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ENERGY EFFICIENCY IN FRENCH HOMES: HOW MUCH DOES IT COST ?

Edouard CIVEL[1,2,3,*] and Jérémy ELBEZE[2]

A strong cut in heat consumption can be realized by the thermal renovation of buildings: this article gives an assessment of energy savings achievable in the French residential stock and their associated investment costs. A bottom-up approach, using a dataset on material and labor costs for renovations and a thermal model (including a representation of the "rebound effect") is applied to a description of existing dwellings in France. Renovation investment costs increase with the efficiency target of the housing stock: two inflection points are identified, for 40% and 60% reduction targets. If the first inflection is driven by a quantity effect, the second one is pushed by a price effect. Specificities of the thermal renovation market imply a lock-in risk: at the micro-scale, the discount rate could induce households to realize low ambition renovations, whereas at the macro-scale, having successive short-term objectives triggers important over-costs, above 15% of the optimized investment costs. We suggest that policy-makers take the risk of low ambition renovations into account, as it may nip the potential of energy savings in the bud. Relevant policies would set today the long-term efficiency target and earmark public incentives, like tax credits or interest-free loans, to ambitious renovations.

JEL classification: Q47, Q48

Chaire Economie du Climat
Palais Brongniart, 4ième étage
28 place de la bourse
75002 PARIS

1. EconomiX, Université Paris-Ouest Nanterre La Défense, 200 avenue de la République, 92001 Nanterre, France

2. Climate Economics Chair, Palais Brongniart 28 Place de la Bourse, 75002 Paris, France.

3. Saint-Gobain Recherche, 39 quai Lucien Lefranc, 93303 Aubervilliers, France

* Corresponding author: edouard.civel@chaireeconomieduclimat.org

1 Introduction

Improving energy efficiency is a major challenge in addressing the energy transition objectives in the European Union and specifically in France. Today's energy policies need to achieve a triple objective: decarbonizing energy production, ensuring supply security and maintaining the competitiveness of energy prices. Renewable energies and energy efficiency are the main tools to pursue these goals, but if renewable energies can offer low-carbon energy, these technologies are not yet scalable, profitable and predictable enough. Hence the need to enhance the efficiency of our energetic systems (DePerthuis and Jouvet (2013)): by reducing the final energy need, energy prices could be better controlled, industry competitiveness could be upgraded, reliance on exterior energy producers could be reduced, and greenhouse gas emissions could be mitigated (Chevalier et al. (2013)).

Across the European Union, 26% of final energy consumption is dedicated to residential buildings (EC (2014)). This part is slightly higher for France, at 28%. After transportation, the residential building sector is the largest consumer of final energy. Such an important consumption raises concerns: firstly about supply security, as the EU imports more than 50% of its energy. Secondly for global warming: the European Commission has set several ambitious targets in order to cut European greenhouse gas emissions by 40% compared to 1990 levels for 2030, and by 80-95% for 2050. These CO2 goals are associated with energy efficiency targets (27% increase for 2030 compared to 1990, and 32-41% for 2050 compared to the 2006 peak (Roadmap (2011))). In order to meet these ambitious goals, the European Commission and the French government have introduced various public policies, which efficiencies are discussed (Charlier and Risch (2012)).

The building sector is a very large energy efficiency field, residential buildings in particular. In Europe, about 70% of domestic energy is used for space heating, and this need could be dramatically reduced. Three kinds of actions can be envisioned to improve houses and buildings' efficiency, all along the energy value chain. First of all primary energy consumption and greenhouse gases emissions can be reduced by switching energy sources, from electricity to biomass for instance. Secondly, final energy consumption can be reduced for the same energy need by replacing a boiler by a more efficient one. Thirdly, energy losses and heating needs can be curbed by renovating the thermal envelope of buildings. If the first two types of actions reduce energy consumption by improving the source and the transformation of energy, only the thermal renovation of buildings' envelopes really target a reduction of the end-use energy needs (Jochem et al. (2000)). Indeed, old houses and buildings undergo important heat losses simply through the envelope, and therefore need stronger heating. A wide range of technologies exist for insulating the envelope components (walls, windows, roofs and floors) allowing a strong cut in energy needs. The use of top-technological solutions can eventually turn buildings into almost zero-energy ones (Li et al. (2013)). The present work only focuses on envelope renovation, to increase end-use efficiency.

Some studies have been carried out to estimate the costs of a deep renovation to turn a building stock into low consumption buildings. The Ecofys report "Renovation tracks for Europe up to 2050" (Boermans et al. (2012)) indicates the amount of investments needed from now up to 2050 to reach a deep renovation of the whole European Union stock. According to that report, for a deep renovation scenario, about 160 Billions €/year should be invested from 2015 to 2050 to enhance buildings envelopes in the EU. However this study considers only two building archetypes for houses, and does not give flexibility to the renovations. Likewise, a study from Lechtenböhmer and Schüring (2011), while giving flexibility to renovation options, still lacks a detailed description of the building stock.

Other studies have applied a technical-economic optimization to specific buildings in order to estimate which measures apply and when in order to minimize costs over time. Ferrara et al. (2013) study a specific French house in their article. Terés-Zubiaga et al. (2015) optimized the renovation of collective dwellings in Spain. But these case studies carried out to calculate an optimal level of energy efficiency for a very specific building do not produce appropriate information for policy-makers, who are setting targets for a national building stock. Several works like Tommerup and Svendsen (2006) have demonstrated the numerous economic advantages of pursuing a renovation of the building stock in the long term, but a good assessment of the initial investment costs is necessary and needs to be processed at the country scale as the European building stocks can vary greatly from a country to another (Kohler and Hassler (2002)).

Bottom-up estimations of the building stocks and of their end-use energy consumption have been performed for several European countries (Swan and Ugursal (2009), Mata et al. (2014)), and more specifically on the French building stock by Ribas Portella (2012). But none of the previous studies coupled that description with the possibility of enhancing the envelope.

The research work presented in this article aims at understanding how the investments needed for the thermal renovation of buildings' envelope evolve, firstly at a single building scale, and then at a country scale. In order to answer this question, the paper develops a bottom-up methodology: a dataset on technologies is used with a description of the French residential stock to envision the various renovations possible. A thermal model is also estimated to link the performance of the envelope with the energy consumption for space heating. Those points are described in section **2**. The first optimization algorithm, on single buildings, highlights the merit-order of technologies and the key-role of windows and exterior insulation in the growth of renovation costs. The second optimization algorithm, on the whole building stock, isolates two inflection points in the progression of the stock renovation costs. The first one, occurring for an efficiency target of 40%, can be interpreted as a volume effect ; the second one, occurring for a 60% reduction, is interpreted as a price effect. Section **3** develops the results of these optimization algorithms. In section **4**, results are discussed in terms of public policies, as it appears that some lock-ins in the renovation processes could lead to major over-costs if renovations are not smartly planned in time.

2 Methodology

Our description of the French residential sector is based on several studies : we chose 24 home types, varying by their architecture and their construction period. In this paper, single-family dwellings are classified as "houses" and multi-family dwellings are classified as "buildings". This classification is described in section **2.1**. The characterization of house and building archetypes enables us to assess an efficiency indicator of the thermal envelope in each case: the mean U-value U_G, the envelope's overall heat transfer coefficient. This indicator is calculated as the average of each envelope component's U-value weighted by its relative importance in the envelope surface. The envelope is constituted of four components : walls, windows, roof and floor. The U-value (heat transfer coefficient, expressed in $[W.m^{-2}.K^{-1}]$) of a component represents the quantity of heat which crosses one square meter of this material when it is submitted to a temperature difference of one kelvin on each side of it. When insulating a component, its U-value decreases.

Then, the main energy efficiency technologies which can be used to reduce energy losses in buildings are presented. These data provide the U-values and costs of these technologies (including labor and material costs). This data set is described in section **2.2**.

For each building type, this data set is used by the module 1 (see figure 1) to minimize investment costs for increasing targets of mean U-value (section **2.3**). Module 1 is an algorithm screening every possible technology combination for an initial given dwelling and selecting the one displaying a U_G that respects the constraint at a minimal investment cost.

