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Abating CO_2 emissions in the building sector: the role of carbon pricing and regulations

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LIST OF ABBREVIATIONS

ADEME	French Agency for Environment and Energy Management
CIRED	International Research Center for the Environment and Development
CO_2	Carbon Dioxyde
EU	European Union
kWh/y	Kilowatt-hour per year
kWh/m2/y	Kilowatt-hour per square meter per year
kWh cumac	Cumulative discounted kilowatt-hour updated.
m2	Square meters
OH_ID	Occupying homeowners in individual dwellings
OH_CD	Occupying homeowners in collective dwellings
SH	Social housing
T_ID	Tenants in individual dwellings
T_CD	Tenants in collective dwellings

1 Executive summary

This report assesses the efficiency of carbon pricing and regulation in the French residential sector both in terms of energy consumption reduction and distributive effects between tenants and landlords in collective or individual dwellings and social housing.

- Res-IRF, a hybrid energy-economy modeling of the French residential sector over 2008/2050, is used to carry out the analysis through the design of two stylized scenarios differently implementing carbon pricing and a regulative tool embodied by an obligation of renovation in case of dwelling occupation change.
- Res-IRF is designed to handle technological and behavioral specificities in the household sector. For this report, Res-IRF has been recalibrated on statistics and econometrics results in order to represent realistic retrofitting patterns for each dwelling type and a realistic subsidization effect on the investment decision.

The report provides results concerning the dynamics in terms of energy consumption, intensity of heating infrastructure use, retrofitting patterns, building stock energy performance and costs burden related to retrofitting investment and energy bill.

1. The two scenarios converge towards the same level of energy consumption. The scenario implementing an obligation of renovation improves the building stock energy performance through retrofitting more than the scenario with only carbon pricing. The “price signal” instrument is inefficient to trigger investments in case of split incentives (including the landlord-tenant dilemma). Energy consumption reduction in the scenario with only carbon pricing is obtained through less intensive use of the heating infrastructure. It reduces the rebound effect but may increase fuel poverty among tenants.
2. The scenario with only carbon pricing can bear more anti-redistributive effects as tenants more contribute to the tax revenues, which may reduce its political feasibility.
3. The energy consumption reduction of these two scenarios does not succeed in reaching the French official reduction target of 38% by 2020 compared to 2008 level. Given the high level of carbon tax in the scenario with only carbon pricing, leading to risks with regard to fuel poverty and anti-redistributive effects, this suggests the necessity to implement an obligation of renovation in the policy mix.

2 Introduction

In October 2009, the EU set the appropriate abatement objective for Europe's greenhouse gas emissions at 80-95% below 1990 levels by 2050. At the national scale, France is legally committed to reduce its greenhouse gas emissions by 75% by 2050 compared to 1990 level, and to improve final energy intensity by 2% a year from 2015 onwards.

The residential sector has received much attention from policy-makers as it weights both into energy consumption and CO_2 emissions, and as it is suspected to be the sector encompassing the greatest potential for energy conservation at a moderate cost (Levine et al., 2007). To reach the European target, the Roadmap 2050 notably recommends a reduction by 95% in the buildings sector CO2 emissions from 19990 to 2050 (ECF 2010). Legally, Directive 2012/27/EU establishes a common framework of measures for the promotion of energy efficiency and Directive 2010/31/EU focuses on the energy performance of buildings. At the French scale, the residential sector consumed 30% of the total French energy supply in 2011 (in final energy)[1], essentially for heating and hot water purposes. Given the low replacement rate of dwellings, the promotion of energy saving investments in the existing building stock through retrofitting and renewable energy production is all the more a major issue in the French climate policy. Therefore, the French policy package called "Grenelle de l'environnement" (voted in 2009) aims at cutting energy consumption by at least 38% by 2020 compared to their 2008 level and fixed targets of retrofitting 400 000 dwellings per year from 2013 onwards and the 800 000 worst energy efficient dwellings in the social housing stock by 2020.

Although retrofitting can be a profitable investment, all the more with anticipated rising energy prices, specific barriers prevent many households from investing. These barriers, studied in the literature of the "energy efficiency gap", concept introduced by Jaffe and Stavins in 1994 (Jaffe and Stavins 1994), have been categorized either as market barriers, market failures or behavioural failures (Gillingham et al. 2009). "Some market barriers, such as hidden costs (e.g. hassle due to indoor insulation) or consumer heterogeneity, are normal components of well-functioning markets. Likewise, some market failures arise on the markets for energy efficiency, such as imperfect information (uncertainty about future energy prices and the actual energy savings from the use of the energy technologies), split incentives between landlord and tenant, credit market imperfection or innovation externalities. Finally, some behavioural failures, such as bounded rationality and heuristic decision-making, are increasingly cited as systematically moving energy efficiency investment decisions away from cost-minimization"(Giraudet et al. 2012).

Public policies aim at overcoming some of these barriers trough economic instruments (subsidies, zero rate loan, carbon tax, etc.) and non-economic ones (regulation, informative tools, etc.). Actual French policies dealing with the existing building stock have mainly

[1] Source: "Le bilan énergétique de la France en 2011" http://www.developpement-durable.gouv.fr/IMG/pdf/LPS130.pdf

implemented economic instruments: an income tax credit in 2005 and a zero rate loan in 2009 in order to trigger private investment in energy conservation and renewable energy equipment[2]. A very limited carbon tax has also been voted in 2012, but will have an effect only if rates are raised in the next years, which will require new laws. Whereas the zero rate loan has received little success compared to what was expected, the tax credit scheme has been widely used in France: between 2005 and 2008 about one primary residence out of sixteen was renovated while benefiting from it, corresponding to 4.2 million of households (Mauroux et al. 2010) and has had a significant positive effect on retrofitting, despite important free-riding (Mauroux 2012, Nauleau 2013). However, this policy has mainly benefited to the occupying homeowners and the wealthiest households: in 2008, 9.1% of households in the 5th quintile of income have benefited from the tax credit vs. 1.6% of households in the 1st quintile (Mauroux et al. 2010).

Therefore, we can wonder if economic instruments, based on price signal, are the most efficient to solve all barriers causing the energy efficiency gap in the residential sector. Indeed, some barriers, such as the split incentives between tenant and landlords or the transaction costs inherent to a collective decision process, may not be solved by "price signal" instruments, at least as they have been implemented. Moreover, the households more likely to cumulate these specific barriers are the same who are likely to live in the worst existing building stock in terms of energy performance, which raises the issues of fuel poverty and fairness.

This paper addresses this issue in comparing two public policies. In the first one, a high carbon tax is uniformly applied on heating energy consumption in order to encourage energy saving measures. In the absence of market failures, a carbon tax would be the first best in terms of CO2 emissions reduction. In the second one, besides a lower carbon tax, a retrofitting obligation is introduced to compel all homeowners whose dwelling is below a certain energy performance to upgrade it at every change in dwelling occupancy. The retrofitting obligation has already been discussed in France: first proposed by the non-profit organization négaWatt (Salomon et al. 2005), it was discussed during the *Grenelle de l'environnement.* To our knowledge, such a policy has never been experimented. In the UK however, the Energy Act 2011 contains powers so that from 2018 landlords should ensure their privately rented properties meet a minimum energy efficiency standard[3].

The simulation model Res-IRF is used for this purpose. Res-IRF is a partial equilibrium and techno-economic model developed at CIRED (Giraudet et al. 2012). It is designed to handle technological and behavioural specificities of the household sector, in order to model both the dynamics of the building stock through retrofitting and new buildings, and households' behaviour in terms of energy consumption. It focuses on energy consumption for

[2] Other policies have been implemented, designed at the regional level or in function of households' characteristics but most of them have still taken the shape of economic instrument. Other non-economic instruments such as a program for renovation dedicated to poor households, called "Habiter mieux", are marginal and no study is available yet.

[3] https://www.gov.uk/getting-a-green-deal-information-for-householders-and-landlords

space heating which covers 66% of energy demand in the French household sector. For this report, Res-IRF has been recalibrated on the basis of statistics and econometrics results, in order to better represent the different types of dwellings in terms of retrofitting patterns, and the effect of subsidization on investment decision. Statistics and econometrics results are based on data coming from the "Energy Management" EM survey, annually supervised by the French environmental agency ADEME (TNS Sofres - ADEME 2012, Nauleau 2013). This survey provides detailed information about retrofitting investment (retrofit options, the households' and dwellings' characteristics, subsidization, etc.). Preliminarily to the results, we present the statistics and econometrics underlying the calibration.

Res-IRF models several economic instruments aiming at reducing the final energy consumption of the residential sector through energy performance and consumption behaviour. Five instruments are considered, which can be ordered in three classes in the model: subsidies (i), which lower upfront cost; taxes (ii), which increase energy related operating costs; and regulations (iii), restricting the set of choices related to energy efficiency.

The remainder of this paper is organized as follows. Section 2 provides an overview of Res-IRF. Section 3 presents statistics and econometrics results based on the EM survey used for the calibration. Section 4 details the scenarios chosen to enlighten the comparison between the two public policies. Section 5 analyses the results. Section 6 concludes.

3 An overview of the Res-IRF model.

Res-IRF describes the dynamics of the French residential building stock through the construction of new dwellings and the retrofitting of existing ones. It is built on a discrete-continuous representation of energy consumption, linking choice of discrete energy efficiency option to continuous adjustments of households heating behaviour (Dubin and McFadden 1984).

3.1 Technological representation of the building stock.

The dwelling stock is disaggregated by energy carrier (electricity, natural gas, fuel oil, wood), efficiency class (as labelled by the French energy performance certificate) and type of investors (occupying or non-occupying homeowners, of individual or collective dwellings plus social housings) to account for households heterogeneity. A large share of the data comes from the ANAH database (Marchal 2008). The performance of the existing stock, (built before 2008, the initial year of the model, hereafter the "existing building stock"), ranges from class G, the least efficient (over 450 kWh/m2/y of primary energy for heating, cooling and hot water and ventilation) to class A, the most efficient (below 50 kWh/m2/y of primary energy). Figure 1 (resp. Figure 2) shows the distribution of the existing building stock among the energy efficiency classes (resp. the type of investor). The dynamics of the energy performance of the existing building stock comes from the retrofitting process as described in section 3.2.

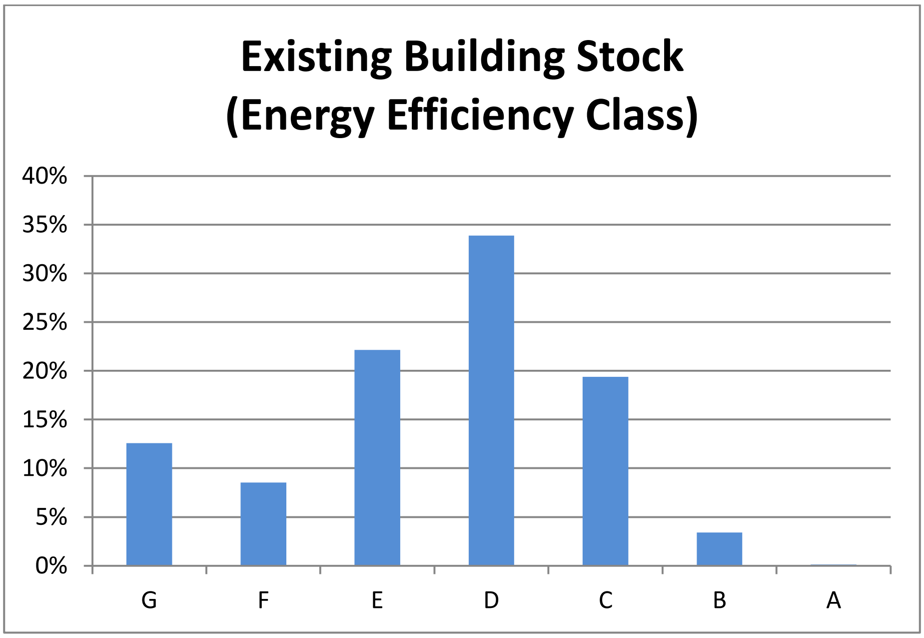

Figure 1. Initial Housing Stock by energy class.

