other energy uses are modelled much more simply by price and income elasticities. Given the relatively weak link between the residential submodel and the computable general equilibrium, our framework for policy analysis belongs to the engineering bottom-up family (as defined by Swan et al, 2009) but incorporates innovative features like decision-makers’ heterogeneity, imperfect information and endogenous retrofit dynamics.

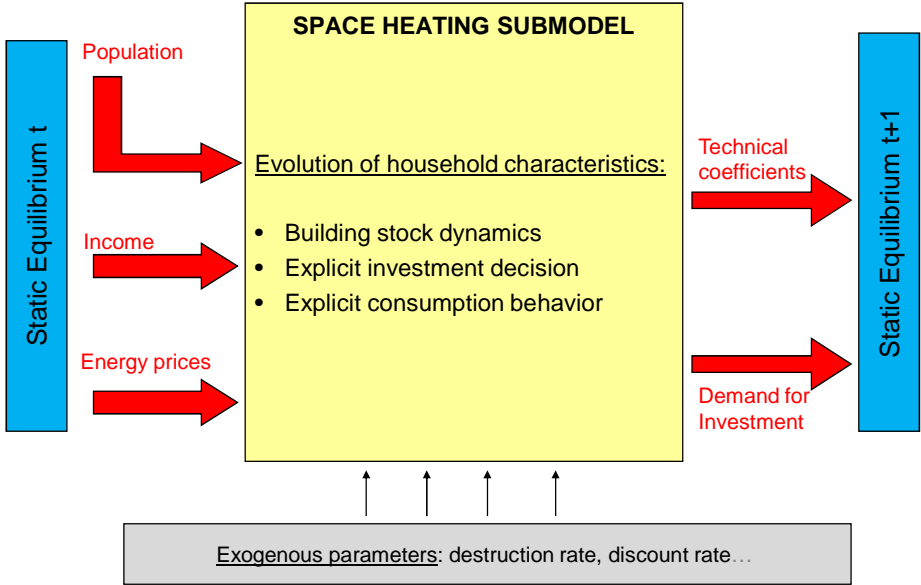


Figure 3: Connection of the residential submodel to IMACLIM-R France

3. Reference scenario

3.1. Data and calibration

The main macroeconomic variables of our model benefit from the much documented data set issued by INSEE, like the number of dwellings by type of agents, the average number of inhabitants per household or the average dwelling size. The exogenous population scenario is also provided by INSEE (Robert-Bobée, 2006). The annual rate of dwellings that get out of the stock (mostly by pure destruction) has long been a poorly known value. It was commonly considered to be 0.1% but Allaire et al (2008) recently found higher values, ranging from 0.3 to 0.4%. We thus set it exogenously to 0.35% and make the assumption that the stock of each energy class cannot go below 5% of its initial stock. All these parameters are calibrated to reproduce the 2008 new constructions. For other uses than space heating, price and income elasticities are basically set at -0.5 and 0.2 respectively, except for specific electrical uses where income-elasticity is set at 2 and decreasing, to simulate a rapid increase of the demand in the next years followed by saturation after several decades. According to many experts, such a tendency is likely to happen because of the multiplication of electrical devices. The segmentation of the pre-2007 building stock by EPD energy class is calibrated on a picture of the 2007 stock made available recently by ANAH (2008).

As we saw in the previous section, the energy efficiency decision relies on important parameters like the heterogeneity of preferences and the discount rate. In CIMS, these parameters are calibrated on stated preference surveys. Such empirical data lacking in France, we used *ad hoc* estimations and experts' advice to calibrate them and eventually subjected them to a sensitivity analysis, as we will see in Section 3.3. Parameter ν is set at 8 both for retrofits and new constructions, a value that reproduces roughly trends of the last five years. This leads for example for a retrofit of class G to a market share of 44% (respectively 0.06%) for the lowest (respectively highest) cost option, that is a shift to E (respectively A). Discount rates are set following Table 1. The lowest value, reflecting the low profitability requirements of a landlord occupying a single dwelling (OI) is set at 7%, a value generally used for basic household investments, and the highest value is set for a non-occupying landlord in collective dwelling (NC) to 50%, representing the fact that this agent will not invest if the payback period is inferior to a few years, which refers approximately to the length of a rental lease. All discount rates hold for lifetimes set at 20, 35 and 25 years for heating systems, insulation and new constructions, respectively. The first two values are the one used for official engineering calculation under the French white certificates scheme (ATEE, 2009); the last one reflects approximately the common length of credits for building a new house.

	Individual dwelling (I)	Collective dwelling (C)
Occupying landlord (O)	7%	15%
Non-occupying landlord (N)	30%	50%

Table 1: Discount rate per type of actor

The most sensitive variable is probably the retrofit costs. As we saw in Section 2.3, our discrete representation requires to aggregate data that are still largely unknown in France. According to many experts, a standard construction costs around 1,200€/m², with additional

cost of 5 to 10% to reach BBC level⁸ and 15 to 30% to reach the BEPOS level. We assumed that the cost of a standard dwelling with an electrical carrier is lower than with other carriers since simple convectors are commonly installed (Table 2a). Conversely, upper label dwellings with electrical carrier are more expensive since they are assumed to incorporate heat pumps. Given the large number of possible packages, retrofit costs are very uneasy to set. There are indications of exponentially increasing costs for increasing energy efficiency in France (ANAH, 2009) and in the UK (BRE, 2009). Therefore, we build a cost matrix with discrete values reproducing such exponentially increasing costs. The costs for improving the performance of the dwelling by one energy class range from 50 to 100€/m² depending on the starting class, and the most expensive transition (from G to A) is bounded by new construction costs (Table 2b).