Thanks to these successive optimizations, a "one-shot optimization curve" is computed for each building type. For each efficiency target, htis curve gives the minimized investment cost and its corresponding technological choices. As these costs are calculated for a house in its initial thermal state, it implies that the investment cost to switch to a higher renovation level is not represented ; it may be discordant from the difference between their two investment costs. We do not represent the possibility for a house to undergo several renovations over time: it is a "one-shot renovation".

In order to link the thermal performance of a house or a building with its energy need and the household effective consumption, we build a simplified thermal model, as discussed in section **2.4**.

Once the U-values are linked with building energy losses, all single-shot curves are combined and minimized in order to build the global renovation curve for the park. Through this method, explained in section **2.5**, we obtain the optimal choice of renovations to achieve each efficiency target of the park.

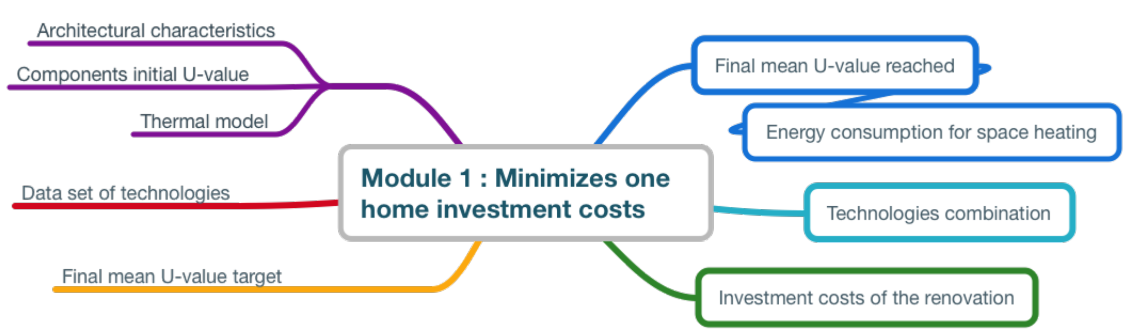

Figure 1 : *First algorithm : inputs and outputs*

2.1 Description of the French residential building stock

A description of the French residential building stock is elaborated using a set of French reports: RAGE (2012), CDC (2007), ADEME (2013), CGDD (2014). The successive public norms on the thermal efficiency of new constructions since 1974 are also used (MEDDE (2012), MEDDE (2009), ADEME (2013)). Buildings' statistics in France and their evolution until 2014 are found in the studies made by the French National Institute for Statistic and Economic Studies (Insee (2015)).

2.1.1 Houses

For single-family houses, a "typical" architectural French house was defined using Insee (2015) statistics. The characteristics of this typical house are described in table 1.

Area	$112m^2$
Number of floors (including ground floor)	2
Height per floor	$2.5m$
Percentage of external walls covered by glass	30%

Table 1 : *Typical French House*

The surface of each envelope component is estimated using this architecture. These areas will be used to two ends in the model. Firstly to estimate the house mean-U-value, designated by U_G in this work (average of each component U-value weighted by the percentage of the envelope's area it represents). Secondly these areas are necessary to calculate the renovation costs.

If all French houses correspond to these architectural characteristics in the model, they are still differentiated according to their construction period. Using the various norms since 1974 (first thermal norm in France), six construction periods are distinguished for houses in France : these construction periods differ by the use of different technologies for walls, windows, roofs and floors, and therefore imply a variable initial performance of the envelope.

Hence the first optimization algorithm (see Figure 1) can be applied on six models of houses. Table 2 gives the typical U-values of these houses' walls, windows, roofs and floors. As thermal norms have become more demanding, the U-values of components have become smaller : the smaller the U-value is, the less heat transfer will occur through the material, and the less energy the house will need for heating.

Construction date	<1974	74-81	82-89	90-2000	2001-2005	2006-2014
Uwalls	2.5	1	0.8	0.5	0.47	0.36
Uwindows	4	3	3	3	2.3	2.1
Uroof	2.5	0.5	0.32	0.26	0.25	0.2
Ufloor	1.2	1.2	0.74	0.5	0.36	0.27

Table 2 : *U-values of envelope's components, according to the house construction date*

2.1.2 Buildings

Given the diversity of collective dwellings, multi-family houses are not gathered under one standard architecture. Eighteen building models are represented, with different numbers of floors, different ceiling heights, different percentages of external walls covered by glass, and different component characteristics.

Nevertheless, to simplify, it is assumed that each building floor (including the ground floor) consists of two apartments, and that all apartments have the same area ($63m^2$, the average area for collective dwellings in France, Insee (2015)).

Table 3 gives the characteristics of the eighteen buildings represented.

Construction	Building category	Number of floors	Height / floor	Walls covered by glass	Uwalls	Uwindows	Ufloor	Uroof
Before 48	Old town Building	4	2,9	25%	2,5	4	1,2	2,5
	Haussmann Building	7	3	30%	2,5	4	1,2	2,5
	Eclectic Building	6	3,2	33%	2,5	4	1,2	2,5
	Old Social Housing Building	7	2,8	28%	2,5	4	1,2	2,5
48-74	Pastiche Building	4	2,6	25%	2,5	4	1,2	0,5
	Bourgeois Building	5	2,8	43%	2,5	4	1,2	2,5
	Medium Town Buildings 68-74	5	2,6	33%	2,5	4	1,2	2,5
	Small Collective Buildings 48-74	5	2,65	25%	2,5	4	1,2	0,5
	Large Collective Buildings 48-74	10	2,5	33%	2,5	3	1,2	2,5
	Towers 48-74	21	2,5	50%	2,5	3	1,2	2,5
75-81	Medium Town Buildings 75-81	5	2,6	35%	0,43	3	1	0,51
	Small Collective Buildings	5	2,5	32%	0,43	3	1	0,51
	Large Collective Buildings 75-81	11	2,5	33%	0,43	3	1	0,71
	Towers 75-81	11	2,5	50%	0,43	3	1	0,71
After 81	Buildings 82-89	7	2,6	30%	0,42	2	0,74	0,4
	Buildings 90-2000	7	2,6	30%	0,33	2	0,5	0,17
	Buildings 2001-2005	7	2,6	30%	0,33	2	0,25	0,17
	Buildings 2006-2013	7	2,6	30%	0,33	2	0,25	0,17

Table 3 : *Architecture and component U-values of French building stock*

Altogether, twenty four types of houses and buildings are used to represent the whole French residential sector. Module 1 is applied on those buildings, giving for each of them the optimal choice of technologies corresponding to a precise target.

2.2 Data set on material and labor costs in renovation

To evaluate costs for dwelling thermal renovation, we benefited from the support of the CSTB and we used Bâtiprix (2015), a French data base on prices in construction, including both material and labor costs, with a set of academic articles and official reports dealing with the costs of renovation (Lechtenböhmer and Schüring (2011), Ferrara et al. (2013)). All available options and associated costs are presented in appendix A for houses and in appendix B for buildings. Costs are given with a VAT of 5.5%, which is the VAT applicable in France for thermal renovations.

- For walls, the main technologies available are interior thermal insulation (ITI), using various thicknesses of glass wool, and exterior thermal insulation (ETI), using various thicknesses of rock wool or expanded polystyrene with coating. Interior insulation is less expensive[1], but also less efficient. The best solution for wall insulation is a combination of interior and exterior

[1]Interior insulation has hidden costs : firstly the house/the building cannot be inhabited during the period of renovation, and secondly the loss of inhabitable surface lowers the value of the dwelling (an important point in the areas where land prices are high, for instance in city centers). These types of costs are not taken into account ; presented costs only include material and labor costs.

insulation. The program gives the possibility of not acting on the walls (*statu quo*) : the price is then zero and the U-value is not modified.

- For windows, four options are available, including the *statu quo*: double-glazed windows, double-glazed windows with argon, and triple-glazed windows. Prices are significantly higher for these technologies.
- For the floor, the technology is an insulation with different thicknesses of rock wool, typically used on the underside of floor slabs.
- For the roof, house attics are considered as non-inhabitable[2]. The technologies available for these houses are rolls of mineral wool (with various thicknesses) and blown granulated rock wool. For buildings, the reference technology used is polyurethane for roof terrace, with various thicknesses.