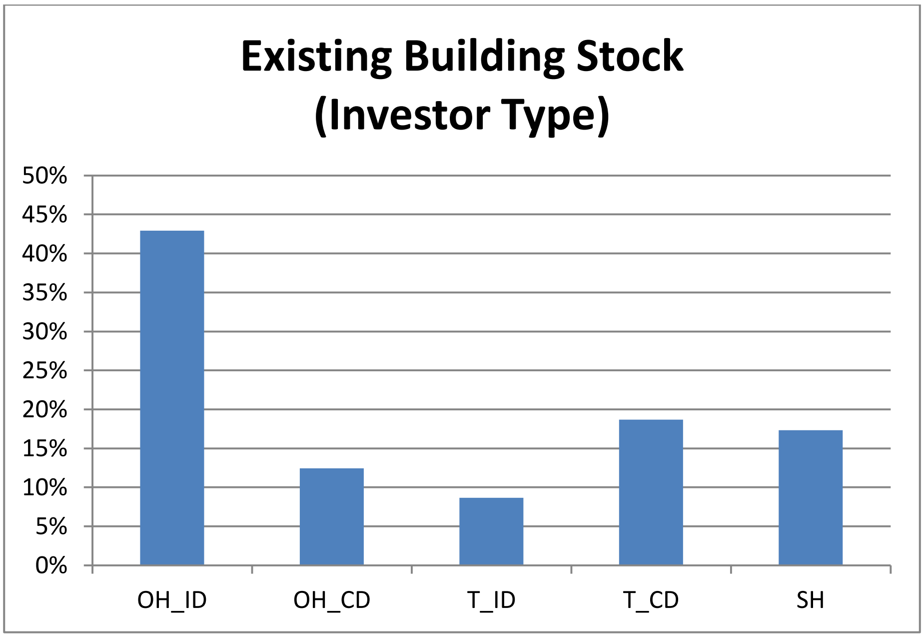

Figure 2. Initial Housing Stock by type of investor. OH and T stand respectively for occupying home-owner and tenant, ID and CD for individual and collective housings. SH stands for social housings.

Each year, demand for new construction arises from demolition, population growth and a demand for increased floor surface per capita (Giraudet et al. 2012). The performance of buildings constructed from 2008 onwards (hereafter the “new building stock”) is split into three categories: the ‘BC05’ or Building Code 2005 level (from 250 to 120 kWh/m2/y of primary energy, depending on the local climate), ‘LE’ or Low Energy buildings (50 kWh/m2/y) and 'ZE' or Zero Energy buildings, for which primary energy consumption is lower than the renewable energy they produce. Res-IRF implements current building code regulation for new constructions to conform to the 'LE' level in 2012 and to the 'ZE' level in 2020. Successive regulations are implemented in Res-IRF as a restriction of energy efficiency options. Figure 3 sums up the level of energy performance for each category of building.

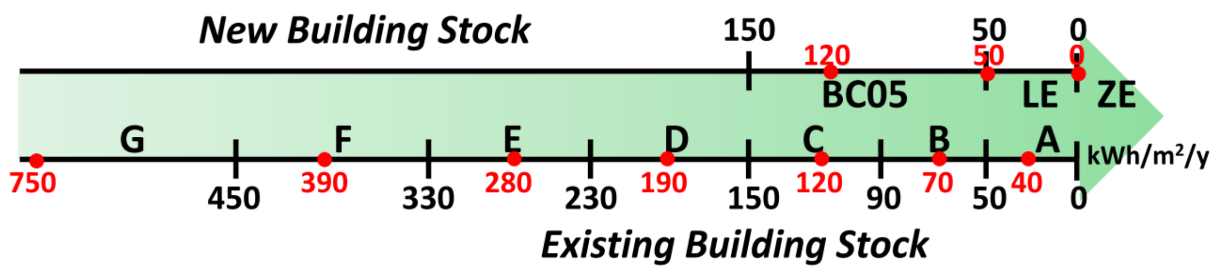

Figure 3 : Efficiency classes of New and Existing Building Stock in Res-IRF. In black the "official" energy efficiency classes as defined in the legislation. In red the discrete values used in Res-IRF (in primary energy).

No explicit technology is represented in Res-IRF, but implicit packages of measures on the building envelope (insulation, glazing, etc.) and the heating system that together achieve discrete levels of energy efficiency.

3.2 Drivers of energy performance of the building stock.

In existing dwellings, energy efficiency improvements result from investment options that upgrade existing dwellings to higher energy classes (e.g. from G to F, . . . ,A; from F to E, . . . ,A; etc.), as well as from fuel substitution. As in some other models (e.g. CIMS, NEMS), such transitions are determined by logit functions, which allocate to each investment option i a market share MS_i inversely proportional to its life cycle cost LCC_i, weighting investment cost against lifetime-discounted energy operating expenditures, (equation (1)).

$$MS_i = \frac{LCC_i^{-\eta}}{\sum_j LCC_j^{-\eta}}, \eta > 0, \quad (1)$$

The smaller the life cycle cost, the more the option is chosen. The best economic option in terms of LCC is the most chosen, but suboptimal economic options are adopted as well. η is called the heterogeneity parameter because it encapsulates the fact that in real life, buildings and households differ, even among a given Res-IRF category.

The life cycle cost LCC_i is the sum of the initial investment cost, the discounted cumulative savings due to future energy savings and the intangible costs, as described below. Initial investment costs for each energy class switch are detailed in Table 1.

Table 1. Initial Investment Costs for retrofitting (in €/m2)

Initial/Ending Energy Class	F	E	D	C	B	A
G	**91**	**163**	**241**	**325**	**421**	**530**
F		**76**	**156**	**244**	**344**	**458**
E			**84**	**175**	**279**	**397**
D				**95**	**202**	**325**
C					**112**	**239**
B						**132**

Res-IRF enriches this framework with market and behavioural failures that have been empirically established. Investors are assumed to have myopic anticipation as regards future energy prices: we assume that the energy prices used to calculate lifetime-discounted energy operating expenditures are the means of past energy prices of the last two years. Myopic anticipation stands for both a market barrier linked to uncertainty and a behavioural failure. Imperfect information is emphasized through the calibration of "intangible costs" that fill the gap between observed technology choices and choices that would be made under perfect information (Jaccard and Dennis 2006). The gap is narrowed in the long-run by a decreasing function of intangible costs with cumulative knowledge, representing information acceleration or the "neighbour effect" (Axsen et al., 2009) which corresponds to an information externality. Finally, specific discount rates to each investor are used to catch the 'landlord-tenant dilemma' (IEA 2007), which splits incentives between tenant and landlord[4]. Table 2 summarizes the market and behavioural failures represented in Res-IRF.

Table 2. Barriers to energy efficiency in Res-IRF

Barriers to energy efficiency (non-exhaustive list)		Tentative representation in Res-IRF
Market barriers	Uncertainty	Myopic expectations*
	Hidden costs	Fixed intangible costs
	Heterogeneity of markets and preferences	Heterogeneity parameter
Market failures	Split incentives	Heterogeneous discount rates
	Information externalities	Decreasing intangible costs
	Innovation externalities	Learning-by-doing functions

*Note that myopic expectations could also be classified as a heuristic decision-making.

[4] The model only feature private, and not public, discount rates, which are much higher than those used in public project assessments.

For each dwelling category, the annual number of retrofits is a logistic function of the average net present value of all retrofitting options (including intangible costs) weighted by their market shares. In order to represent other barriers specific to each investor which cannot be modelled by differentiated discount rates (such as difficulties inherent to a collective decision process or liquidity constraints) five renovation functions were calibrated, one for each type of investor. The two parameters of each function were determined so as to reproduce real data (see more details in the following section).

Overall, energy efficiency improvements in the existing building stock (*i.e.* increased quantity and/or quality—the ambition—of retrofits) result from changes in the relative profitability of various retrofitting options, induced by energy price variations and sustained by retrofitting cost decrease. The latter follows the self-reinforcing process of information acceleration on the demand side, and learning-by-doing on the supply side (Gillingham et al. 2008, Wing 2006). This evolution is countervailed by the natural exhaustion of the potential for profitable retrofitting actions.

In new constructions, one single type of investor more simply chooses one option among nine combinations of potential energy carriers and energy efficiency levels; cf. Giraudet, Guivarch, and Quirion (2012) for more details.

3.3 Drivers of energy consumption: the rebound effect.

According to identity (2), energy used for space heating E_{fin} (in kWh/y) can be seen as a product of the building stock S (in m2), the specific consumption under conventional utilization assumptions $\frac{E_{conv}}{S}$ (in kWh/m2/y of primary energy) which is the inverse of the energy efficiency of the stock (categorized into energy efficiency classes in Res-IRF), and the ratio between conventional and actual consumption $\frac{E_{fin}}{E_{conv}}$, representing a dimensionless "service factor" or utilization rate of the heating infrastructure. This identity allows to distinguish the two possible sources of energy savings: on the one hand, an increase in energy efficiency, i.e. a decrease in energy consumption per unit of energy service $\frac{E_{conv}}{S}$; on the other, an increase in "energy sufficiency", which may come either from a decrease in surface S or by a more restrictive utilization of the heating infrastructure, $\frac{E_{fin}}{E_{conv}}$. Conversely, the direct rebound effect, that is the fact that "consumers may choose to heat their homes for longer periods and/or to a higher temperature following the installation of loft insulation, because the operating cost per square meter has fallen" (Sorrell et al. 2009) implies an increase in $\frac{E_{fin}}{E_{conv}}$.

$$E_{fin} = S \frac{E_{conv}}{S} \frac{E_{fin}}{E_{conv}} \quad (2)$$

In order to represent the direct rebound effect, actual energy demand is adjusted by a constant elasticity curve (the value of the elasticity is -0.505) linking the service factor E_{fin} / E_{conv} to the annual conventional fuel bill at current energy prices (see Figure 4). This relationship was derived statistically from a study made by Allibe (2012) using data coming from a survey of customers of the French electricity company EDF. It states that the higher (lower) the energy expenditure, the more (less) restrictive the utilization.

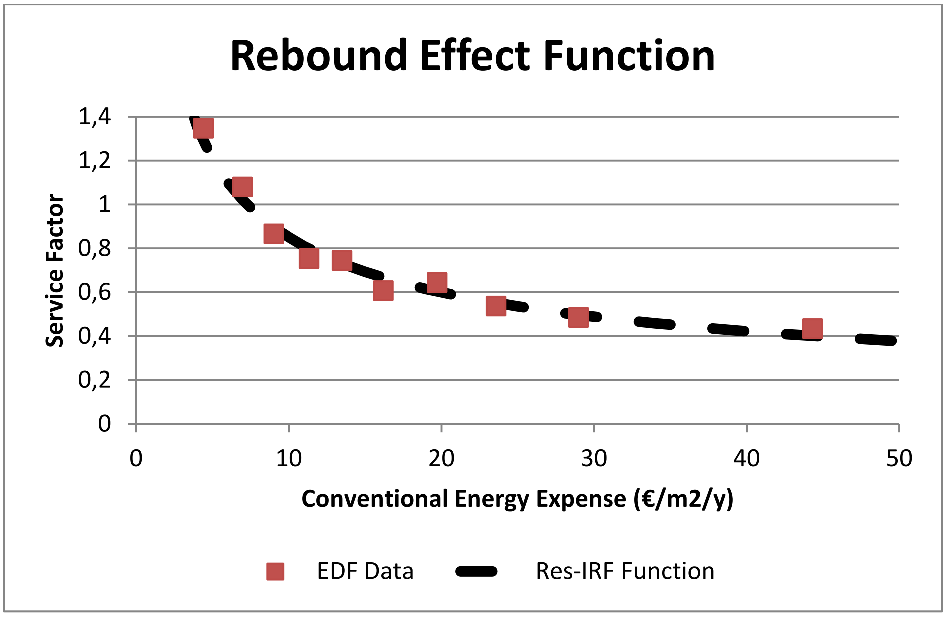

Figure 4. Rebound Effect Function

4 Calibration

In this section we only detail the latest modifications of Res-IRF, namely the calibration of the different logistic retrofitting functions according to the different types of investors. Initially, retrofitting rates' differentiation between all types of investors was due to heterogeneous discount rates[5]. To see other essential parts of the Res-IRF model, such as the calibration of intangible costs, and the value of all the parameters of the model, see (Giraudet et al. 2012).