a. Construction costs in €/m² by energy carrier and by energy class

	RT05	BBC	BEPOS
Electricity	1150	1370	1600
Natural gas	1200	1350	1600
Fuel oil	1200	1350	1600

b. Retrofitting costs in €/m² for transitions from initial to final class

		Final class					
		F	E	D	C	B	A
Initial class	G	50	150	300	500	750	1050
	F		60	160	310	510	760
	E			70	170	320	520
	D				80	180	330
	C					90	190
	B						100
	A						

Table 2: Cost matrices

Two different behaviour curves (as introduced in Section 2.4) are used for single and collective dwellings, since consumption adjustment possibilities differ significantly in these two cases. These curves are estimated with a logistic fit by combining data from ADEME and ANAH. A correction factor is applied to reproduce the 2007 space heating consumption of 254 TWh (ADEME, 2008).

Parameters of the retrofitting market also lack of empirical data and are calibrated on an *ad hoc* manner. According to qualified experts, learning perspectives in the building sector are limited and lower for retrofitting than for new construction, because of more concentrated labour, decision-makers and technology in the latter case. We thus set the learning rate for new constructions at the conventional 20% value (Sassi, 2008). We set it at 10% for retrofits, which is a rough average of values given for separate technologies, e.g. 12-14% for condensing boilers and values below 10% for building envelopes (Weiss et al, 2009; Jakob et

⁸ A recent demonstrative project on 2200 dwellings exhibited higher additional costs of 15% but this is additional cost will most likely decrease in the next future due to learning (MEEDDM and ADEME, Bâtiments basse consommation: l'ADEME dresse un premier bilan prometteur, Press communiqué, 19 June 2009).

al, 2004). The way one can derivate aggregated learning rates from separate measures has been discussed by Ferioli et al (2009).

The historic number of retrofitted dwellings and other data relative to retrofits that follow are given by OPEN (2008) and ADEME (2008). The annual retrofitting activity is quite stable at 11% of the building stock but dominated by basic measures that do not lead to thermal improvements, like wall painting (for an average expenditure of 3,810€ per household). Only 3% of these works lead effective and significant savings (CAH, 2008). To reproduce that number, we set the rate of energy efficiency improvements by at least one energy class at 0.6% in 2007⁹ and let it evolve endogenously. This provides the 2007 *effective* number of retrofits. The NPV calculation reflects the savings potential coming from the retrofitting of a maximum share of the 2007 stock set at 50%. This allows for the calibration of a parameter giving the *theoretical* number of retrofits for each unit of positive NPV. The information index is eventually calibrated to reflect the discrepancy between effective and theoretical number of retrofits. It increases in the next time steps with cumulated retrofits.

3.2. Business as usual case

We run the model with endogenous energy prices until 2030 to build a business as usual scenario. This first run closely reproduces some variables that were not calibrated, as shown in the first three rows of Table 3.

	Usual values	Model
Annual energy expenditures for space heating	21.6 billion Euros 2006, i.e. 342€/inhabitant for all energy, including wood (Besson, 2008)	20.4 billion Euros in 2008, i.e. 320 €/inhabitant for electricity, natural gas and fuel oil only
Retrofitting expenditures	11.6 billion Euros in 2006 for 11% of the stock (Girault, 2008)	2.4 billion Euros in 2008 for 0.6% of the stock subject to high efficiency improvements
Annual reduction of the unitary energy demand for space heating	3.3% in 2005 and 2.7% over 1973-2005 (ADEME, 2008)	2.9% in 2008 and 2.5% on average on the whole period
Direct rebound effect for space heating	Sorrell et al (2009) review values ranging from 1.4% to 58% and suggest a mean value of around 20%	39%

Table 3: Comparison of the model outcomes to benchmark values

As shown by Figure 4a, the building stock in square meters increases by 20% between 2008 and 2030, a projection in line with (Traisnel, 2001). The pre-2007 existing stock still represents 74% of the 2030 stock, which confirms the common thinking that much attention should be paid to the retrofitting of existing buildings. Figure 4b shows that the energy demand for space heating decreases by an average of 1.3% annually in spite of a twice higher annual decrease of the conventional unitary consumption. Therefore, half of the energy efficiency gains are counterbalanced by building stock increase (+1%/year average) and sufficiency relaxation (+0.3%/year average). The latter effect represents short-term adjustments and has thus a strong influence on annual variations.

⁹ In BEAM simulations, this value is set at 0.6% in the reference scenario and 2% in aggressive scenarios (Teissier et al, 2008)

Figures 4c and 4d show the results of logit investment choices on the building stock's structure for $\nu=8$. Cumulated RT 2005 constructions account for 88% of the post-2007 stock in 2030, while BBC and BEPOS levels penetrate very slightly. Most of the savings come from improvements in the structure of the pre-2007 stock, especially from the marked decrease of class G dwellings, often qualified as “thermal wrecks”. Actually, a breakthrough in energy efficiency improvement trend occurs in around 2013, when class G renovation reaches a tipping point, and energy efficiency improvements are even reduced from 2020 when class G reaches a plateau (Figure 4d). These early large savings are driven both by the high profitability of investments in class G retrofitting (leading in to a higher renovation rate following the process described in Equation 5) and the “worst class destroyed first” hypothesis. Running the model under a “no destruction” assumption leads to a consumption reduced by only 17% in 2030, compared to 26% in the business as usual case. This means that destruction of existing dwellings and their replacement by new constructions, which affects only 0.35% of the pre-2007 stock each year, accounts for 35% of the savings reached in 2030.