2.3 One-shot optimization for single buildings

The technological options and the architecture of homes presented above are used here to realize one-shot house and building renovations. In the model, the initial inputs are the buildings' architectural characteristics and the U-values of their components. The model gives the initial mean U-value ($=U_G^i$). This mean U-value can be considered as a reliable indicator of the thermal efficiency of a building. The lower the mean U-value of the building, the less heat it looses and the less energy it needs. For instance old houses built before 1974 and not retrofitted have a mean U-value of about $2.5W/(K.m^2)$ and have a final energy consumption for space heating over $200kWh/(m^2.an)$, whereas recent houses, built after the French 2012 thermal norms were introduced (*RT 2012*), have a mean U-value around $0.6W/(K.m^2)$ and consume less than $80kWh/(m^2.an)$ for space heating (these final energy consumptions are the ones estimated by the prediction thermal model).

Other inputs of the module are the previously detailed data on available technologies and their corresponding costs for each component. The last input added to the module is the target mean U-value we fix : U_G^t. It acts as a constraint: the final mean U-value reached after renovation ($=U_G^f$) will be equal to or lower than U_G^t.

A thermal model is also included in the module : it is then possible to fix not a constraint in terms of performance for the envelope (U_G^t), but a target in terms of final energy consumption ($Cons_{feh}$).

When the program is launched, its objective is to minimize the total investment costs. The solution gives the mean U-value that was reached (and the corresponding final energy need if a thermal model is included), total investment cost, the details of this cost per component, and which technologies are chosen for each part of the building envelope.

This optimization is performed for each building type, and repeated for a gradient of target mean U-values, starting from the initial U-value, when all the *statu quo* solutions are chosen by the program, up to the best U-value that can be reached, when the program chooses the top solution for each component insulation.

Then, for each building, we construct the curve of the minimized investment costs to reach a U_G^f. The curves are presented in section **3.1**.

[2]In the case of an inhabitable attic, data costs are also available: the technology would be mineral wool between herringbone. Its costs are between two and three times higher than costs for non-inhabitable attic technologies. Nevertheless, this increase in price, if it modifies the overall investment costs of the renovation, does not change the merit order between insulation of the roof and the other components of the envelope.

2.4 Thermal model

On the basis of a simple thermal model inspired by the 3CL-DPE method, a French official method to estimate building energy consumption for space heating (MEDDE (2012), MEDDE (2009)) and using the PhD thesis realized by Allibe (2012), we link the performance of the envelope (represented by the mean U-value = U_G) to the final energy consumption for space heating: $Cons_{feh}$ expressed in $[kWh/(m^2.an)]$. We use one simple model for theoretical consumption $Cons_{feh}^{theo}$ and a second one integrating behaviors for a better predicted consumption $Cons_{feh}^{pred}$. Both follow equation (1).

$$Cons_{feh}(U_G) = \frac{U_G * A_{envelope} * D_{h.ref} * I}{Boil_{eff} * L_s * 10^3} \tag{1}$$

Where:

- U_G = mean U-value of the building $[W/(K.m^2)]$. It is calculated by algorithm 1 on the basis of the architecture and materials of each building.
- $A_{envelope}$ = total area of the building envelope $[m^2]$. It is calculated by the program thanks to information on building's architecture.
- $D_{h.ref}$ = number of degrees - hour needed to heat up the space during a year (depending on the climate) $[K.h]$. The 3CL-DPE method provides $D_{h.ref}$ for all French metropolitan departments ; these numbers are estimated to reach a temperature of 18^{o}C with the heating system, considering that other contributions (lighting, biological heat) will be enough to reach the setpoint temperature of 19^{o}C. In the model we use the average value for French metropolitan departments weighted by their population. The $D_{h.ref}$ used is then 53756.81 $K.h$.
- L_s = Living space $[m^2]$. In order to estimate the need per m^2, the total living space area in the house/building needs to be provided.
- $Boil_{eff}$ = Boiler efficiency. It depends on the particular heating system of the building. The efficiency of a regular boiler is usually between 0.85 and 0.95 ; for this paper we will assume that this efficiency is equal to 0.9 for all buildings.
- I = factor of intermittence ; a house is not continuously occupied during the year : especially during days when people work outside, heating systems can be turned off. The factor of intermittence is between 0 and 1.
  - → The theoretical consumption model $Cons_{feh}^{theo}$ uses the reference values of intermittence : $I_0 = 0.85$ for houses and $I_0 = 1$ for buildings, as it is considered that common heating is widespread in collective dwellings and that central boilers are not turned off during the heating period.
  - → The predicted consumption model $Cons_{feh}^{pred}$ integrates the behavior of households by allowing the variation of intermittence. On the one hand, when U_G is high, the intermittence is lower: households adopt strategies to reduce their consumption (decrease temperature setpoint in bedrooms, or turn off heating when outside). But on the other hand, when U_G is small, the intermittence will be close to 1: a better insulated dwelling

allows to choose a higher temperature setpoint higher[3]. The expression of this $I = f(U_G)$ is inspired by Allibe (2012) :

$$I(U_G) = \frac{I_0}{1 + 0.1 * (\frac{U_G}{U_{G_0}} * \frac{H_{c0}}{H_c} - 1)} \tag{2}$$

Where :

* H_c = Ceiling height per floor $[m]$, and $H_{c_0} = 2\ m$.
* $U_{G_0} = 1\ W/(K.m^2)$

This thermal model is used to estimate the theoretical and predicted consumption of a typical house and building. These consumption rates are compared to average real consumption rates (RAGE (2012)) by processing linear regressions on the obtained points to estimate the relation (theoretical, predicted and empirical) between U_G and $Cons_{feh}$. Figure 2 compares the theoretical, the predicted and the empirical regressions for houses. It appears that the prediction model gives a fair estimation of real consumption rates.

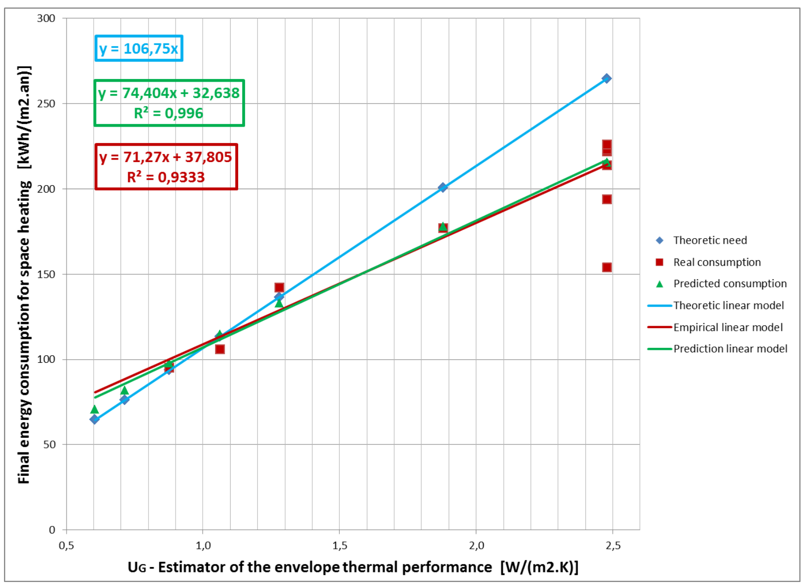

Figure 2 : *House linear models of heat consumption*

For both houses and buildings, real consumptions show a strong relationship with U_G. The choice of a linear regression is justified. Theoretical consumptions are globally consistent with real ones, but a difference subsists between theoretical models and the ones based on real consumptions. In the case of both houses and buildings, the theoretical model overestimates consumption for high values of U_G, and underestimates consumption for small values of U_G. This results in a gentler slope for real consumptions model. The predicted model is much more similar to the empirical model ; modeling household behaviors by a variation of the intermittence with the performance of the

[3]It is the "rebound effect": a gain in energy efficiency implies a lower cost for the same energy service and then demand for that service may increase.

envelope seems legitimate. In the present paper we use the prediction linear model to link energy consumption and envelope performance. Equations (3) and (4) present the relations obtained for houses and buildings.

$$Houses^4 : Cons_{feh}^{pred}(U_G) = 74 * U_G + 33 \tag{3}$$

$$Buildings : Cons_{feh}^{pred}(U_G) = 68 * U_G + 4 \tag{4}$$

At the national scale, the predicted models estimate the final energy consumption of the sector for space heating at $33.0 Mtoe$. According to official figures given by the CEREN (2015), residential energy consumption in 2013 for space heating was $29.1 Mtoe$. The real energy consumption is then 12% inferior to the calculated one[5]. This gap is similar to the ones found in the literature until now for space heating in France (22% for Mata et al. (2014), 18% for Ribas Portella (2012)).