A recent version of Res-IRF was calibrated using statistics and econometric results based on data coming from the annual "Energy Management" (EM) survey, described in section 4.1.

[5] Assumed discount rates are: 7% for the occupying homeowners in individual dwellings, 10% for the occupying homeowners in collective dwellings, 35% for the tenants in individual dwellings, 40% for the tenants in collective dwellings.

For each of the five logistic retrofitting functions, the two parameters of the logistic function are calibrated thanks to two exogenous retrofitting rates. The first one comes from real data (EM survey), and is the situation observed over 2009/2010, which has a homogenous positive level of subsidies. The second one is a hypothetical situation, similar to the real situation but with subsidies set to zero. The EM survey allows us to determine real retrofitting rates with subsidies for each type of investor as defined in Res-IRF (section 4.2). Moreover, an econometric study using the same dataset assessed the effect of the French tax credit rate implemented in 2005 on the retrofitting rate (Nauleau 2013). We use these results to estimate that hypothetical retrofitting rates without subsidy would be 20% lower that the rates with subsidies abovementioned (section 4.2). Further, in order to assess the robustness of the calibration, we make, for both retrofitting rates and energy savings, a comparison between values derived from the survey and values calculated by the model Res-IRF during the time period 2008-2011 (section 4.4).

4.1 Calibration data

Res-IRF is calibrated using statistics and econometrics results based on data coming from the annual "Energy Management" (EM) survey. Every year, around 10 000 households are asked about their residential energy consumption and the investments they have or not made, in order to improve the energy efficiency of their dwelling. A first questionnaire provides socio-economic variables, housing information (type of building, heating energy source, building date, etc.), and information about dweller's situation (occupation status, move-in date).

Those who have invested in retrofitting during the last year (around 10% each year) answer a second questionnaire to provide information on retrofitting types, investment costs, some payment modalities, the economic or non-economic incentives investors have benefited from (including tax credit), as well as other qualitative information such as their motivation, personal context, satisfaction, etc. In this second questionnaire, each investment is described by 1 to 4 items taken from a retrofitting options list. Retrofitting options include insulation (external insulation of wall, internal insulation of wall, roof, attic, ceiling, windows, shutters), heating system improvement (thermostatic valves, heat cost allocators, ambient thermostat, programming equipment), new heating system (radiator, boiler, wood stove, heat-pump, solar heater) or heating system replacement (with information on fuel switching).

The EM survey reports all retrofitting measures concerning building energy performance the households have made in their dwelling during the last year, from minor to major renovations. By contrast, Res-IRF only models retrofitting measures able to make the dwelling upgrade to higher energy classes (e.g. from G to F, . . . , A; from F to E, . . . , A; etc.), which means that only retrofitting measures above a certain threshold of energy performance are represented in Res-IRF. Therefore, to estimate the retrofitting rates for each investor, we select retrofitting measures in the EM survey that are able to make dwelling upgrade to higher energy classes. To take into account the fact that on the macro scale, two small retrofitting projects may be equivalent to a big one, we choose relatively low standards. In addition, we make further verification by comparing the energy savings calculated in Res-IRF and those derived from this survey (see further).

The chosen perimeter of retrofitting measures, called the Res-IRF perimeter, includes all combinations of at least two retrofitting measures among the following categories: opaque surface insulation / glazed surface insulation / ventilation / heating system improvement / installation of system producing renewable energy. Are also considered retrofitting measures only including opaque surfaces insulation when the investment cost is above 4000€[6].

Annex A provides the main statistics from this database. Table 6 (resp. Table 7) details the distribution of the main households' variables (resp. the main dwellings' ones) on both the full sample over 2008/2011 and the sub-sample including only retrofitting observations included in the Res-IRF perimeter. We see that the chosen variables of segmentation in Res-IRF, namely the status of occupation and the building type, are the most determinant. Indeed, the owner-occupiers are over-represented in the retrofitting sub-sample (91%) compared to the full sample (65%), as well as the individual houses which are 85% in the retrofitting sub-sample, compared to 56% in the full sample. As regards other households' variables, the wealthiest households, those having a "35-54 years old" head of household and those having recently moved into a new dwelling are over-represented in the retrofitting sample, although more slightly. As regards other dwellings' variables, older buildings, those located in the coldest climate zones (1 and 2) and in rural areas are also over-represented in the retrofitting sub-sample. Therefore, although other barriers could be identified in Res-IRF thanks to the introduction of other socio-economic variables determining the decision of investment (Jakob 2007), in particular the liquidity constraints correlated with the household income level, we assume that the combination of the status of occupation and the building type sufficiently captures households' heterogeneity. Besides, income level heterogeneity is addressed to some extent since income is correlated with the occupation status.

As regards retrofitting measures themselves, the database contains 1294 observations over 2008/2011 with retrofitting investments included in the Res-IRF perimeter. Most of them are combinations of two single measures (72%), then single opaque surface insulation or a combination of three measures, at around 13% each (Table 8 in Annex A). As regards the distribution of retrofitting types, Table 9 in Annex A provides the annual market shares for each retrofitting type. The most common measures are windows insulation, with annual market shares between 40 and 50%, then roof insulation (30/38%), indoor wall insulation (24/32%), and boiler retrofitting, especially the replacement without fuel switch (13/20%).

Table 10 in Annex A also provides mean annual costs for each retrofitting measure. The most expensive measures among those dealing with heating systems are the installation of heat pumps (around 9000/13000 euros). The cheapest ones are the installation of regulation

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[6] The Investment costs to shift from energy efficiency class G to energy efficiency class F are 93 euros per m2 the initial year. Considering a house of 112m2, the total costs are 10400 euros. .

systems. As regards insulation, measures on outdoor wall are the most expensive (around 6300/8300 euros), measures on indoor walls the cheapest ones (around 1800/2500euros).

4.2 Estimation of retrofitting rates (with subsidy) through statistical study

We use the mean of retrofitting rate over 2009/2010 as the reference of retrofitting rates *with subsidy*. Indeed, since retrofitting rates are low, especially for non-occupying homeowners of collective dwellings or social landlords, it is useful to increase the sample size using two years to decrease the statistics variability due to small sample size. 2009/2010 is appropriate as subsidy levels were homogenous over this period, as well as their impact on the retrofitting rate (Nauleau 2013). We find a global retrofitting rate of 3% (Table 3).

The first column of Table 3 shows real 2009/2010 retrofitting rates for the different categories of investor. Again, we see that barriers specific to the collective decision process and linked to the tenant-owner dilemma play a great role given the gap between the different retrofitting rates : from 0.2% for the tenants in collective buildings to 5.2% for the owner-occupiers in individual house.

4.3 Estimation of retrofitting rates (without subsidy) through econometric estimation

Using the same dataset, the econometric study made by Nauleau (2013) assesses the effect of subsidization on households' retrofitting investment. In France, an income tax credit was implemented in 2005 in order to encourage households to invest in energy conservation measures or renewable energy in their dwelling. A before/after estimation method is performed on data coming from the EM survey available over 2001/2011. As regards opaque surfaces insulation measures, a reform on the tax credit base occurred in 2009, splitting the tax credit period in two. During the first period, between 2005 and 2008, only material costs have been eligible to the subsidy. During the second period, labour costs were introduced in the tax credit base. In most cases, tax credit rates were 25% of the tax credit base but could vary in specific situations[7]. Given all the evolutions in the tax credit rates (data provided by the tax credit scheme), especially due to the 2009 reform, and given the distribution of the opaque surfaces insulation measures and their average repartition between labour and material cost[8] (data provided by the EM survey), the overall tax credit rate corresponded to 16% of total investment cost during the first period and 25% during the second one. Results indicate that the tax credit had no significant effect on private retrofitting investment during the first period but had a significant positive effect during the second one. As regards the second sub-period, over 2009/2011, the study concludes that 20% of the observed

[7] In case of dwelling occupation change for example. See Mauroux (2012) for a complete description of the income tax credit scheme.

[8] The mean labor cost is 34.5% of the total cost for the opaque surfaces insulation measures over 2009/2011. Since 2009, the EM survey has asked households to detail their investment cost in terms of material and labor cost, which enables is to produce statistics about the repartition between material and labor cost for each retrofitting type.

retrofitting rate can be ascribed to the subsidization effect. We recall that, since a before/after estimation was performed, estimates for the two “after” sub-periods have to be interpreted relatively to the pre-subsidy period (over 2001/2004). That is to say for the second sub-period estimates: a situation with 25% of subsidy rate to be compared to a situation without any subsidy.

Therefore, assuming that the subsidization effect has the same effect on investment decision for all retrofitting options modelled in Res-IRF as for opaque surface insulation measures, we use this result in order to calibrate the subsidization effect in Res-IRF. Starting in 2009/2010 from a situation in which the tax credit was implemented with a rate at 25% (like in the second period for opaque surfaces insulation), we impose that the same situation without any subsidization would lead to a decrease in the retrofitting rate of 20% of the retrofitted rate output with subsidization[9]. The second column of Table 3 shows the hypothetical retrofitting rates without subsidization for each investor type.

Table 3. Retrofitting rates used in the calibration.

Investors type	Retrofitting rate (subsidy) Source: EM Survey over 2008/2009 and own calculations	Retrofitting rate (no subsidy) Source: Econometric study by Nauleau (2013): 20% decrease
Occupying homeowners of individual dwellings (OH_ID)	5.10%	4.10%
Occupying homeowners of collective dwellings (OH_CD)	1.76%	1.41%
Tenants of individual dwellings (T_ID)	1.48%	1.18%
Tenants of collective dwellings (T_CD)	0.17%	0.14%
Social housings (SH)	0.71%	0.56%
Total	2.98%	2.38%

4.4 Comparison of real data with Res-IRF outputs

Figure 5 compares the evolutions of the global retrofitting rate between Res-IRF outputs and EM survey statistics. We see that Res-IRF succeeds in reproducing the same range of values and the dynamic tendencies in the global retrofitting rate, although Res-IRF outputs’ annual variations are flatter than EM survey statistics’ ones.

[9] Therefore, we assume that the subsidization effect relatively to the retrofitting rate is the same for each dwelling category. Although it may not be the case, the EM survey does not allow us to check it. Moreover, this effect being in relative terms, the subsidization effect in absolute values is lower for categories with low retrofitting rate.

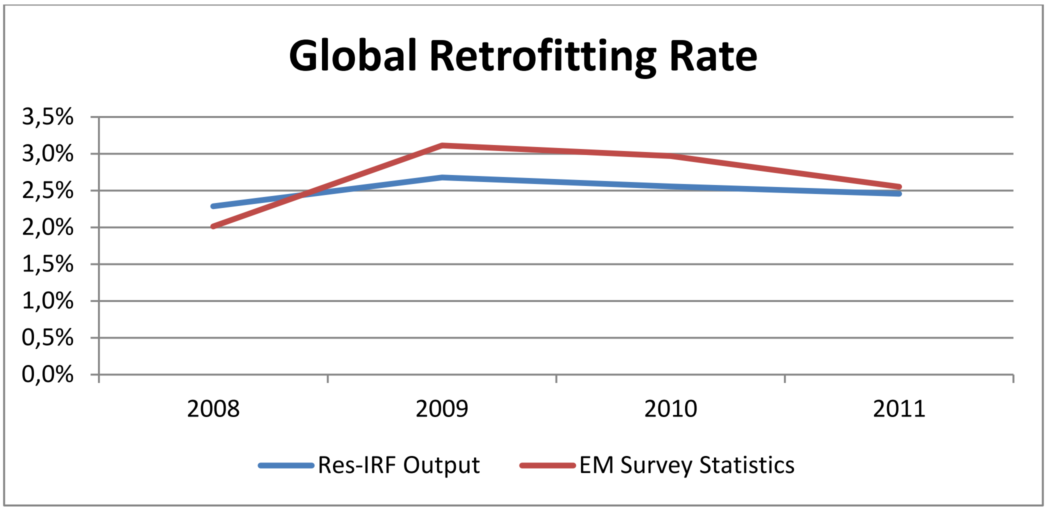


Figure 5. Global retrofitting rate of Res-IRF Output versus the estimated data from the EM Survey Statistics.