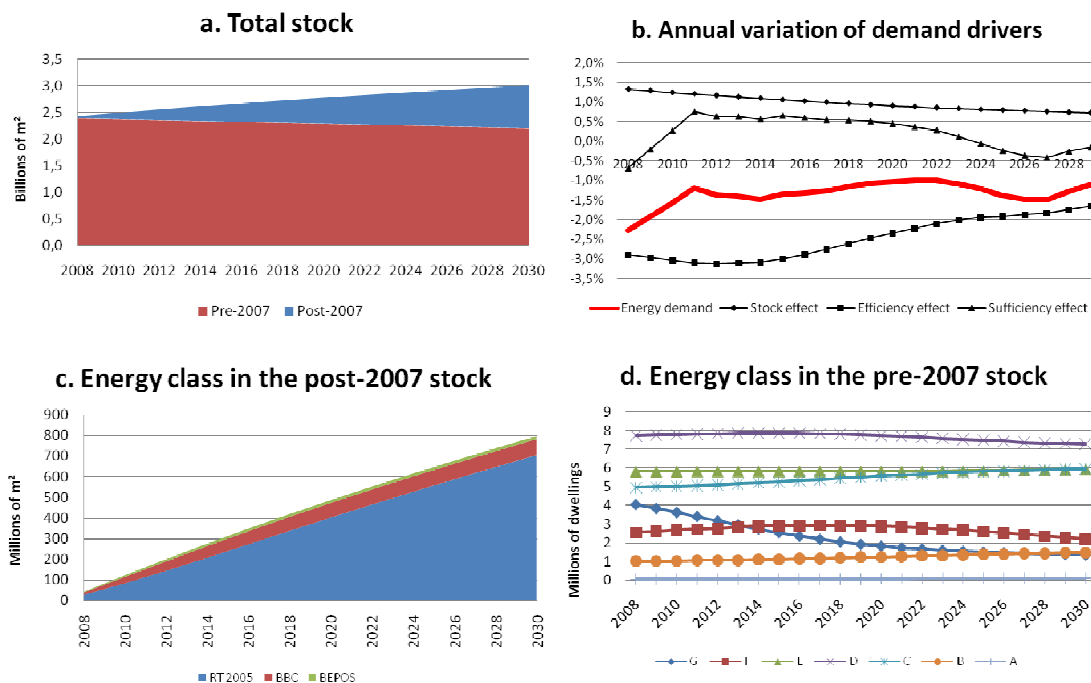


Figure 4: business as usual main results¹⁰

We find that the average cost per dwelling for improvements by at least one energy class range between 15,500€ and 17,000€. Benchmark models¹¹ suggest values for such investments ranging from 12,000€ to 30,000€ and CAH(2008) suggests the mean value of 20,000€.

¹⁰ In Figure 4b we have basically differentiated Eq.1: $\Delta E/E = \Delta S/S + \Delta(E_{conv}/S)/(E_{conv}/S) + \Delta(E_{fin}/E_{conv})/(E_{fin}/E_{conv})$

¹¹ Results from the following simulation bottom-up models covering the French residential sector are used as benchmark: Energy Efficiency in Buildings (EEB), developed by (WBCSD, 2009); ENERTER, developed by Energies Demain (Houdant et al, 2009); Built Environment Assessment Model (BEAM) (Teissier et al, 2008); BETEL (Raux et al, 2006).

On the whole, this first run brings confidence on calibration and a slight tendency to pessimism on dynamic evolutions. Actually, the model figures out that the business as usual trends are far from the 2020 objective, with a 16% decrease for space heating. Taking into account all uses (roughly represented, see Section 2.6), the overall consumption is eventually increased by 5% in 2020. This pessimistic outcome may be partly due to the large rebound effect it encompasses compared to usual values for space heating (Table 3, last row).

3.3. Sensitivity analysis

We have emphasized in Section 3.1 that given the broad set of *ad hoc* parameters, sensitivity analysis was needed. We focus here on the key behavioural parameters ν and the dispersion of discount rates for retrofitting. They both determine theoretical market shares of energy classes (Equations 3 and 4) used also in the calculation of the number of retrofits (Equation 5). Therefore, they determine both the quantitative and qualitative retrofitting dynamics.

		Conventional demand	Final demand
Price scenario	Constant	-22%	-17%
	Constant 1%/yr increase	-25%	-29% (*)
	IMACLIM-R	-29%	-26%
Discount rate values for agents (OI;OC;NI;NC)	(7;7;7;7)	-36%	-30%
	(7;9;13;15)	-32%	-28%
	(7;15;25;30)	-29%	-26%
	(7;15;30;50)	-29%	-26%
	(7;30;70;100)	-27%	-24%
Nu values	1	-22%	-22% (*)
	2	-25%	-23%
	5	-28%	-25%
	10	-29%	-26%
	50	-29%	-26%

Table 4: conventional and final energy demand for space heating in 2030 for different scenarios (see text for interpretation of cases *)

As shown on Table 4, unsurprisingly the higher ν , i.e. the more convergent towards best available technology the preferences, the larger the energy savings. As well, the lower the discount rates, the larger the savings. If we take a closer look to the mechanisms at stake on key variables on Figure 5, we see that as expected, these parameters change both the renovation rate and qualitative choices. On Figure 5a, we see that trends are very similar between (7;15;25;30) and (7;15;30;50) cases, where non-occupying landlords make almost no investment. This suggests that heterogeneous discount rates have threshold effects since above certain values (around 25%), actually the internal rate of return of retrofitting investments, a whole type of agent will not undertake energy efficiency measures.