2.5 Global optimization for the whole building stock

Using the optimized curves obtained for each type of building in section 2.3 and the number of dwellings each building type represents in the French building stock (see Annex C), we build a second optimization algorithm. By stages of 5%, the module 2 (see figure 3) minimizes the investment costs on the whole French building stock in order to reach a target energy consumption reduction for space heating, called an "efficiency target" in this working paper. This second algorithm screens every possible combination of optimal renovations calculated by module 1 while weighting each dwelling by the number it represents in the French housing stock ; for each efficiency target, it selects the combination with the lowest total investment cost.

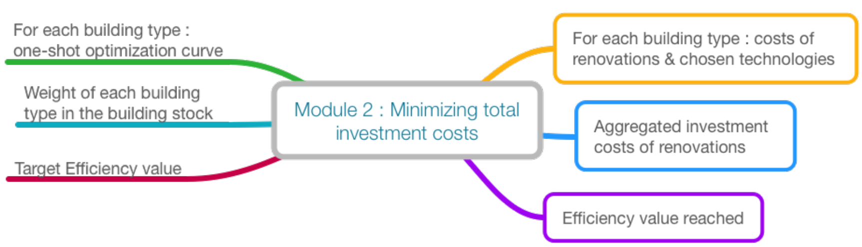

Figure 3 : *Second module inputs and outputs*

[4]The constant term given by the regression is consistent with our thermal model: we do not envisage the possibility for houses to change their ventilation systems, therefore the module cannot reduce the losses induced by ventilation. In a first approximation, it is estimated that 15 to 20% of the energy consumption of old houses for space heating is due to ventilation losses, namely between 30 and 40 $kWh/(m^2.an)$, which is the number given by the regression.

[5]Two factors explain this over-estimation : firstly we do not take into account already refurbished buildings ; secondly, in the last thirty years, the average area of houses has strongly increased, from $96m^2$ in 1984 to $112m^2$ in 2014 (see Insee (2015)). But this evolution is not represented in our model, resulting in an overestimation of the total area of old houses, which consume more, and an underestimation of the total area of recent houses, which consume less. A differentiation of house areas allows for quick ciphering of the overestimation : if we give houses a more realistic living area in regard to their construction period, the gap with official figures is lowered by 30%.

3 Results

3.1 One-shot optimization - Algorithm 1

3.1.1 Houses

For each type of house, the optimization program (module 1) is run in order to see how renovation investment costs evolve with an increasing efficiency target.

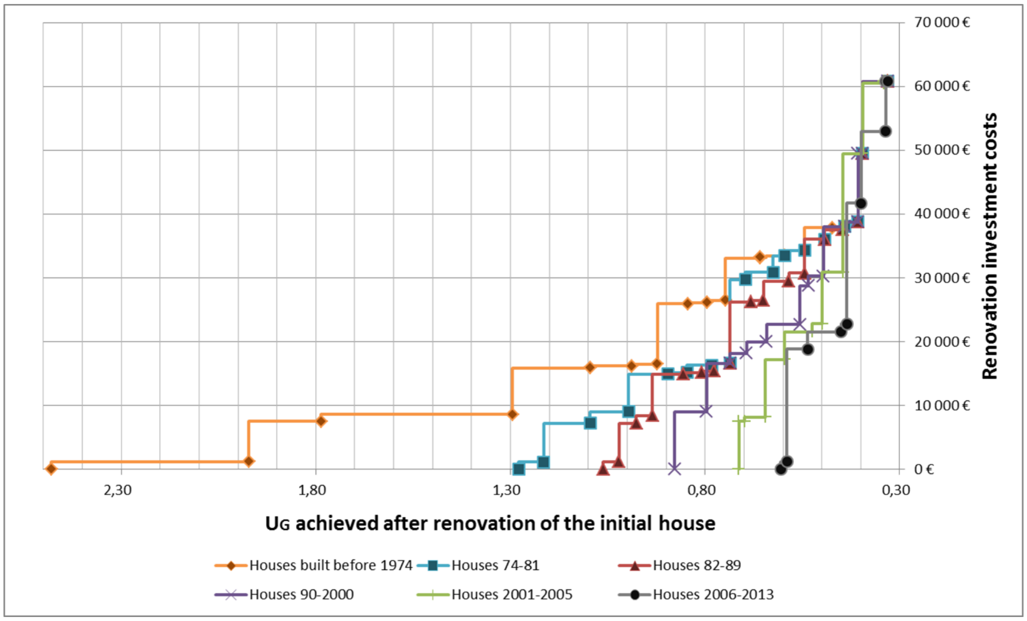

Figure 4 *: Investment costs to enhance typical house envelopes*

Each point on figure 4 indicates the investment necessary to reach an efficiency target (U_G^f) for a house built in the period of the curve and never refurbished before. Module 1 gives the minimized investment cost and its corresponding technological choices for each efficiency target. The investment cost to switch from a given renovation level to a higher one is not represented and may be discordant from the difference between their two one-shot investment costs.

For low investment costs, it is possible to substantially improve old houses efficiency. More recent houses have a lower initial U_G, and have steeper optimization curves : to improve recent houses, it is necessary to use immediately expensive technologies. In the end, to achieve the best insulated theoretical house ($U_G \simeq 0.33$), top technologies for each component are needed and the investment costs of all houses reach the maximum : the last three points of improvement are common to almost all houses, needing investments from 40 to 60k€.

As the module also gives the chosen technologies for each point, we can deduce the merit order for house technologies. The merit order varies with the construction period. Table 4 gives the results for the 6 different houses : it is the order of choice of components to insulate. We differentiate between interior (Int.) and exterior (Ext.) insulation as these technologies have significantly different investment costs and imply unusual constraints. The energy equipments (boilers, etc.) are not represented ; the paper focuses on envelope improvements.

Date	<1974	74-81	82-89	90-2000	2001-05	2006-14
1st	Roof	Roof	Roof	Roof	Floor	Roof
2nd	Int.Walls	Floor	Floor	Floor	Int.Walls	Windows
3rd	Floor	Int.Walls	Int.Walls	Int.Walls	Roof	Ext.Walls
4th	Windows	Windows	Windows	Windows	Windows	Floor
5th	Ext.Walls	Ext.Walls	Ext.Walls	Ext.Walls	Ext.Walls	X

Table 4 : *Merit order of component for improving energy efficiency*

For almost all houses, the first component to insulate is the roof. Indeed, the roof is responsible for approximatively 30% of heat losses in old houses. Second and third components chosen are floor and internal wall insulation (ITI) for houses built prior to 2005. For the same houses, the fourth choice is the replacement of windows, and finally the exterior insulation of walls, a very efficient technology but also very expensive. The merit order for houses built since 2006 is different, as these houses have been constructed under strict thermal norms. Their improvement then needs expensive solutions : windows as second choice, external wall insulation (ITE) as third choice.

These one-shot renovation curves reveal a special evolution of investment costs in thermal efficiency ; they are not linear, or exponential, but follow a trend with steps that are more or less marked. Indeed, for each component, there is a range of technologies with various but close U-values and gradually rising prices. But their insulating power is limited to that range of U-values. When for a given component the best insulation technology is chosen, further investments will target another component. Often, this point triggers an important new investment to bridge a gap and reach a new band of U-values. Each of these steps corresponds to the addition of another choice in the merit order table.

In figure 4 we can identify several steps : for houses built before 1974, there is a first step for $U_G \sim 1.9$ which corresponds to internal wall insulation. The second identified step is for $U_G \sim 1.2$, with floor insulation. The third step is for $U_G \sim 0.9$ and the replacement of windows. The last step occurs at $U_G \sim 0.4$ with the use of external wall insulation.