Table 4 gives the mean retrofitting rates per category of investor comparing Res-IRF outputs with EM survey statistics over 2008/2011. It shows that Res-IRF also succeeds in closely reproducing the differences among each category of investor.

Table 4. Retrofitting rates of Res-IRF Output versus the estimated data from the EM Survey Statistics

Investor category	Res-IRF Output (mean 2008-2011)	EM Survey Statistics (mean 2008-2011)
Occupying homeowners of individual dwellings (OH_ID)	4,7%	4.50%
Occupying homeowners of collective dwellings (OH_CD)	1,8%	1,45%
Tenants of individual dwellings (T_ID)	1,4%	1,19%
Tenants of collective dwellings (T_CD)	0,2%	0,28%
Social housings (SH)	0,7%	0,45%
Total	2,5%	2,6%

Another output provided by Res-IRF is the annual amount of conventional energy savings (before the rebound effect) resulting from total investments in retrofitting. We use the EM survey in addition to official data coming from the French Energy Performance certificate scheme[10] as regards conventional energy savings in order to translate each retrofitting measure into conventional energy savings. Then we can compare them with Res-

[10] http://www.developpement-durable.gouv.fr/1-le-secteur-du-batiment.html

IRF outputs. Energy savings are specific to each retrofitting type and depend on the climatic zone, the building type and the heating energy source of the dwelling (available information in the EM survey). They are expressed in kWh cumac[11]. They are transformed into annual energy savings to be compared to Res-IRF outputs. For insulation measures, energy savings data are most often expressed in kWh cumac per square meter of insulated surfaces or per window. As the EM survey does not provide such information, we use the total investment cost, available in the EM survey, to estimate the number of insulated surfaces or windows thanks to OPEN data on cost per window per m2 of insulating layer for each insulating measure (OPEN 2009)[12]. For several cases, the retrofitting type reported in the EM survey is less detailed than the ones presented in the Energy Performance certificate scheme. In those cases, we use the mean of the different retrofitting measures weighted by their market shares (In Numeri-ADEME 2012).

Figure 6 compares Res-IRF outputs with estimates based on statistics derived from the EM data over 2008/2011 as regards annual conventional energy savings. The two series are in good accordance. This indicates that the exclusion of small retrofitting measures in the perimeter used to estimate retrofitting rate does not matter at an aggregated level. They also have similar dynamic tendencies. However, the energy savings in the model seems to decrease faster than in reality. The explanation is that the most profitable retrofitting investments are made in priority during the first years and then the stock of profitable retrofitting actions progressively exhausts. A possible explanation of the rapidity of this exhaustion could be that Res-IRF does not consider congestion effects or capacity constraints in the supply side.

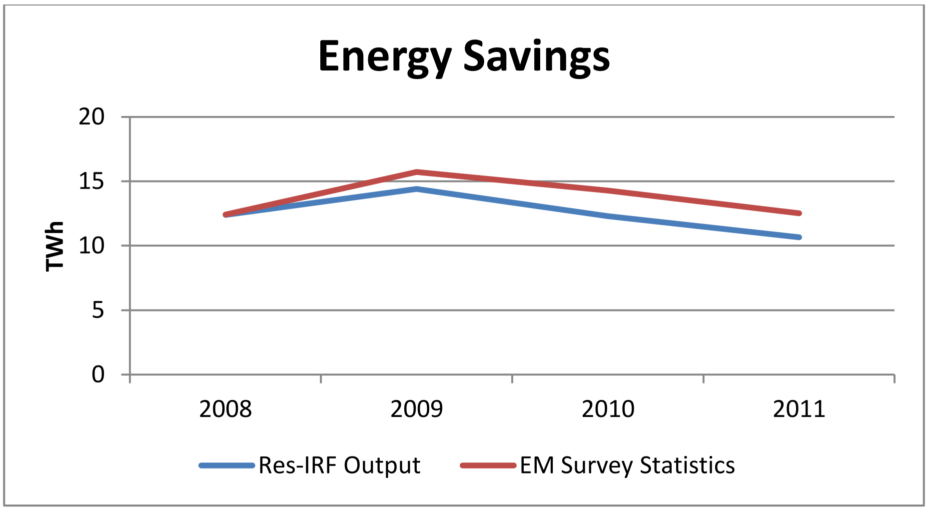


Figure 6. Annual energy savings due to retrofitting of Res-IRF Output versus the estimated data from the EM Survey Statistics.

[11] Cumulative over the life expectancy of the equipment (around 15 years for systems producing heat or renewable energy and 35 years for insulation measures on the building shell) discounted at 4%.

[12] OPEN is a survey similar to the EM survey, carried out less frequently and more detailed as regards the retrofitting measures.

5 Scenarios

This paper compares a pure "price signal" instrument versus a mix of price signal instrument and regulation. The "price signal" instrument takes the form of a carbon tax and would be the first best in terms of cost per avoided CO2 emissions in the absence of market failures, which is not the case (see section 2). Regulation takes the form of a retrofitting obligation (RO). The two scenarios rely on the carbon tax but at a different rate, and only one also relies on the retrofitting obligation. They have been built in order to lead to the same output in terms of energy consumption in the long run. These are summarized in Table 5.

The scenario "TAX75" introduces a carbon tax in 2015 at 75€ per ton of CO_2 emitted, increasing at 4% per year (so the tax reaches 296€/ton in 2050). All heating energy sources are taxed[13]. Contrary to the assumption of myopic anticipation for future energy prices, the tax is perfectly expected by the agents.

In the Scenario "RO+TAX40", a similar carbon tax is introduced in 2015 but at "only" 40€ per ton of CO_2, following the official Quinet report (Quinet et al. 2008). It increases also at 4% per year (so the tax reaches 158€/ton in 2050). As regards the implementation of a retrofitting obligation, it assumes that, in 2016 (respectively 2020, 2024 and 2028), all buildings corresponding to the level of energy performance G (respectively F, E and D) have to upgrade to at least energy class C at each change in dwelling occupancy. To do so, retrofitting choices for these dwellings are restricted to options above the threshold. In a study by CREDOC (2010), the rates of building occupancy changes are estimated at 1.5%, 15.2% and 9.9% of for respectively the occupying homeowners, tenants and tenants in social housings. To take into account barriers to the retrofitting obligation implementation (such as the congestion in the retrofitting supply sector or the probable reluctance of landlords to change tenants after the reform), we decrease these values by 20%. In addition to mandatory retrofits, *business as usual* endogenous retrofits are still taken into account, net from the retrofits that usually follow changes in occupancy.

[13] Electricity consumption is taxed based on the assumption that a kWh of electricity corresponds to 180 g CO2, as was the case in the 2000 French carbon-energy tax proposal. This value is higher than the actual average value but lower than the marginal value which would stem from an electricity dispatch model (Bonduelle and Joliton, 2007).

Table 5. Scenario policy design

Scenario	Instruments	Design
TAX75	Carbon tax	75€ per ton of CO2 in 2015, increasing at 4% per year
	Retrofitting obligation	None
RO+TAX40	Carbon tax	40€ per ton of CO2 in 2015, increasing at 4% per year
	Retrofitting obligation	At each occupancy switch, obligation to upgrade, at a minimum of energy class C, all energy class G dwellings (resp. F, E, D) in 2016 (resp. 2020, 2024, 2028)

These scenarios can be considered as extreme. Politically speaking, an initial level of carbon tax at 75€ has little chance to be voted. In the same way, the retrofitting obligation would have to be smoother to get a chance to be feasible, at least in terms of capacity constraints in the market. However, the analysis of these stylized scenarios avoids multiplying *ad hoc* assumptions helps us to grasp the underlying drivers.

As regards other policies, the tax credit scheme and the building code regulation for new buildings have already been implemented and legislated in France for the next years. They are then incorporated in the same way in both scenarios.

The tax credit has been implemented since 2005 to encourage households to invest into energy conservation measures or renewable energy production in their dwelling. Rates range from 15 to 50% of investment cost and subsidies are capped at around €15,000 per dwelling. In Res-IRF, the tax credit is in place from the initial year to 2020. The tax credit rate considered is the average tax credit rate for all the retrofitting measures included in Res-IRF perimeter (see section 4.1) weighted by their market shares and costs, leading to a rate of 12% in 2008 and 25% in 2009 (effective rates are slightly lower, the amount of the subsidy being capped at 15 000€).

The building code regulation compels new constructions (initially ruled by Building Code 2005) to conform to Low Energy level in 2012 (50 kWh/m2/y of primary energy for heating, cooling, hot water and ventilation) and to Zero Energy level in 2020. Successive regulations are implemented in Res-IRF as a restriction of energy efficiency options.

Finally, the energy prices for the different energy carriers are the same for both scenarios. From 2007 to 2011, they are derived from the PEGASE database. There is a very large uncertainty concerning the future of energy prices, but most likely energy prices in the next decade will be on a growing trend (World Energy Outlook 2012). Therefore, we make a relatively conservative choice by increasing the energy prices by 1% per year after 2011. In Annex B, Figure 17 and Figure 18 gives the Res-IRF assumptions for energy prices and carbon tax in both scenarios.

6 Results.

6.1 Energy Consumption

Figure 7 shows the energy consumption (in primary energy) from 2008 to 2050. After 2030, the consumptions are almost identical for the two scenarios, but as we will see, the drivers of consumption are very different. The peak in 2009 is due to the low energy prices, which mechanically induces a rebound effect. Starting at 381 TWh in 2008, energy consumption reaches 174 TWh in 2050, corresponding to a decrease by 53%. As regards the medium run, energy consumption reaches 293 TWh in the scenario “TAX75” and 303 TWh on the scenario “RO+TAX 40” in 2020, leading to an energy consumption reduction of respectively 23% and 21% compared to 2008. Thus, the French official target of 38% reduction in the existing building stock is not reached, which is in line with previous analyses (Giraudet et al., 2011).

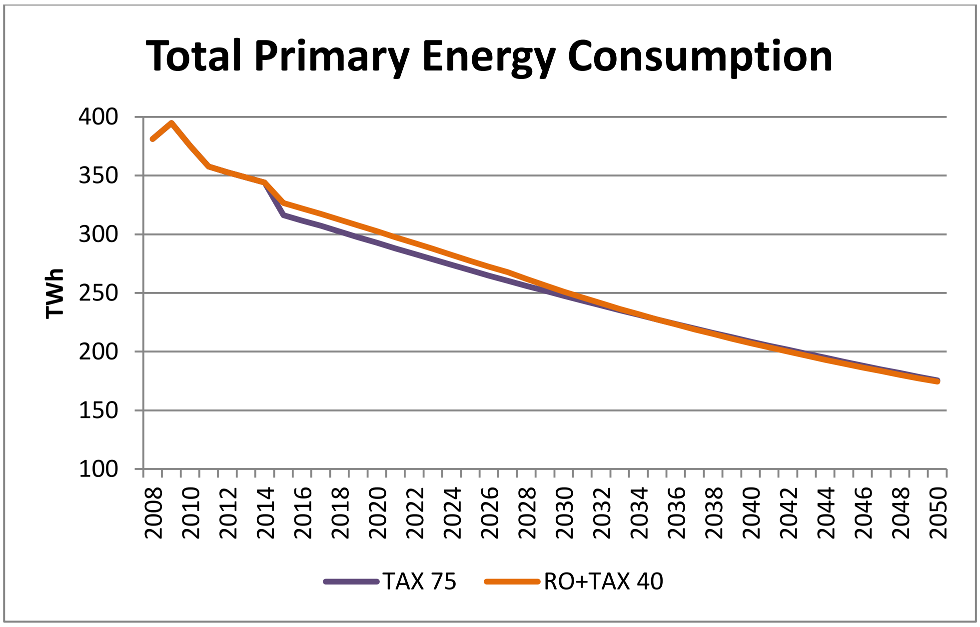
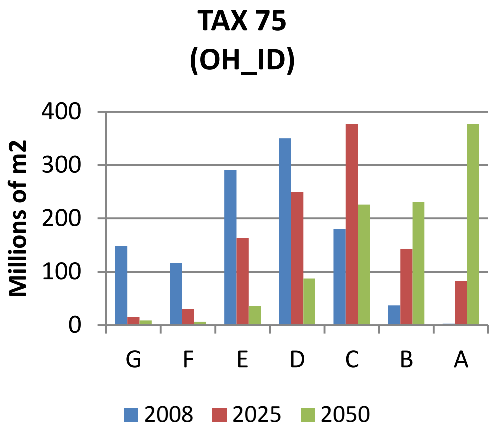
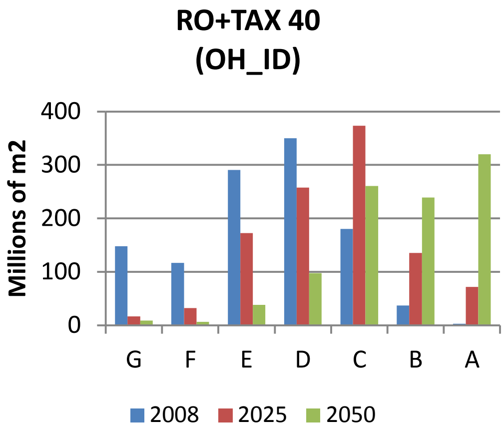


Figure 7. Energy consumption outputs for the two scenarios.