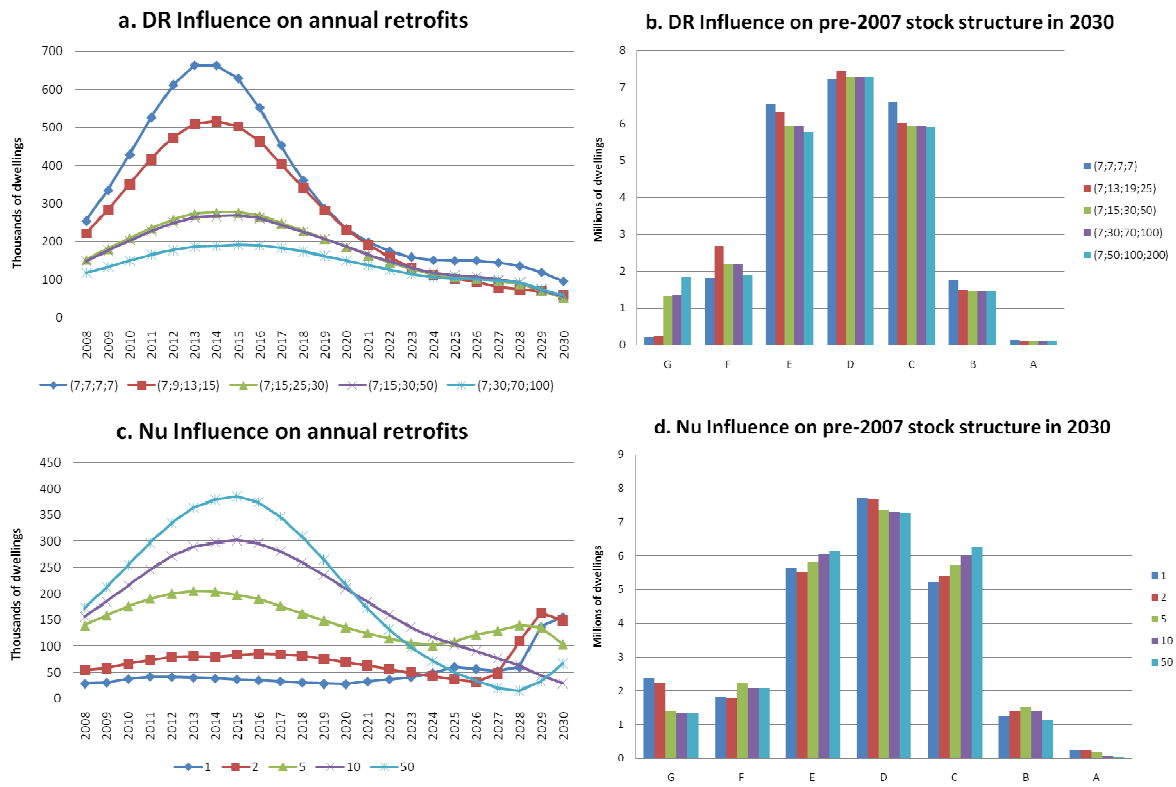


Figure 5: Sensitivity of key variables to discount rate heterogeneity (DR for agents OI;OC;NI;NC) and parameter ν (Nu)

To determine the core behaviour of our model, we also compare the business as usual scenario (IMACLIM-R prices) to a constant price scenario (0% increase) and a constantly increasing energy price scenario (1%/yr. increase), as shown on Figure 6a. Our endogenous price scenario is close to the constant price scenario because France’s residential energy demand in terms of expenditures is dominated by electricity, which is produced at a relatively constant cost by nuclear power plants and whose price is largely regulated. Between constant and constantly increasing price scenarios, the interpretation is straightforward. In the constant price scenario, retrofitting occurs but qualitative choices are not modified over time by energy price variations. This results in low energy efficiency improvements and thus in sufficiency relaxation (increasing service factor on Figure 6c) by shifts towards the left side of the behavioural curve in Figure 1. In the constantly increasing price scenario (*), choices are modified towards better solutions, which leads to higher energy efficiency improvements. But as suggested by the decreasing service factor, the expected shift towards the left side following efficiency is more than compensated by shifts towards the right side of the behavioural curve following increased energy expenditures. In the IMACLIM-R price scenario, price increase is not sufficient to make energy service factor dominate, but it generates more energy efficiency than constantly increasing price. Price variations lead to reduced energy demands ranging from -17% to -29% in 2030.