We can find steps for all types of houses, but the addition of a new choice in the merit order does not systematically generate steps. Nevertheless, for all houses, the replacement of windows and external wall insulation create steps, as these options are particularly expensive. On the one hand, the step for window replacement occurs at $U_G \sim 0.7$ for 74-81 and 82-89 houses, at $U_G \sim 0.75$ for 90-2000 houses, and at $U_G \sim 0.55$ for 2000-05 and 2006-14 houses. On the other hand external wall insulation creates a common last step to go under $U_G \sim 0.4$.

If the choice of internal wall insulation was excluded (for economic reasons, or other ones), it is important to note that external wall insulation would take its place in the merit order : walls are a key-component to curb energy losses.

3.1.2 Buildings

For each building type, the optimization program (module 1) is run in order to see how renovation investment costs evolve with increasing efficiency targets. Full graphs of renovation investment costs for buildings can be found in Annex D. These optimization curves show less explicit steps (except for windows): the curves do not have the stairway aspect of house optimization curves. This is due to the architecture of buildings in which the areas of windows and walls are much more important than the ones of the roof and floors.

3.2 Optimization on housing stock - Algorithm 2

This section presents the optimization of the complete residential stock, using the second algorithm. While one-shot curves show explicit technological steps for houses, but much less explicit steps for buildings, the global optimization curve presents a piecewise linear progression with two inflections.

All curves computed in the previous section are used in an optimization program targeting the whole residential stock. To realize a targeted reduction in final energy need for space heating, each type of houses and buildings is weighted with its volume in the French stock, and the global investment cost is minimized. Figure 5 presents the result of these successive optimizations.

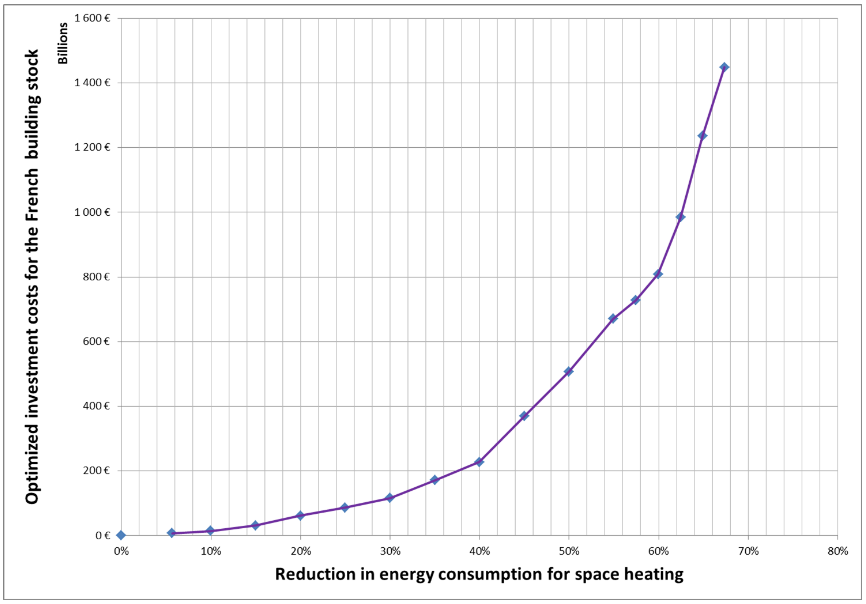

Figure 5 : *Global investment costs on French residential stock to reach an efficiency target*

Cost increase is exponential : reaching an efficiency target of 30% costs about 100B€, a 50% reduction 500B€, and a 67% reduction over 1400B€.

A piecewise linear approximation seems to provide a good fit of the observed curve. The two inflection points identified are $\sim$ 40% and $\sim$ 60%. The slope before and after the first inflection point is multiplied by five, and again by three before and after the second inflection point ($\sim$ 75%). These inflections raise the question of how relevant it is for policy-makers to go beyond them. What is the optimal level of energy efficiency public policies should target ?

In order to understand which are the factors driving these inflections, the evolution of the number of refurbished houses and buildings and the evolution of the average investment costs of the realized renovations are studied in figure 6.

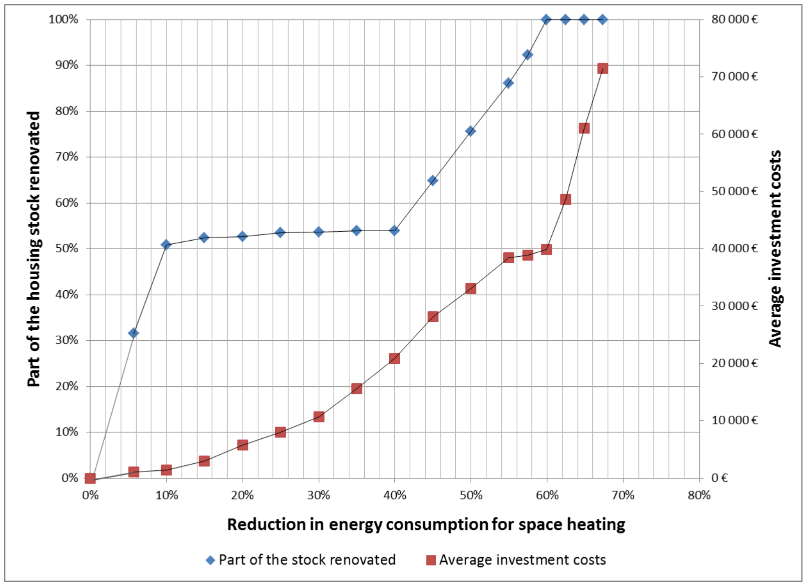

Figure 6 : *Comparison number of renovations / average investments*

The number of renovations (lozenges on figure 6) increases strongly over two periods: the first one occurs from 0% to 10% reduction in energy needs, where the progressive integration of all dwellings (houses and buildings) built before 1974 drives the increase. Up to a target of 40%, the optimization module recommends retrofitting this old residential stock only, which represents about 53% of French dwellings. Secondly, from 40% to 60% targets, more recent houses and buildings need to be included gradually and the number of renovations grows. From the 60% goal and beyond, it is necessary to renovate the whole stock.

Average investment costs per renovation (squares on figure 6) mainly present two inflections in the growth: there is a first trend up to 30%, where the slope becomes a little steeper. Beyond the 60% reduction target, the slope becomes much steeper. The last three points correspond to renovations targeting all the envelope's components and using top-technologies (external wall insulation, low-emission double-glazing or triple-glazing, maximum roof and floor insulation thickness).

These curves explain the inflections of the global investments curve. The first inflection at 40% is driven by a *"quantity effect"* : beyond 40% reaching efficiency targets at a minimal investment cost necessitates to renovate more recent houses/buildings. However, the second inflection at 60% is driven by a *"price effect"*. As actions are undertaken on the entire residential stock at that point, the only way to curb the energy need is to realize deeper renovations, which are very expensive : renovation costs per house exceed 50 000€, and average renovation costs per building may exceed 250 000€.

Figure 7 illustrates the successive steps in the global investment curve. The first linear regression (up to a 40% reduction in energy need) represents *shallow renovations* of the French residential stock : actions only concern internal wall insulation, roof and sometimes floor. They exclusively target houses and buildings constructed before 1974, and do not constitute global renovations of these dwellings.

From a 40% to a 60% reduction in energy need, the second linear regression represents *medium renovations* of the French residential stock. Actions targeting all of the envelope's components and more recent dwellings are realized, but external wall insulation and highly efficient windows are not yet chosen.

Finally, to curb energy needs by more than 60%, the third linear regression represents *deep renovations* of the dwelling stock. The entire French residential stock needs to be retrofitted and the whole structure of dwellings is targeted by these refurbishments. Deep renovations allow to achieve the most efficient envelope, but are also much more expensive than the previously detailed renovations.

The dotted curve draws the optimal investment curve without a behavioral factor. The difference between the two curves corresponds to a "rebound effect". We see that the "rebound effect" is very important at the national scale : the maximum reduction in energy need is 82%, whereas it is only 67% in energy consumption.