6.2 Housing Stock

Figure 8 shows the evolution of the “existing” housing stock (buildings constructed before 2008) for the two scenarios. We display separately the distribution of the building stock into the seven energy classes for each type of dwellings: the occupying homeowners in individual dwellings (OH_ID) or in collective dwellings (OH_CD), the tenants in individual dwellings (T_ID) or in collective dwellings (T_CD) and the social housing (SH).


TAX 75
(OH_ID)
Millions of m2
400
300
200
100
0
G F E D C B A
2008 2025 2050


RO+TAX 40
(OH_ID)
Millions of m2
400
300
200
100
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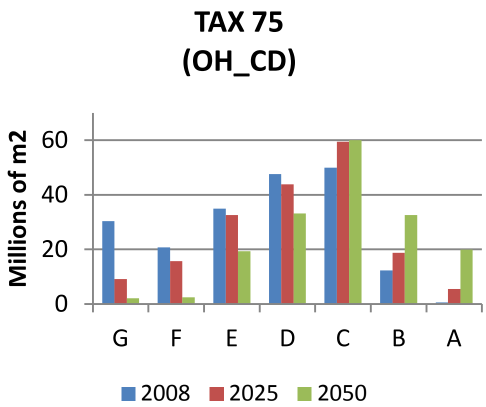
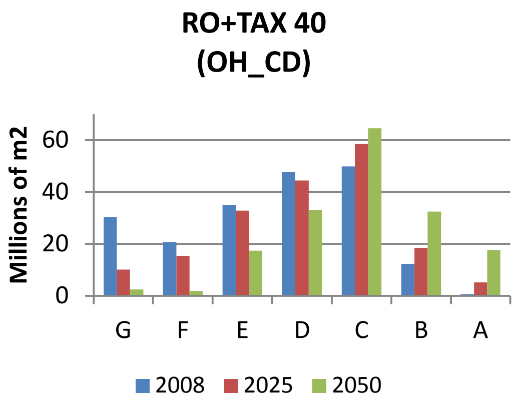
G F E D C B A
2008 2025 2050


TAX 75
(OH_CD)
Millions of m2
60
40
20
0
G F E D C B A
2008 2025 2050


RO+TAX 40
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Millions of m2
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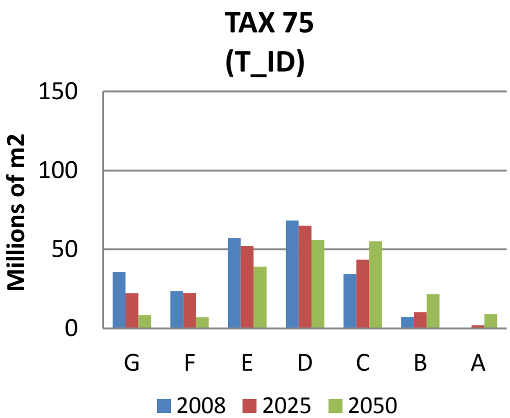
2008 2025 2050


TAX 75
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Millions of m2
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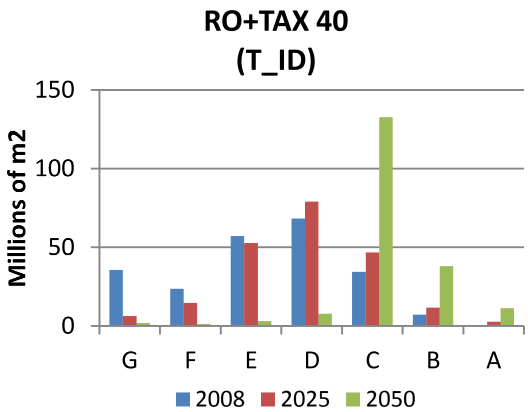
G F E D C B A
2008 2025 2050


RO+TAX 40
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Millions of m2
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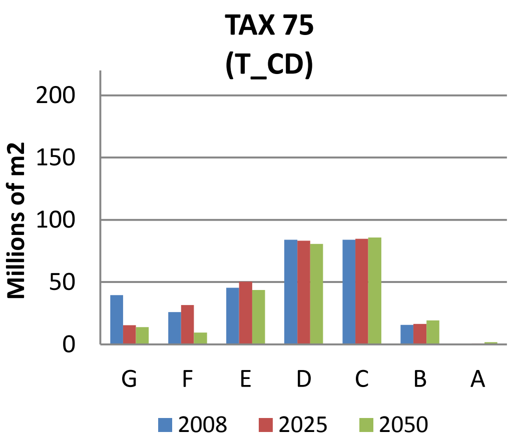
G F E D C B A
2008 2025 2050


TAX 75
(T_CD)
Millions of m2
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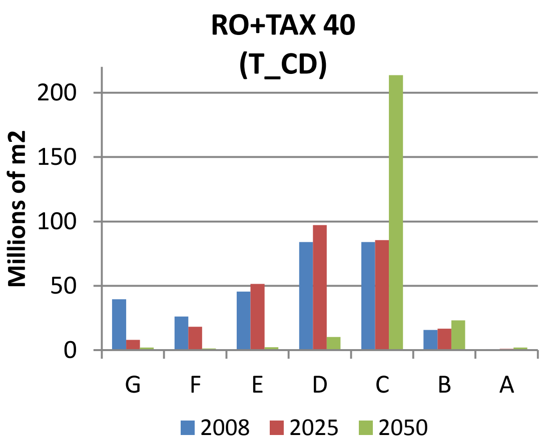
G F E D C B A
2008 2025 2050


RO+TAX 40
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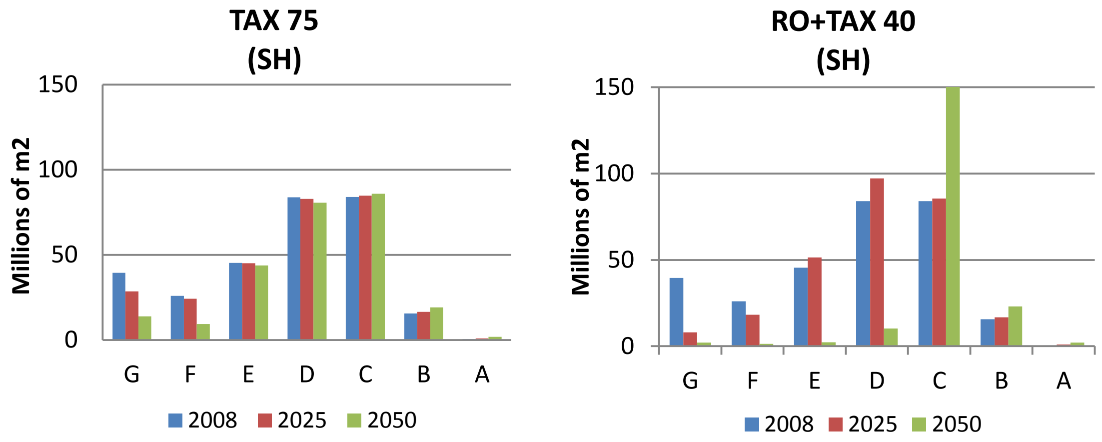


Figure 8. Evolution of the housing Stock differentiated in energy classes for the two scenarios. OH_ID and T_CD stand respectively for Occupying Homeowner in Individual Dwellings and Tenant in Collective Dwellings.

For simplicity, we focus our analysis of these results on the two polar categories, OH_ID and T_CD, since they display the most remarkable differences in their dynamics. The dynamics of the housing stock of the other types of investor are in between these two extremes: OH_CD being closer to OH_ID and T_ID and SH being closer to T_CD, reflecting that the occupation status drives more the retrofitting process.

The OH_ID investor is the most "rational" in terms of economic behaviour. Therefore the carbon tax is very effective to foster retrofitting. In 2008, most of the OH_ID housing stock is composed of dwellings of energy class E and D. Energy class B and A dwellings are almost non-existent, and energy class G and F dwellings represent a significant share. In both scenarios, by 2025, energy class G and F dwellings almost disappear and the largest share of dwellings is at energy class C. In 2050, the bulk of the dwellings is at energy class C, B or A (the highest share). Therefore, the dynamics of the OH_ID housing stock is extremely similar for the two scenarios TAX 75 and RO+TAX 40. Because the price signal is stronger in the TAX 75 scenario, the retrofitting options leading to high energy class buildings are slightly more chosen (it is particularly visible for energy class A buildings).

Conversely, the dynamics of the T_CD housing stock are remarkably different under the two scenarios. In the TAX 75 scenario, the T_CD dwellings are almost never retrofitted, except for the very energy-inefficient ones (G and F energy classes). Because of all the barriers to retrofitting for this type of investor (modelled by higher discount rates and by specific retrofitting function parameters) the price instrument is not effective to induce retrofitting. In this context, the Retrofitting Obligation (RO) makes the difference. However, its effect is only visible in 2050. We recall that RO compels energy class G dwellings (resp. F, E, D) to be upgraded up to energy class C from 2016 onwards (respectively 2020, 2024 and 2028). Therefore, in 2025, RO has started respectively 9, 5 and 1 years previously for energy class G, F and E buildings (Table 5). Since only a share of dwellings is concerned by the RO every year (in case of occupancy change), it takes more time than a few years to eliminate a given energy class. As regards energy class G, there are nearly no more dwellings to be retrofitted when the RO starts. Moreover, we see that, in case of RO for the T_CD, the retrofitting option chosen in majority upgrades to no more than the energy class C, for compliance. Therefore, in 2050, the majority of the T_CD buildings are in energy class C. This peak is not visible for the OH_ID in the RO+TAX 40 scenario, as the carbon tax makes them choose more up-grading retrofitting investments.

6.3 Intensity of energy use

In 2050, the average energy efficiency of the housing stock in the RO+TAX 40 scenario is higher than in the TAX 75 scenario (126kWh/m2/y compared to 149kWh/m2/y). Since the energy consumption is the same in the long run, it means that the drivers of energy consumption reduction are different. Figure 9 shows the dynamics of the intensity of energy use, encapsulated by the service factor, *i.e.* the ratio between real and conventional energy consumption (see section 3.3). We see that the intensity of energy use is lower in the TAX 75 scenario all along the period. Indeed, in the TAX 75 scenario, the T_CD dwellings are almost not retrofitted, so the tenants live in poorly energy-efficient buildings, while the tax-included energy price is high. Strengthening sufficiency is then the way to reduce the energy expenses. As tenants are over-represented in the lowest deciles of income (CGDD 2012), this may increase fuel poverty. Therefore, the carbon tax can be considered as a mean to reduce the rebound effect but we have to pay attention to the disparities between the different dwellings categories, which can induce such undesired side effects.