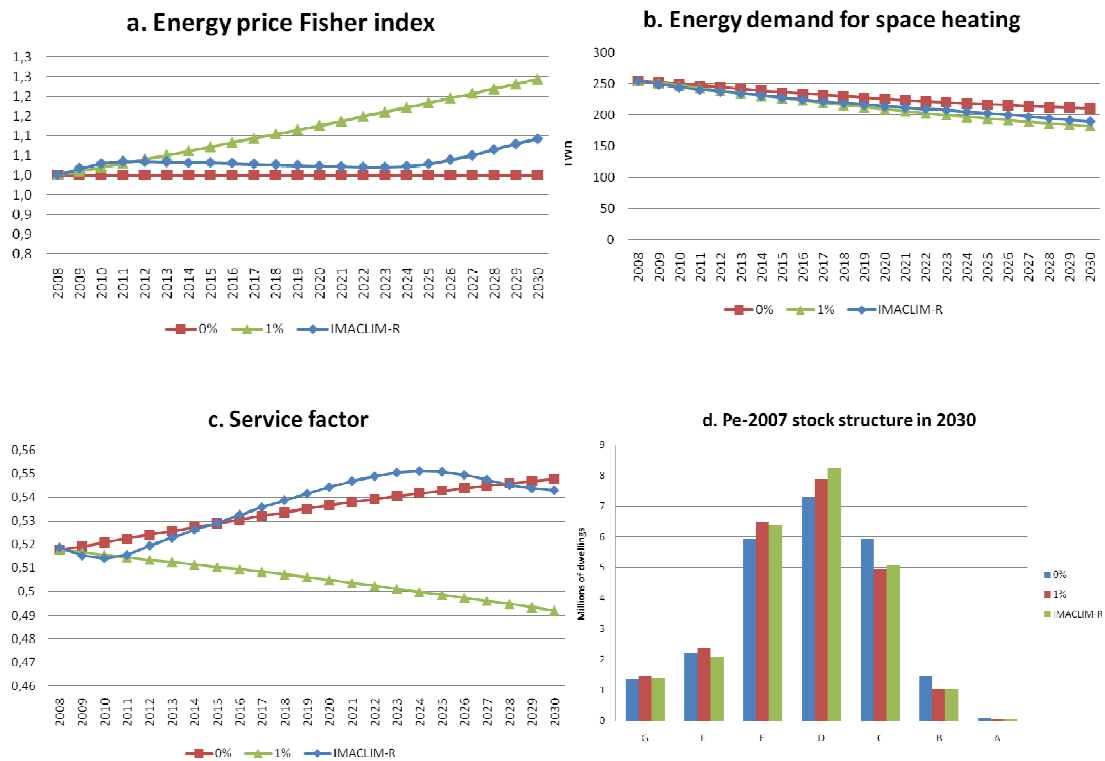


Figure 6: Sensitivity of key variables to energy price scenarios

It is worthwhile to recall that any progress in energy efficiency is systematically countervailed by sufficiency relaxation, except in cases (*). Therefore, discrepancies on conventional energy demand (a proxy for energy efficiency) between scenarios are mitigated when dealing with final demand, as we can see on Table 4.

4. Policy impact evaluation

4.1. Instruments represented

We implement three important policy instruments already existing or about to be implemented in France as well as in many European countries (IEA, 2008):

- **Taxes:** we simulate the CO₂ tax or *Contribution énergie climat* about to be implemented in France. Following the prospective study of CAS (2008), we set it at 32€/tonCO₂ in 2010 and let it increase by 5% annually. The recycling modalities are still under discussion but the tax is very likely to be entirely rebated lump-sum to consumers, which is our assumption. We also model an end-use energy tax, calibrated to generate the same revenue than the CO₂ tax in 2010 and increasing by 5% every year. In both cases, tax free prices are still myopically expected but the taxes are perfectly expected.
- **Regulations:** one of the first agreements following the *Grenelle de l'environnement* process was to set thermal requirements for new buildings to BBC level in 2012 and to BEPOS level in 2020. Benefiting from less agreement is the discussed regulation on existing buildings that would require any retrofitting works to reach a certain level of

final efficiency. We set this requirement to reaching at least class D starting from 2010, which represents for the worst buildings an obligation to spend at least 300€/m².

- *Subsidies*: a tax credit scheme for investments like insulation, boilers replacement, heat pumps or double glazing window has been implemented in 2005 in France, covering shares of the initial investment ranging from 15 to 50%. Since 2009, a zero rate loan has also been implemented for investments meeting eligible conditions (30,000€ minimum expenditure, etc.). We model both of these instruments as a single subsidy of 20€/m² for every retrofit action upgrading the energy class, which represents approximately 2,000€ for an average dwelling.

Taxes and subsidies are modelled basically by an energy price increase and a reduction of investment cost, respectively. Such processes may change the investment decision by modifying the life cycle cost of each option and/or the consumption behaviour by modifying the energy expenditure. In the regulation case, logit choices in Equation 3 are basically enforced.

To keep consistency in the comparison of policies behaviours, they are all implemented in 2010 (we thus anticipate by two years the BBC level thermal requirement). As the maintenance of subsidies is currently debated, we suppose that they are removed in 2020, but running the model until 2030 allows us to evaluate their persistent effect. Since we do not detail here fuel switch issues, we focus on policy impacts on energy consumption and not on CO₂ emissions. Administrative costs are not taken into account. We evaluate the impact of each instrument in terms of effectiveness, i.e. its contribution to the 2020 national target, and cost-effectiveness, i.e. cumulated and 4% discounted monetary savings net from investment costs¹² compared to the reference evolution in 2030. In the subsidy case, we use the non-subsidized retrofitting cost (confounded with price) to represent the social point of view: although not paid by consumers, the subsidy is eventually funded at the taxpayer's expense. Similarly, the tax free price is used in energy expenditures calculation in the tax case, which is assumed to be entirely rebated to consumers.