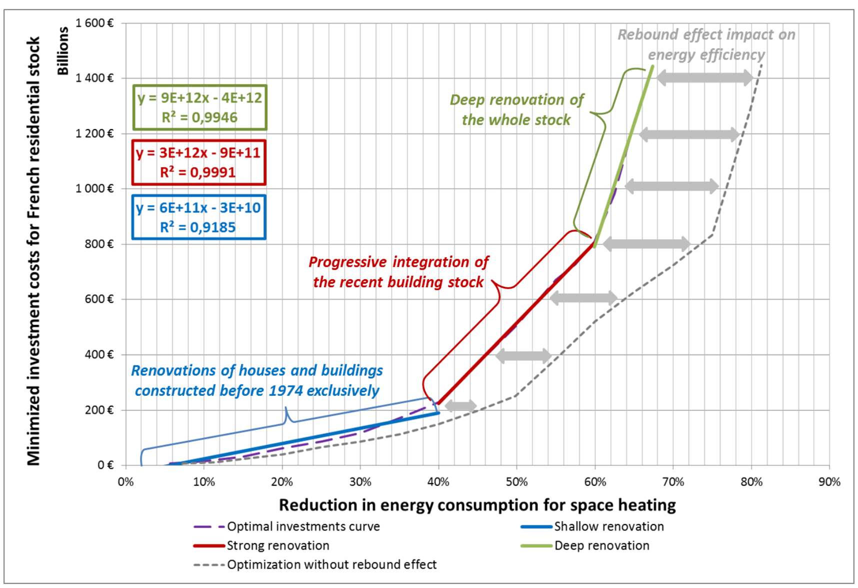

Figure 7 : *Investment costs on French residential stock : the linearity by pieces explained*

3.3 Comparing house and building costs per square meter

In order to contrast the investments in single-family houses and in collective dwellings, we compare the prices per square meter. The matrices (Tables 5 and 6) represent the renovation investment costs per square meter necessary for a typical house/building in order to reduce the energy consumption for space heating. Houses correspond to the archetypes outlined in section **2.1.1** ; for buildings, the following characteristics were chosen :

- Ground floor + Six floors ;
- Two flats per floor (including ground floor) ;
- 30% of glass surface on the external walls ;
- 2.6m of height per floor ;

We still take into account the construction period of the buildings (before 1948, 1948-1974, 1974-1981, 1982-1989, 1990-2000, 2001-2014) as this provides information on the initial U-values of the different envelope components. For these typical houses and buildings, we use the average $D.h.ref$ value on French metropolitan departments in the thermal model.

	Predicted consumption of final energy for space heating [kWh/(m2.an)]											
Costs/m2	220	180	165	130	115	100	90	80	70	60	55	% ID
ID < 74	0 €	10 €	67 €	77 €	143 €	147 €	236 €	297 €	338 €	442 €	543 €	55%
ID 74-81				0 €	64 €	133 €	145 €	275 €	322 €	442 €	543 €	11%
ID 82-89					0 €	75 €	137 €	236 €	322 €	442 €	543 €	10%
ID 90-2000						0 €	81 €	178 €	271 €	442 €	543 €	10%
ID 2000-05							0 €	73 €	204 €	442 €	540 €	6%
ID 2006-13								0 €	168 €	372 €	473 €	8%

Table 5 : Matrix for houses - Individual Dwellings (ID)

	Predicted consumption of final energy for space heating [kWh/(m2.an)]											
Costs/m2	180	160	120	100	90	80	70	60	50	40	35	% CD
CD < 45	0 €	38 €	47 €	66 €	81 €	166 €	168 €	186 €	191 €	216 €	301 €	23%
CD < 74	0 €	38 €	47 €	66 €	81 €	153 €	167 €	185 €	192 €	216 €	301 €	36%
CD 74-81						0 €	71 €	123 €	148 €	204 €	301 €	11%
CD 82-89								0 €	87 €	202 €	301 €	7%
CD 90-2000								0 €	71 €	133 €	291 €	10%
CD 2001-13									0 €	133 €	281 €	13%

Table 6 : Matrix for buildings - Collective Dwellings (CD)

In both cases, renovations of old houses/buildings are more expensive at the beginning ; but to reach the best performance, recent houses/ buildings prices increase strongly and are close to old dwelling prices. Prices per m^2 to reduce energy needs at their lowest levels are significantly higher for houses than for buildings. This is due to a "compactness" effect : the volume increases faster with the size of the dwelling than its envelope area. As a building has a greater living space than a house, it has a smaller envelope surface to insulate per square meter. Moreover, the lowest consumption a house can reach ($55kWh/(m^2.an)$) is higher than for a flat ($35kWh/(m^2.an)$).

These costs per square meter are consistent with the literature on renovation costs in France (Sidler (2012), Branger (2011)).

4 Discussion

4.1 The lock-in risk and additional costs at the household scale

Houses and buildings renovation can target a wide range of thermal performance: refurbishment costs increase as targets get more ambitious, and imply different technological choices (sections **3.1.1** and **3.2.1**). But once a building is retrofitted to achieve a certain level of performance, several barriers, both behavioral and financial, make it unlikely for a second refurbishment to take place in an extended period of time.

From a financial point of view, sequencing the renovation measures introduces several additional costs. Firstly, mobilizing various companies several times in a row induces more costs than a "one-shot" type of action (for instance, site-installation costs): these costs will be called "indirect additional costs". Secondly, in a systemic approach of the building, achieving a better target most of the time implies a different choice of technologies. This different choice involves replacing some components: the initial investment in the first renovation components is then partially lost. This loss is called "direct additional costs". The results of the modules only allow to assess these direct additional costs, which constitute a price floor of additional costs brought by a succession of renovations. But this is a static analysis: once introduced a discount rate on the future investments, we estimate that households have an incentive to sequence the refurbishment of their dwelling over 10 or 15 years. For any discount rate chosen above 6%, our results show that households would save money by postponing a heavy renovation and realizing only a low ambition renovation.

The case of a house built prior to 1974 is studied. Its initial energy consumption for space heating is about $220kWh/(m^2.an)$. We set a first target for this house to cut its consumption by half, thus coming to $110kWh/(m^2.an)$. The necessary investments amount to 16000€. This first renovation, here called a "low-level renovation", selects an interior insulation for walls with 4cm of glass wool, an attic insulation with a mineral wool roll of 30cm, and a floor insulation with 10cm of rock wool slab underside. Windows are not changed to achieve this target. If a second target is set at $70kWh/(m^2.an)$, the house will need to have its windows replaced. As they were not replaced during the first renovation, there will be no direct additional costs due to windows. However, achieving the top-level target also implies to install a thicker wall insulation: from 4cm the house switches to 10cm of glass wool. The combination of these two renovations costs 46000€; but if it had been realized on the initial unrefurbished house, it would have cost 38000€[6]. These over-cost assessments do not include indirect additional costs and therefore constitute a price floor of additional costs brought on by a succession of renovations. We introduce then a time-horizon and a discount rate for the household. In this case study, the annual heating bill for the house is estimated at 2200€. We apply a discount rate of 10% [7] to the investments and the energy bills over various scenarios, changing household's time horizon (from 10 to 30 years) and timing of renovations: one-step renovation, two steps renovation with a second step occurring at year 5, 10 or 15. In all cases, the dynamic approach favors a two-steps renovation over a one-step renovation.

[6] The direct additional cost of setting these successive steps represents an over-investment of 20% compared to the top-level renovation realized in one step. In the case where windows would have already been changed during the first renovation, this over-investment could reach 65% compared to the top-level renovation in one step.

[7] The private discount rates considered in the literature on energy efficiency usually ranged between 10% and 30% (Train (1985), Charlier (2012)). We chose 10%, a higher discount rate would only strengthen our results by lowering both future investments in energy efficiency and future benefits of energy savings.

This dynamic approach shows that time preference fosters a low-ambition renovation for households which have decided to realize one. However, from a behavioral point of view, a refurbishment implies a significant investment in terms of money but also of time (to contact and select craftsmen and materials), and poses several constraints for households: for instance, households may have to find another place to live while the house is being retrofitted. Refurbishments thus represent a temporary but important loss of welfare, often not perfectly anticipated, which make households less likely to engage in another renovation for the same dwelling (Sidler (2012)). Therefore, low or medium-level renovations could kill a part of the energy efficiency potential by this "lock-in" effect.