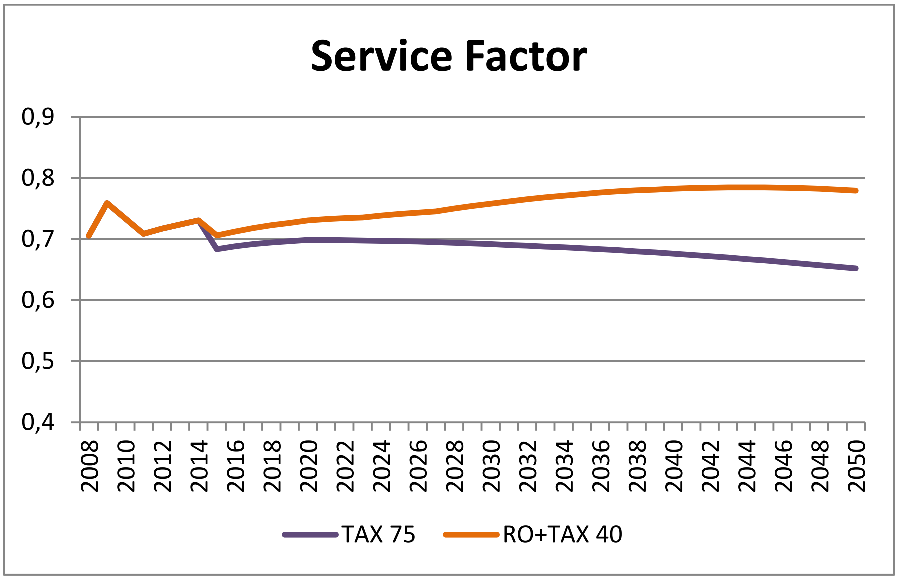


Figure 9. Evolution of the service factor, or the utilization rate of the heating infrastructure (the ratio between real and conventional energy consumption), in both scenarios.

6.4 Retrofitting

Figure 10 displays the mean retrofitting rate in the existing housing stock for the two scenarios. As the carbon tax starts in 2015 and the Retrofitting Obligation in 2016, the paths before 2015 are identical. The peak in 2009 corresponds to the increase in the tax credit scheme from 12% to 25%. Similarly, the decrease of retrofitting in 2021 is explained by the end of the tax credit scheme. Before 2012, the variations of the energy price also impact the number of retrofitting since economic agents have myopic expectations and consider recent past energy prices. We can finally see that the introduction of the carbon tax in 2015 induces an increase in retrofitting.

The different years of implementation of the RO (every four years from 2016 for energy class G dwellings to 2028 for energy class D dwellings) impact very significantly the annual number of retrofitting investments. The peaks of annual retrofitting rates increase because of the structure of the existing housing stock: in 2016, there are very few buildings under the retrofitting obligation (energy class G buildings) whereas in 2028, they constitute a significant share of the housing stock (energy class D buildings). The dynamics of the retrofitting rates in the "RO+TAX40" scenario is clearly stylized as we imperfectly consider potential congestion effects in the retrofitting supply sector or potential landlords' aversion for dwelling occupation change due to the reform (we just decrease the pace of building occupancy switching). Politically speaking, this regulative tool would have to be implemented in a smoother way but we have chosen to keep its design simple to make the analysis easier.

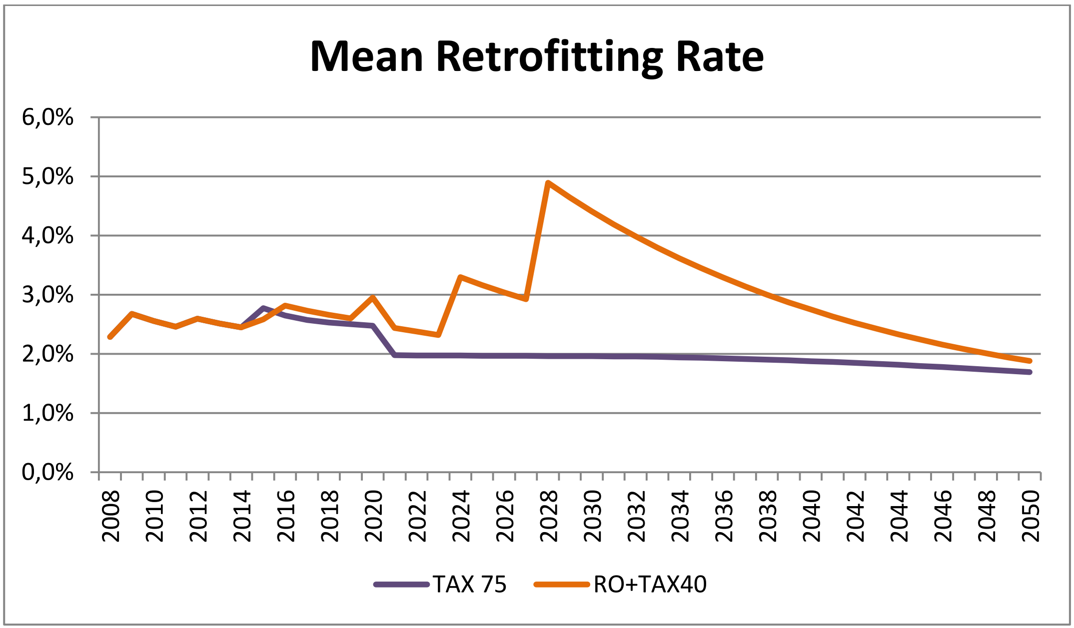


Figure 10. Mean retrofitting rate (in percentage of the existing housing stock) for the two scenarios.

The retrofitting rate is a partial measure of the energy efficiency level of the renovation as retrofitting options are heterogeneous in terms of energy efficiency. Figure 11 shows the average amount of conventional energy savings per m2 retrofitted, which we call the mean retrofitting amplitude. We see that this amplitude is on a decreasing trend for both scenarios. As mentioned before, in Res-IRF, the most economically efficient retrofitting investments are made first, so there is a natural exhaustion of the potential for profitable retrofitting actions.

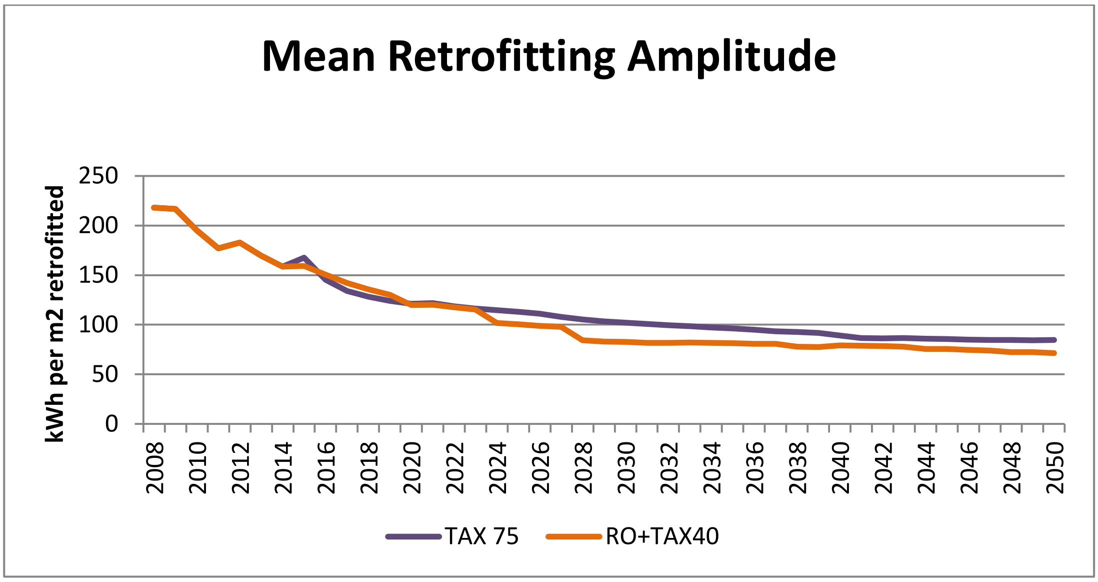


Figure 11. Evolution of the average amount of conventional energy savings achieved through retrofitting for both scenarios.

Figure 12 disentangles the retrofitting rates for three investor types: the occupying homeowners of individual dwellings OH_ID, the tenants of collective dwellings T_CD and the social housings SH[14]. RO impacts the dynamics of renovation only for the tenants of collective dwellings and the social housings. The first reason is that the RO legislation in the scenario is always one step behind the actual state of OH_ID dwellings. For example in 2020, there are almost no OH_ID dwellings below energy efficiency class F. The second reason is that the rate of change in building occupancy is much lower in OH_ID dwellings.

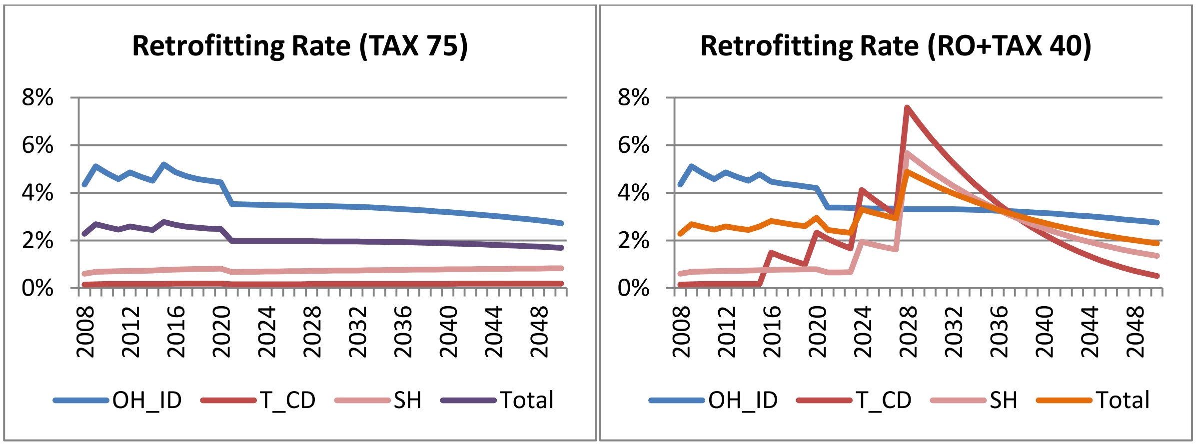


Figure 12. Evolution of the average retrofitting rates for each investor type in both scenarios.

[14] Results as regards the occupying homeowners of collective dwellings OH_ID and the tenants of individual dwellings T_ID are not presented as they are intermediate situations.

6.5 Costs

Figure 13 shows the agreggated amount of retrofitting expenses for both scenarios, distinguishing between the occupier homeowners (OH) and the others (tenants and social housing T+SH). Retrofitting expenses follow roughly the retrofitting rates curves. From 2008 to 2020, they oscillate around 8 billion euros per year. The overwhelming part of them are dedicated to occupying homeowners dwellings. The differences between the two scenarios arise in 2016, then they amplificate. The major difference is that a significant share of retrofitting expenses concerns social housings and rented dwellings in the scenario RO+TAX40. Even though, this share is not so important compared to share of retrofittings in these dwellings categories. This is because T+SH face lower retrofitting costs than OH. Indeed, retrofitting in these type of dwellings are generally of low ambition in terms of energy efficiency (the final energy efficiency class is usually C, the minimum level of compliance with the retrofitting obligation) whereas occupying owner dwellings keep being retrofitted to high energy-efficiency standards and retrofitting costs increase with the level of energy performance. Besides, they concern more collective dwellings than individual dwellings, which are smaller (110 m2 for the individual dwellings, 75 m2 for the collectives ones), and retrofitting costs are expressed in €/m2, leading to smaller retrofitting expenses (see Table 1 in section 3.2.).