4.2. Effectiveness and Cost-effectiveness analysis

As we can see on Table 6, every instrument lead to additional energy gains compared to the reference situation. But the model outcomes that the 2020 objective of reducing residential consumption by 38% compared to 2008 is very unlikely to get reached for all uses, whatever the means. Our model does not focus on other uses than space heating (modelled simply by price and income elasticities) but if we only consider heating consumption, generally considered as the main driver of energy demand reductions in the residential sector, all scenarios are still far from the path.

¹² All monetary costs and expenditures are labelled in current Euros.

	Energy consumption		CO ₂ emissions	
	Space Heating	All uses	Space Heating	All uses
Reference case	-16%	+5%	-28%	-9%
CO ₂ Tax	-25%	-3%	-36%	-16%
Final energy tax	-25%	-4%	-36%	-16%
Regulation	-16%	+5%	-29%	-9%
Subsidy	-19%	+4%	-31%	-10%

Table 6: Effectiveness of policy instruments in terms of reduced energy consumption in 2020 compared to 2008

Nevertheless, as we can see on Table 7, all instruments except subsidies procure net social benefits in 2030. Actually, the payback date is 2010, 2018 and 2022 for end-use tax, CO₂ tax and regulation, respectively. The reasons are exposed in Figure 7. Due to our endogenous energy price settlement in the IMACLIM-R static equilibrium, energy savings (Figure 7a) lead to lower price increases compared to the reference case for subsidies and regulations and to absolute tax free price decrease with taxes, for higher energy savings (Figure 7b). Therefore, the cumulated energy expenditures are about 20% lower with taxes compared to the reference (Figure 7c). This is large enough to widely compensate the high additional investment that occurs with taxes (Figure 7d). In the subsidy case, the retrofitting expenditures are in the same order of magnitude as the CO₂ tax until 2020, but with much less energy savings because of an additional rebound effect compared to the reference case. This explains the net social cost of this policy instrument. The regulation, although socially benefiting, does not lead to a situation significantly different from the reference case.

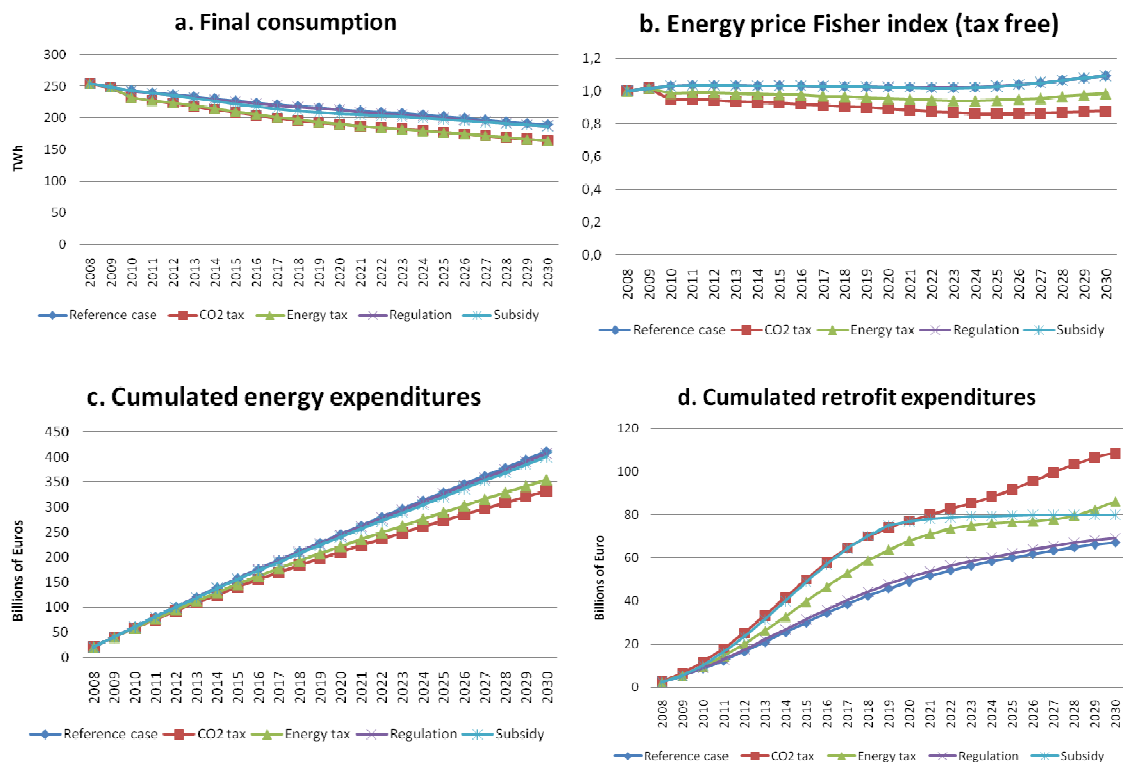


Figure 7: Energy consumption and cost data

This first analysis provides a rough ranking of instruments in terms of cost-effectiveness, where taxes are ranked first, the regulation second and the subsidy third. This ranking is in line with (Giraudet et al, 2008).