4.2 Over-costs at the macro-scale

In the previous section, realizing a renovation was considered as a household decision for its own utility; nevertheless, energy efficiency of the residential stock is also a major challenge for the State (as specified in the introduction of this paper). At the national scale, public policies with ambitious long-term objectives are often designed on a gradual basis, with increasing targets over time. However, in our sector, we can question the relevance of such a logic, as we underlined in the previous section that small renovations could lock-in the renovation process. In this section we compare the relevance of setting an evolutive target over time versus setting today the long-term target in order to achieve the same final efficiency of the residential stock.

We use the algorithms developed in this paper to compare two different renovation paths for France from the social planner's point of view. For both scenarios, the long-term energy efficiency target of the residential stock is 60%, and the period of investments considered is thirty years. In the scenario 1, the social planner sets at the beginning of the thirty years period the long-term target and invest each year the same amount in order to achieve the renovations. In the scenario 2, the social planner sets at the beginning of each decade a new target to achieve - respectively a 30%, 45% and 60% reduction in energy consumption compared to year 0 for the first, the second and the third decade. Inside each decade of the second scenario, the yearly investment of the social planner is constant.

Achieving a 30% reduction requires the realization of internal wall insulation for old buildings and houses, with 4 to 6 cm of glass wool. Moreover, the roofs of the same dwellings need to be insulated (20cm of mineral wool for houses, 6cm of polyurethane for roof terraces). These actions represent a 116 Billion €investment in the French stock. However, if the national target then becomes 45%, renovations will have to be performed on other building types, and old building will need to have their internal wall insulation changed and double-glazed windows installed. Part of the first investment, corresponding to the first wall insulation, will be lost. This second renovation implies an investment of 329 Billion €. Cumulated investments of the two renovation waves are significantly higher than the one-wave investment necessary to achieve a 45% reduction. Likewise, if the efficiency target for the residential sector is then reassessed at 60%, a new wave of renovations will again trigger direct additional costs, mainly due to the replacement of double-glazed windows by low-emission windows or triple-glazing. This third investment represents about 608 Billion €, but if added to the previous investments, the static total investment realized to reach a 60% target rises to 1 053 Billion €. Compared to the direct renovation necessary to reach that same efficiency goal, the sequencing in three renovation waves engenders 245 Billion €of direct additional costs. This price floor of over-costs already represents 30% of the optimal renovation costs needed to achieve the 60% reduction in energy consumption in a static approach.

Table 7 presents global investments and yearly investments necessary in both scenario, as well as the number of yearly renovations it implies, to achieve the energy consumption reduction targets in the residential sector. Investments are discounted in order to take into account time preference.

	Yearly investments		**Yearly renovations (houses & buildings)**	
	Scenario 1	***Scenario 2***	***Scenario 1***	***Scenario 2***
First decade	27 B€	12 B€	675 172	1 088 000
Second decade	27 B€	33 B€	675 172	1 303 271
Third decade	27 B€	61 B€	675 172	2 025 515
Sum discounted at the rate of 3,5%	495 B€	574 B€	20 255 147	44 167 856

Table 7 *: Comparison of the two renovation paths from the social planner point of view*

This application demonstrates how the additional costs at the dwelling scale could generate important over-costs at the macro-scale: the second scenario, which favors short-term objectives, is 16% more expensive than the first scenario, which favors a long-term objective, for a discount rate fixed at 3.5%. This discount rate is the one proposed by FranceStratégie (2013), which is the French institution in charge of the evaluation of public policies for the Prime Minister. It is consistent with the literature (Gollier (2002)) which advocates for a discount rate between 2% and 5% for public investments. In our study, the first scenario stays preferable to the second scenario until a discount rate of 7%, which ensures the reliability of the result.

Moreover, at the macro-scale, sequencing renovations creates another lock-in: the congestion of the construction industry. Indeed, realizing small renovations dramatically increases the global number of renovations to be undertaken before 2050. Such an activity in this sector seems very difficult to achieve, as current objectives of 500 000 dwellings renovated per year, are already far from being reached (CGDD (2015b)). The congestion of the construction industry is then another argument in favor of the first scenario : our algorithms allow to estimate the annual rate of renovations over the period. The scenario 1 implies about 675 000 building renovations per year during thirty years, a number which seems difficult to achieve but still more realistic than the scenario 2, which implies about 1 million renovations per year during the first decade, 1.3 million during the second decade and above 2 millions during the third decade.

4.3 What implications for public policies ?

Setting an evolutive target for energy efficiency in the building sector could trigger off important over-costs, or even nip the potential of energy savings in the bud. Public policies should set the long-term energy efficiency target for the residential sector today. The global optimization curve for the complete residential building stock can provide interesting information. As we can follow the trend of investment costs, the two inflection points raise the question of going beyond them.

As demonstrated in section **3.2**, the first inflection point of global investment cost is driven by the necessity of progressively including the whole building stock in the renovations. It is a quantity effect, therefore even with a strong cut in technology prices, this inflection will not soften strongly. Moreover, this first inflection occurs for energy efficiency targets around 40%: such a target may be considered as not ambitious enough regarding energy transition challenges.

The optimized cost curve then follows a quasi-linear trend until the 60% reduction in energy consumption, where the second inflection occurs. This second inflection is due to the strong increase in mean renovation costs. Indeed, to go beyond a 60% efficiency target, all houses need an internal and external wall insulation, and all buildings need an exterior insulation, even the ones that were built since 2005. The associated costs are very high and they explain the steeper slope. However, the relevance of achieving the theoretical maximum (67%) can be questioned as it is an investment of 640B€more than a 60% target. It almost doubles the investment costs needed for renovation whereas it only generates 7% of additional efficiency. Unless a breakthrough innovation completely softens that inflection, in the actual state of the art, the recommendation could be to target a 60% reduction in energy consumption in the long term. Indeed, most technologies used to achieve the 60% goal are mature. Moreover, the improvement of equipment performances (boilers, thermodynamic pumps, etc.), not employed in this paper, could bring on additional energy efficiency in this area.

Once this 60% target is set, the global optimization module for houses and buildings makes it possible to know what are the corresponding optimal renovations. As far as houses are concerned, the technological combinations chosen for houses built before 2000 are homogeneous. Indeed, top-level technologies are chosen for all components : maximum thickness for internal wall insulation, roof insulation and floor insulation, and the use of triple-glazing for windows (with efficient frames); however external wall insulation is not needed. For houses built after 2006, no action is needed on walls, but triple-glazed windows are necessary. As for buildings, technological choices are more or less homogeneous for buildings anterior to 1990 : thick internal wall insulation, top-level insulation for roofs and floors, and double-glazing with argon or triple-glazing for windows. For buildings built between 1990 and 2000, the recommendation is only to change windows, with the use of low-emission double-glazing. Finally, buildings posterior to 2000 do not need important renovations to achieve that target.

Achieving that 60% target implies the renovation of all houses, and of 87% of all collective dwellings. This means that 19 millions of houses, and 1 million of buildings (corresponding to 12.8 millions of collective dwellings) have to be renovated in the long term: this represents about 32 millions of dwellings, it means 95% of existing dwellings in France. By 2050, the construction sector will need to have ramped up in order to perform this very high number of renovations: about 1 million of dwellings, corresponding to 675 000 houses and buildings, need to be renovated each year to achieve this goal.

A relevant strategy could be to set the long-term energy efficiency target now, and to schedule public incentives, as the tax credit for energy transition in France, over time. The economic literature has underlined the need of public policies to trigger energy efficiency investments (Charlier and Risch (2012)). But instead of supporting all small renovations in the building stock at once, they should target each building type successively and only support bunch of works which bring the building to the targeted efficiency. This kind of policy was difficult by the past as a technology allowing a control of thermal efficiency did not exist ; however, today, this technology is developing quickly and could be useful to these public policies (European project PERFORMER (2015)). Starting by very old and badly insulated buildings, public incentives would progressively target more recent buildings. As policies would be focused on a few building types, they could offer a more substantial financial support for each dwelling, and with short-term objectives, could be more easily evaluated.

5 Conclusion

Our study investigates how refurbishment investment costs evolve in the French residential stock. The present work is focused on envelope improvements and reductions in energy consumption. In particular, one-shot optimization curves show the key-role of efficient windows and external wall insulation in the rise of envelope enhancement costs. They also highlight how a short-term uniform low-target renovation can impede the energy efficiency potential of a building, making it more expensive to reach a very efficient envelope in the long term.