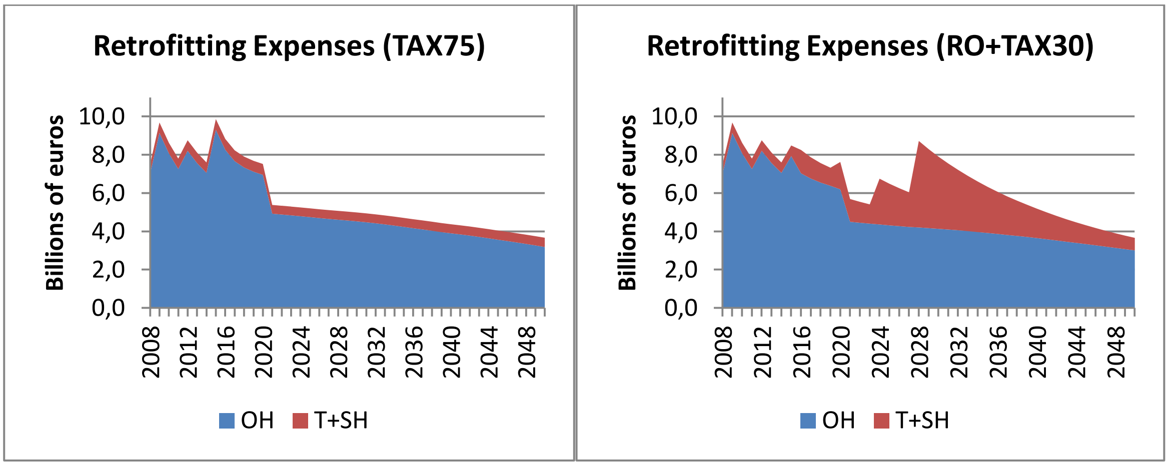


Figure 13. Retrofitting expenses (before tax credit subsidization), separated by housings occupied by the owners, and the rest (social housings and housings occupied by tenants)

Figure 14 shows Res-IRF outputs on the cost of the tax credit scheme. It oscillates around 2 billion euros per year. These costs are in line with the reported costs (CGDD 2012b) (around 2.7 billion euros in 2009, 1.9 in 2010, 1.3 in 2011).

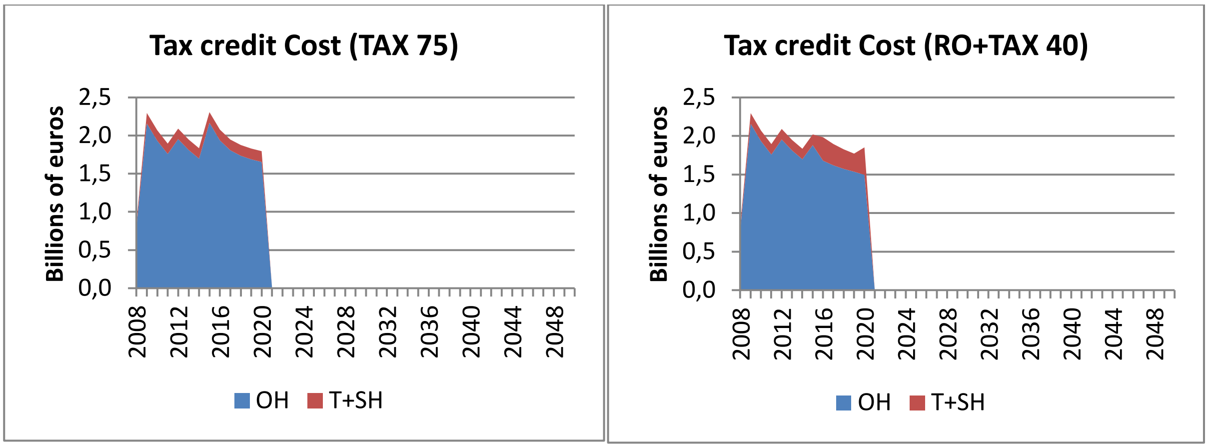


Figure 14. Public expenses dedicated to the tax credit

As shown in Figure 15, the carbon tax revenues are increasing in both scenarios, from 2.9 billion euros in 2015 to 5.4 billion euros in 2050 for the TAX 75 scenario, and from 1.6 billion euros in 2008 to 3.0 billion euros in 2050 in the RO+TAX 40 scenario. The decrease in the tax base is thus more than compensated by the increase in the tax rate. The gap between the two scenarios mainly comes from the fact that the tax is roughly twice bigger in the TAX 75 scenario.

In 2050, carbon tax revenues from tenants represent 51% in the TAX 75 scenario and 45% in the OR+TAX 40 scenario, whereas they represent only 38% of the housing stock in surface. This is due to the fact tenants stay in relatively less energy-efficient buildings. Therefore, the carbon tax adds to the burden of their energy expenditures more heavily than for the occupier homeowners (for the same level of comfort). The distributive effect depends on the way the carbon tax revenues are then reallocated to households. If revenues are rebated as a lump-sum to households, as in the proposal accepted by the French Parliament in 2009, the carbon tax clearly bears an anti-redistributive effect, all the more in the TAX 75 scenario. Avoiding this effect would require targeting the rebates on relatively poor households.

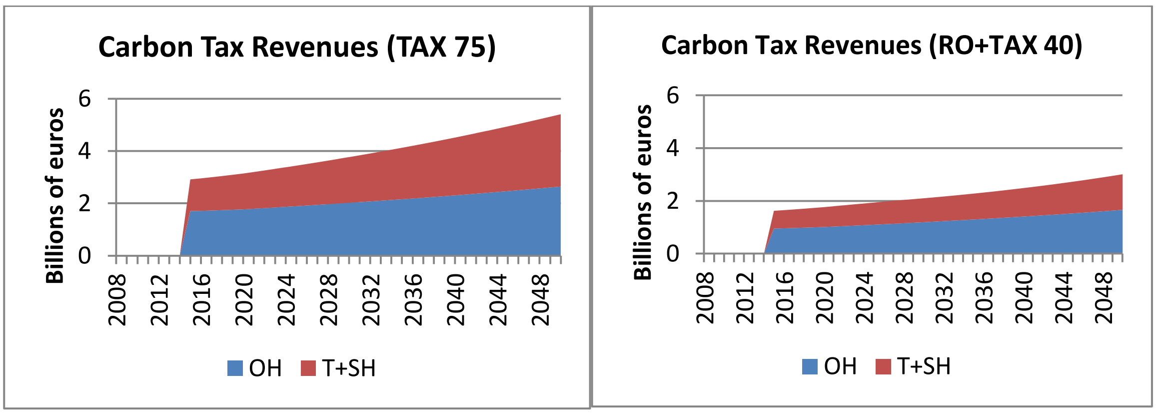
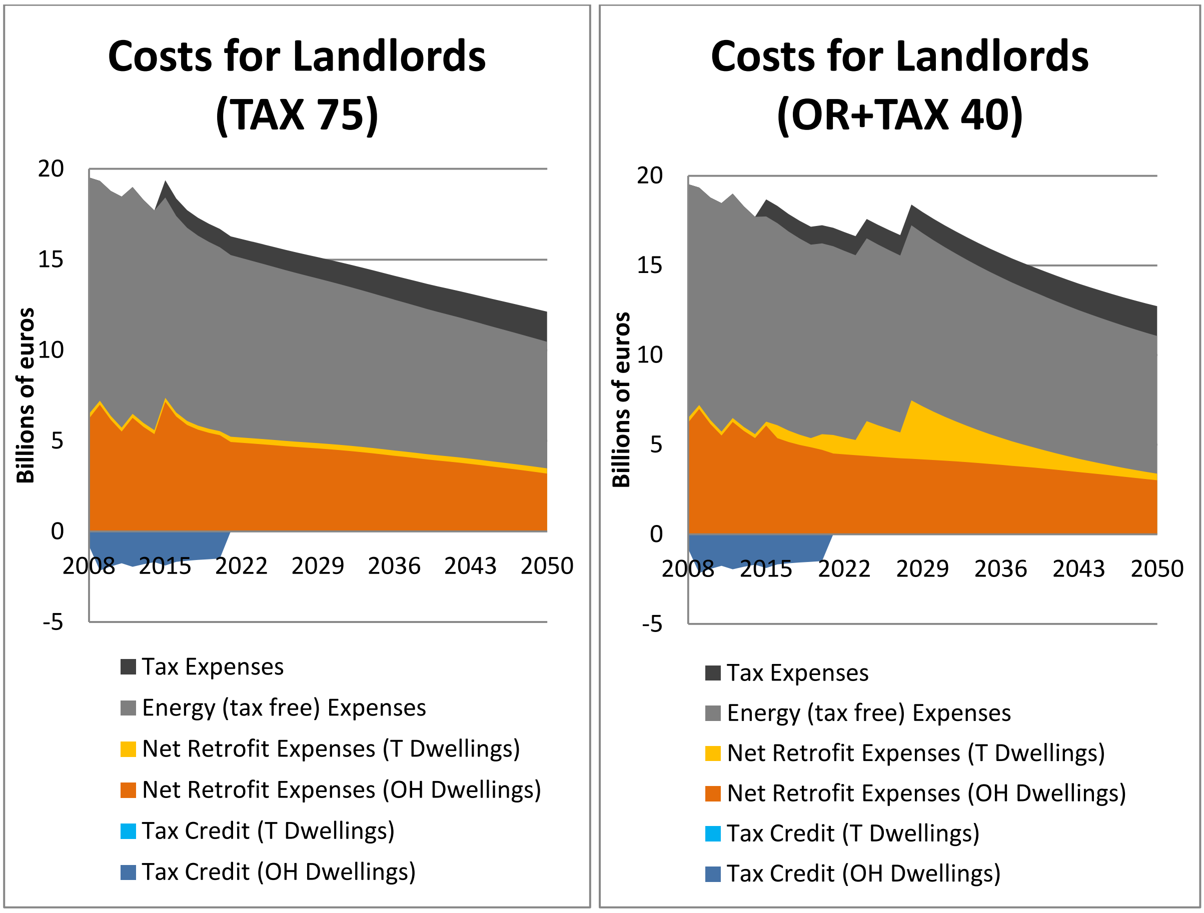


Figure 15. Evolutions of the carbon tax revenues.

Finally, Figure 16 clarifies the distributive effects of the two policies. For both scenarios, the costs are piled up separately for homeowners and tenants (we make the reasonable assumption that landlords carry the retrofitting costs in tenants' dwellings). As regards owners, the difference between the two scenarios mainly concerns landlords. In the RO+TAX40 scenario, they bear additional costs compared with the TAX 75 scenario due to the RO for the tenants' dwellings. Conversely, tenants save money due to a better energy efficiency of their dwellings, which lowers their tax-included energy bill, and a lower tax in the RO+TAX40 scenario. In addition to the financial improvements, they have an increased well-being because of a better energy service (higher temperature or factor service).

In both scenarios, energy expenses generally decrease thanks to energy efficiency improvements despite the increase in both the tax-free energy prices and the carbon tax, except for the tenants in the TAX 75 scenario. Indeed, between 2008 and 2050, the tax-included energy bills respectively decrease by 42.2%, 39.1% and 21% for landlords in the TAX75 scenario, landlords in the OR+TAX40 scenario and tenants in the OR+TAX40 scenario whereas they only decrease by 2.8% for tenants in the TAX75 scenario. We can also see that the burden of the carbon tax in the total, tax included, energy bill is larger for tenants than for owners, especially in the TAX 75 scenario.