	Cumulated additional investment (bl€)	Cumulated monetary savings (bl€)	Net social benefits (bl€)
CO₂ Tax	18	33	15
Final energy tax	8.0	24	16
Regulation	0.93	1.7	0.75
Subsidy	5.4	4.0	-1.4

Table 7: Cost-effectiveness of policy instruments compared to the reference case in 2030 (4% discounted)

4.3. Determinants of the overall consumption

We try now to separate effects of policies on both efficiency and sufficiency. The former is analysed by the conventional consumption, i.e. the consumption given by the stock structure under conventional assumptions (with a service factor set at 1 in Equation 3) while the latter is analysed by the aggregated service factor over the stock, i.e. the ratio between the final and conventional consumption.

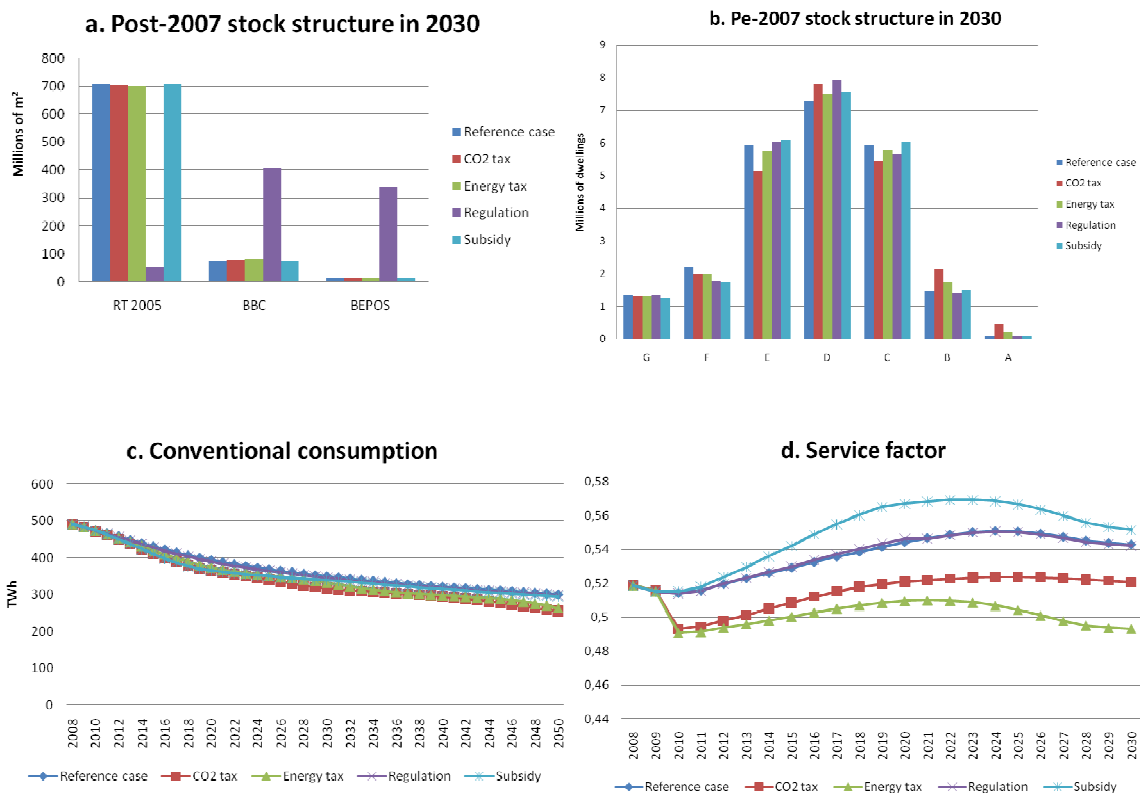


Figure 8: Determinants of the final demand for space heating

We see that the regulation is the only policy which modifies significantly the structure of the post-2007 building stock (Figure 8a). We recall that it sets thermal requirements for new buildings at BBC level in 2010 and BEPOS in 2020. Price instruments hardly change the building stock's structure, because of the low share of variable energy costs in the life-cycle cost calculation for construction projects. In the pre-2007 stock, the regulation that requires each retrofitting action to reach at least class D has a qualitatively lower impact (Figure 8b),

which indicates that such a level is weakly additional. The resulting conventional consumption in the regulation case is very close to the reference (Figure 8c) in spite of spectacular savings in new constructions, which indicates that the post-2007 building stock is not a great potential for savings. These low efficiency improvements, with no other energy price effect than reduced energy demand's retroaction in IMACLIM-R static equilibrium (Figure 7b), lead to a service factor very close to the reference case (Figure 8d), which explains why no additional rebound effect occurs in this case compared to the reference case. Conversely, the more efficient pre-2007 stock in 2030 (with also no other price effect than the IMACLIM-R retroaction of increased efficiency) following subsidies markedly increases the service factor compared to the reference, generating thus an additional rebound effect. Taxes induce a sudden reduction of the service factor in 2010 when implemented. Then they remain markedly below the reference evolution, in particular the end-use energy tax decreases in absolute term.

Therefore, taxes generate a “double gain” with large positive effects on both efficiency and sufficiency, whereas subsidies have an opposite effect in improving efficiency and relaxing sufficiency. This mechanism is also in line with (Giraudet et al, 2008). The regulation, given the decision values we used, does not lead to significant changes of these two components compared to the reference case.