The combination of these curves on the whole housing stock presents a double inflection as the efficiency target increases. The first inflection, at 40%, is driven by a quantity effect : reductions in energy needs necessitate a progressive renovation of all the building stock, whereas lower targets only involve the renovation of old buildings. For the second inflection, at 60%, cost increase is driven by a price effect : each building renovation is much more expensive, with the top technology for every envelope component. Achieving the 67% efficiency target on the national stock is almost twice as expensive as the 60% target.

The lock-in effect at the household scale is aggregated at the national one : sequencing the public targets in terms of reduction in energy consumption could lead to major over-costs in the renovation of the French building stock, if they are not smartly scheduled.

However, if the assessment of these investment costs makes it possible to know how to curb energy losses and then reduce the energy need and consumption in the French housing stock, a more complete approach of building efficiency would integrate the choice of boilers as well as heating costs in order to estimate the primary energy consumption. Further research could also include a deeper analysis of the dynamics of these investments.

Acknowledgments

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A Materials for Houses

	Technologies	U-value [W/m².K]	Prices : Labor and material costs, VAT included [€/m²]
Walls	*Statu Quo*	Unchanged	0 €
	ITI Glass wool 4cm	0,77	72 €
	ITI Glass wool 6cm	0,5	74 €
	ITI Glass wool 8cm	0,38	76 €
	ITI Glass wool 10cm	0,3	78 €
	ETI Exp. Polyst. with coating 14cm	0,27	180 €
	ETI Exp. Polyst. with coating 15cm	0,26	184 €
	ETI Rock wool with coating 16cm	0,23	200 €
	ETI(rock 20cm) + ITI(mineral 10cm)	0,11	288 €
Windows	*Statu Quo*	Unchanged	0 €
	4/16/4 double-glazing	2	380 €
	4/16/4 double-glazing argon	1,7	420 €
	4/16/4/16/4 triple-glazing	1,2	480 €
Roof	*Statu Quo*	Unchanged	0 €
	Mineral wool rolls 20cm	0,2	20 €
	Mineral wool rolls 30cm	0,13	22 €
	Blown rock wool 20.5cm	0,22	35 €
	Blown rock wool 29.5cm	0,15	54 €
	Mineral wool between herringbones 10cm	0,35	85 €
	Mineral wool between herringbones 12cm	0,29	87 €
	Mineral wool between herringbones 16cm	0,22	88 €
Floor	*Statu quo*	Unchanged	0 €
	Rock wool slab underside 10cm	0,34	129 €
	Rock wool slab underside 12cm	0,29	134 €
	Rock wool slab underside 14cm	0,25	139 €

B Materials for Buildings

	Technologies	U-value [W/m².K]	Prices : Labor and material costs, VAT included [€/m²]
Walls	*Statu Quo*	Unchanged	0 €
	ITI Glass wool 4cm	0,77	72 €
	ITI Glass wool 6cm	0,5	74 €
	ITI Glass wool 8cm	0,38	76 €
	ITI Glass wool 10cm	0,3	78 €
	ETI Exp. Polyst. with coating 14cm	0,27	180 €
	ETI Exp. Polyst. with coating 15cm	0,26	184 €
	ETI Glass wool clothing 14cm	0,25	196 €
	ETI Rock wool with coating 16cm	0,23	200 €
Windows	*Statu Quo*	Unchanged	0 €
	4/16/4 double-glazing	2	380 €
	4/16/4 double-glazing argon	1,7	420 €
	4/16/4/16/4 triple-glazing	1,2	480 €
Roof	*Statu Quo*	Unchanged	0 €
	Polyurethane for roof terrace 6cm	0,38	100 €
	Polyurethane for roof terrace 12cm	0,19	114 €
	Polyurethane for roof terrace 16cm	0,14	123 €
Floor	*Statu quo*	Unchanged	0 €
	Rock wool slab underside 6cm	0,63	119 €
	Rock wool slab underside 8cm	0,43	124 €
	Rock wool slab underside 10cm	0,34	129 €
	Rock wool slab underside 12cm	0,29	134 €
	Rock wool slab underside 14cm	0,25	139 €

C Volumes of the residential building stock

Table C.1 : *Number of individual dwellings*

Construction period	Number of dwellings	Percentage of the park
< 1948	6 546 000	34%
1948-1974	3 763 950	20%
1975-1981	2 127 450	11%
1982-1989	1 963 800	10%
1990-2000	1 963 800	10%
2001-2005	1 125 000	6%
2006-2013	1 549 000	8%
Total	**19 039 000**	**100%**
Empty	1 267 000	7%
Secondary houses	1 845 000	10%

Table C.2 : *Number of collective dwellings*

Construction period	Number of dwellings	Percentage of the park
< 1948	3 400 081	23%
1948-1973	5 362 294	36%
1974-1981	1 700 783	11%
1982-1989	1 045 722	7%
1990-2000	1 437 867	10%
2001-2013	1 907 254	13%
Total	**14 854 000**	100%
Empty	1 374 000	9%
Secondary houses	1 332 000	9%

D Building one-shot retrofittings

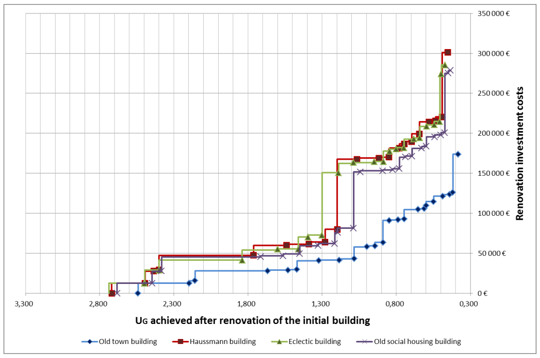

Figure D.1 : *Old building investment costs for one-shot retrofittings*

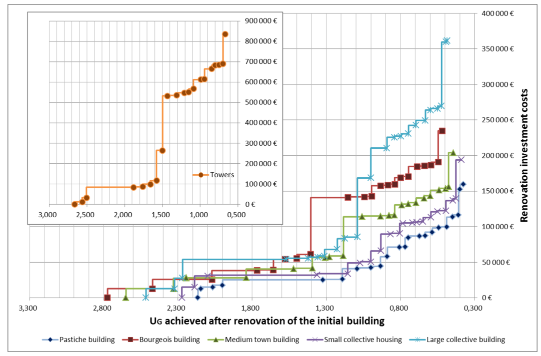

Figure D.2 : *1948-1974 building investment costs for one-shot retrofittings*

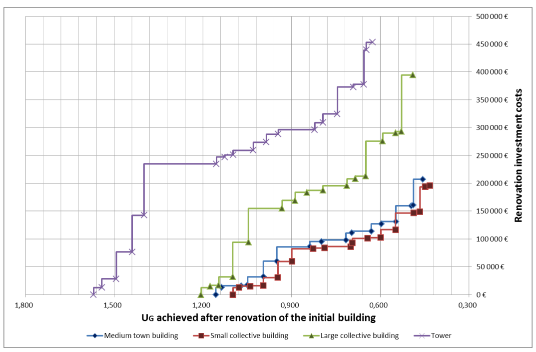

Figure D.3 : *1975-81 building investment costs for one-shot retrofittings*

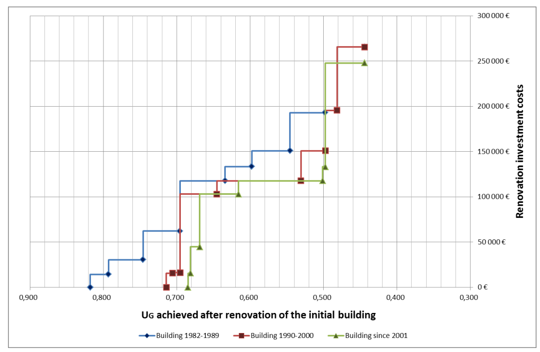

Figure D.4 : *One-shot retrofitting investment costs for buildings since 1982*

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Working Paper Publication Director: Philippe Delacote

contact@chaireeconomieduclimat.org