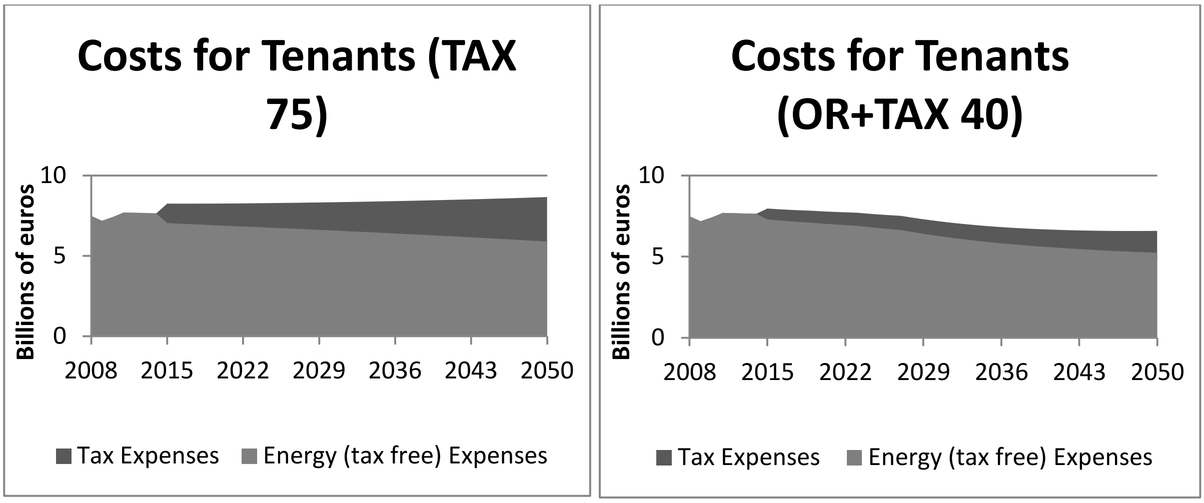


Figure 16. Evolutions of costs for landlords and tenants in the existing housing stock.

7 Conclusion.

Although the building sector is recognized as having major potential for energy conservation, specific barriers studied in the literature of the “energy efficiency gap” prevent many households from investing to retrofit their dwelling, which provides a justification for a public policy. This study assesses the efficiency of two types of public policy in this framework: the “economic instruments” on the one hand, aiming at triggering households’ investment through pure price signal, and “regulation” on the other hand. Res-IRF, a hybrid energy-economy model forecasting the evolution of the energy performance of the French building stock and its energy consumption over 2009/2050, is used for this purpose. This model strives to represent the main barriers to energy efficiency specific to the residential sector distinguishing first between the occupying homeowners, the landlords and the social housing, second between the individual and collective dwellings (section 3). It has also been calibrated on statistics and econometric results on past data over 2008/2011 (section 4). The analysis was conducted through the simulation of two stylized scenarios: a “TAX 75” scenario, which only implements an economic instrument, identified by a strong carbon tax, versus a “OR+TAX40” scenario, in which an obligation of renovation is introduced representing the regulative tool, in addition with a smaller carbon tax in order to make both scenarios converge towards the same level of energy consumption at the long run (section 5).

The results show that this convergence in terms of energy consumption reduction is obtained through different drivers. The “OR+TAX40” scenario improves the energy performance of the building stock through retrofitting more than the “TAX 75” scenario, especially for categories of investors facing stronger barriers. Indeed, the “price signal” instrument embodied by the carbon tax is inefficient to trigger investments in case of split dilemma between tenants and landlords and secondarily in case of collective decision process. Therefore, energy consumption reduction in the “TAX 75” scenario is obtained through a less intensive utilization of the heating systems, which reduces the rebound effect but also increases fuel poverty in certain categories, the tenants in collective dwellings in particular. Moreover, results in terms of cost burden differentiated by households' type, especially the one due to carbon tax, show that the "TAX 75" scenario can bear more anti-redistributive effects, except if tax revenues are reallocated in a progressive way. Finally, in the "TAX 75" scenario, the tax starts at 75€ per ton of CO_2 emitted in 2015 and goes up to 296€/ton in 2050. In this scenario, the carbon tax level could worsen fuel poverty and would be politically difficult to implement. This suggests the necessity to implement a retrofitting obligation to get a chance to reach ambitious reduction targets.

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9 Annex

Annex A. EM survey statistics

Table 6. Statistics on households' variables.

	Full sample over 2008/2011		Retrofitting sample*	
	N	%	N	%
Status of occupation				
renter	12321	32.0	62	6.2
owner	24959	64.8	914	90.9
other	1237	3.2	29	2.9
Annual income of the dwelling				
<18500€	12097	32.4	213	21.9
18500 /36 300€	16662	44.6	475	48.8
>36 300€	8586	23.0	286	29.4
Head of household's age				
<34 years old	851	2.6	8	1.0
35-54 years old	14156	43.4	382	47.9
> 55 years old	17607	54.0	408	51.2
Move in date				
< 3 years	6717	17.7	266	26.6
3 / 10 years	12361	32.5	289	29.0
> 10 years	18920	49.8	443	44.4

* Sample of dwellings having been retrofitted

Table 7. Statistics on dwellings' variables.

	Full sample over 2008/2011		Retrofitting sample*	
	N	%	N	%
Building type				
individual house	21646	56.1	859	85.3
collective flat	16862	43.7	147	14.6
other	49	0.1	1	0.1
Building completion date				
<=1948	9966	25.9	406	40.3
1949/1974	11997	31.1	308	30.7
1975/1981	5064	13.1	125	12.5
1982/1988	3354	8.7	71	7.1
1989/last year	7796	20.2	84	8.4
current year	372	1.0	11	1.1
Climatic zone				
1	22491	58.3	572	56.8
2	11797	30.6	352	35.0
3	4271	11.1	83	8.2
Category of city				
Parisian agglo.	5741	14.9	68	6.7
>100.000 inhab	11165	29.0	228	22.7
20.000/100.000	5134	13.3	115	11.5
2.000/20.000	6832	17.7	182	18.1
Rurals	9686	25.1	413	41.0

* Sample of dwellings having been retrofitted

Table 8. Statistics on global retrofitting measures.

Retrofitting market shares in percentage per year and retrofitting type (total sample size : 1294 observations)	2008	2009	2010	2011	Total in rows
Opaque surface insulation with costs > 4000euros	2.2%	4.0%	3.5%	2.9%	12.5%
2 retrofitting measures	14.3%	20.1%	20.0%	17.7%	72.1%
3 retrofitting measures	2.5%	4.4%	3.7%	2.8%	13.3%
4 retrofitting measures	0.2%	0.7%	0.7%	0.5%	2.0%
Total in columns	19.1%	29.2%	27.9%	23.9%	100.0%

* retrofitting measures are : opaque and/or glazed surfaces insulation, ventilation, installation or replacement of heating system using fossils, electricity or renewable energy and heating regulation systems.

Table 9. Market shares of unitary retrofitting measures (in percentage among all the retrofitting unitary measures).

Retrofitting unitary measures *	Market shares			
	2008	2009	2010	2011
Indoor wall insulation	32.5	25.1	30.0	24.5
Outdoor wall insulation	4.4	9.5	9.6	8.8
Roof insulation	37.6	35.5	34.5	30.8
Window insulation	50.4	48.5	46.5	42.8
Ventilation	4.4	5.4	5.4	3.2
Boiler (first installation)	3.3	4.2	3.4	2.6
Boiler (replacement with fuel switch)	7.2	5.2	3.1	6.0
Boiler (replacement without fuel switch)	14.6	20.6	19.8	13.2
Radiator	13.1	11.1	12.8	21.6
Closed fireplace	3.8	7.5	8.2	7.0
Wood stove / Wood pellet	2.2	3.9	3.9	3.2
Solar heating	2.1	2.7	3.0	2.2
Heat pumps	6.2	5.3	3.3	5.7
Heating regulation systems (programming)	1.6	4.3	3.2	1.1
Heating regulation systems (thermostatic valves)	7.0	5.0	5.9	2.6
Heating regulation systems (other)	7.2	5.7	3.3	2.8

* This list is non-exhaustive but includes the main retrofitting types. The total in column is not 100% since a retrofitting observation can be a combination of 1/4 retrofitting unitary measures.

Table 10. Mean costs of unitary retrofitting measures.

Retrofitting unitary measures	Mean cost in euros 2009			
	2008	2009	2010	2011
Indoor wall insulation	2017	2548	2361	1878
Outdoor wall insulation	6575	6366	8366	7663
Roof insulation	3192	4346	3507	5953
Window insulation	3932	4204	4454	4933
Ventilation	75	1182	829	294
Boiler (first installation)	3284	10861	3264	7305
Boiler (replacement with fuel switch)	4075	6172	3585	9100
Boiler (replacement without fuel switch)	3636	4472	3795	4286
Radiator	1023	2408	2274	1620
Closed fireplace	3879	4166	3600	4160
Wood stove / Wood pellet	1882	4690	3265	4683
Solar heating	7868	6355	10908	5023
Heat pumps	11605	12432	13273	9646
Heating regulation systems (programming)	212	266	184	205
Heating regulation systems (thermostatic valves)	380	588	407	77
Heating regulation systems (other)	273	502	332	170

Annex B. Energy prices and carbon tax forecasts in both scenarios.

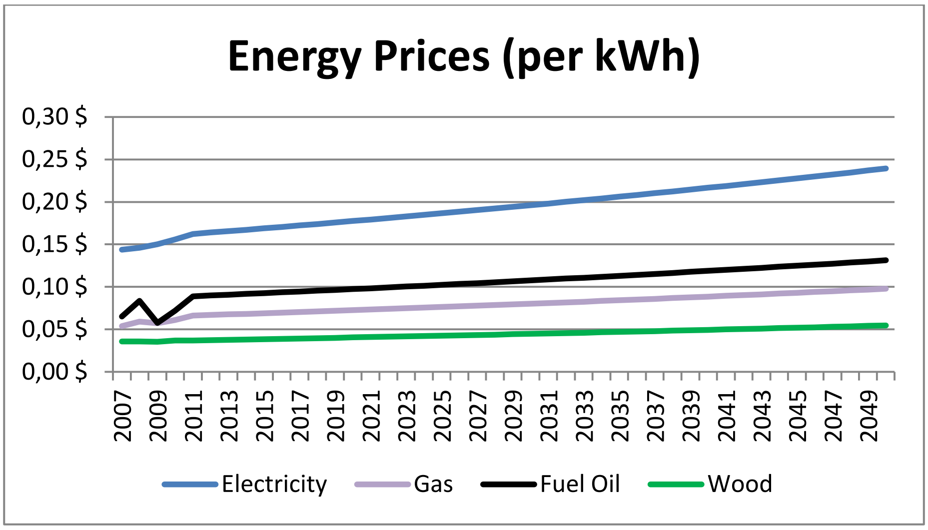

Figure 17. Energy prices (without carbon tax)

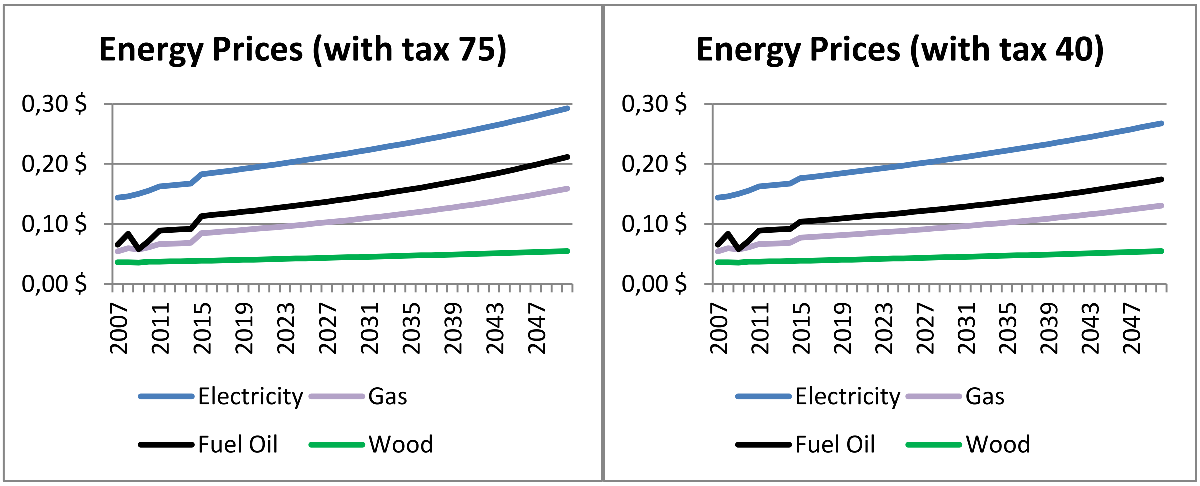

Figure 18. Energy prices (with carbon tax)