4.4. *Determinants of energy efficiency improvements*

We attempt here to investigate the drivers of efficiency improvements by separating the variables of the retrofitting endogenous dynamics exposed in Section 2.5. We recall that the potential for energy savings can be deepened by generally speaking price policies (taxes and subsidies), but also basically by technology learning, which lowers the retrofitting costs and thus their share in life-cycle cost calculation (making the investor more sensitive to variable energy costs and thus more likely to choose efficient solutions). As well, cumulated retrofits increase consumer's information (Figure 2).

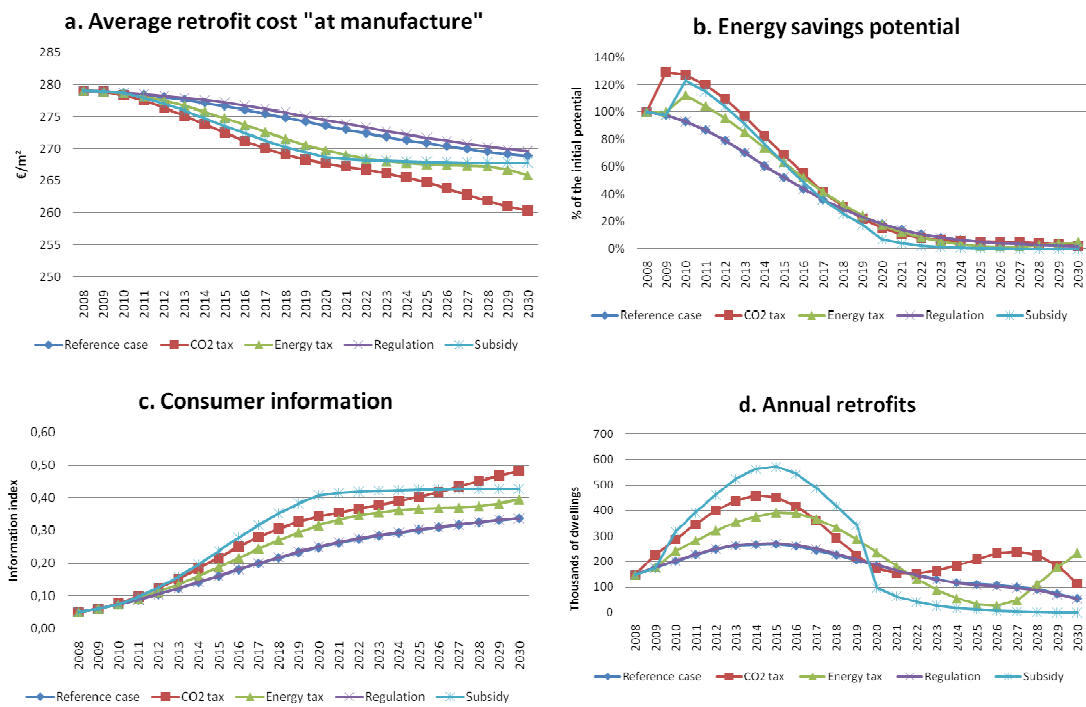


Figure 9: Determinants of energy efficiency improvements

We see on Figure 9b that price policies lead to a sudden deepening of the energy savings potential when implemented in 2010 by turning non-profitable investments into profitable ones. In late years, the active technology learning effect induced by the CO₂ tax (Figure 9a) also helps steadily deepen the potential. But in turn retrofits contribute to the general exhaustion of the potential. As well, cumulated retrofits increase consumer information (Figure 9c). The number of annual retrofits is eventually the result of these countervailing effects (Figure 9d). It should be emphasized that the low values in late years on Figure 9b do not mean that the whole potential is exhausted. It only means that additional effects on costs (investment cost decrease or energy price increases) and behavioural parameters (discount rate lowering or convergence of preferences towards best available technologies) are necessary to create new positive NPV.

5. Conclusions

From a methodological point of view, we introduced the following innovative features in a hybrid model: a clear separation between efficiency and sufficiency; on the demand side, a representation of major barriers to energy efficiency such as heterogeneity of decision-makers and imperfect information; on the supply side, a representation of complex interactions between technology learning and potential exhaustion under endogenous retrofitting dynamics. Moreover, we built our model on an intuitive representation by energy class, based on data made recently available.

From an economic point of view, such a representation enabled us to better understand how policy instruments impact differently energy efficiency and sufficiency. We learnt that:

- Price instruments play on both efficiency and sufficiency and are by far the most cost-effective instrument, leading to net benefits after several years. The CO₂ tax plays rather on the former component whereas the end-use energy tax plays rather on the latter. But on the whole, they lead to very similar results in terms of effectiveness and cost-effectiveness.
- The regulation, as represented, is net benefiting but has a contrasted impact in new and existing dwellings. It is by far the only way to improve the energy efficiency of new buildings, but a higher requirement than class D is necessary for retrofittings to generate effective energy savings.
- Subsidies help progress in efficiency, due notably to information acceleration, but they relax sufficiency. The energy savings are more effective than in the regulation case but still low compared to the reference case and when labelled in financial terms, this policy turns to be a net social cost. Its use should be confined to short-term periods, when advantages can be drawn from its accelerating effect on information and technology learning, in combination with other tools.

From a policy-making point of view, there is a striking gap between the business as usual projections and the national objective of 2020 and the means about to be implemented reduce it very slightly. We can discuss the model design, its sensitivity and our policy representation but the upper bound of the model is clearly below this goal for any policy. Given this result, improving effectiveness is of prior interest from a policy making point of view than cost-effectiveness. Therefore, new radical policies are needed, especially for the huge potential of the retrofitting of existing dwellings.

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