Energy efficiency and split incentives in the residential sector: the landlord tenant problem

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Split incentives are an important barrier to reducing energy consumption in the French housing sector. While landlords want to minimize the cost of purchasing energy-saving systems and see no return on this investment, tenants want to minimize their energy bills. We examine the choices made by homeowners and tenants between consuming and investing in energy efficiency renovations in an uncertain environment. We also test the impact of public policies on the amount a household chooses to invest. We find that at the equilibrium point, even with public policy, a tenant is unwilling to invest. The split incentives problem seems to be partially confirmed. The results show that when a tenant expects high energy costs and, he chooses to invest even in the absence of policy support. However, in such a context, public policies lead to a rebound effect in the tenant's energy demand.

Keywords: Energy Efficiency Investment; Landlord; Tenant; Public Policies; Split Incentives; Uncertainty.

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1 Introduction

While the residential sector consumes more energy than any other economic sector in France, it also has a high potential to save energy, particularly through renovations. Energy demand in the residential sector depends mainly on the use and efficiency of energy systems (see Hausman 1979). Public environmental policies seek to promote home renovations because these are expected to increase efficiency and consequently reduce energy consumption. However, few households actually invest in energy efficient systems (Banfi et al. 2008). This "energy paradox" or "energy-efficiency gap" has been described by several authors (Jaffe and Stavins 1994; Brown 2001; Fisher 1989; Sutherland 1991; Blumstein 1980).

Split incentives are an important obstacle to reducing energy consumption in the residential sector. They arise when participants in an economic exchange do not share the same goal. A standard example is the `landlord-tenant problem' (IEA, 2007). When the owner and the occupier of a housing unit are different people, a split in incentives occurs. While the landlord wants to minimize the purchase cost of energy systems (heating and hot water), and has no return on this investment, the tenant wants to minimize his energy bill. In this case, neither participant want to invest in an energy efficient system.

In France, the split incentives problem concerns many dwellings. In 2008, 42.2% of principal residences were occupied by tenants (11.6 million). People living in rented homes often were younger and had lower incomes than those who lived in homes that they owned. They also tended to be single. Tenants used a higher proportion of their income on energy consumption than owner-occupiers. Lastly, 92% of energy-saving renovation work was done in housing units occupied by their owners (Sofres, 2009).

The landlord-tenant problem has been discussed in the literature. Some theoretical papers, such as Arnott, Davidson, and Pines (1983), examine landlord decisions to invest in quality improvement through renovation. In 2003, Simmons-Mosley used the Stackelberg model to explain decisions by landlords in a neighborhood to abandon property or to renovate. The model shows that as long as one landlord does not abandon his property, the optimal decision for the other landlord is to renovate his property. A household's decision to renovate also has generated some empirical literature. Davis (2010) compares energy-saving system ownership patterns between owner-occupiers and tenants using household-level data. Controlling for household income and other household characteristics, tenants are significantly less likely to have energy-saving systems. Landlords who do not pay the energy bill also are less likely to invest in energy-saving systems. The behavior of households varies depending on whether they own or rent the place in which they live (Levinson, 2004). Rehdanz (2007) examines the determinants of household expenditures on space heating and hot water supply in Germany. Using an econometric analysis and, she shows that these household expenditures are significantly higher for owner-occupied housing. Landlords are less likely to invest in their rented housing. Finally, employing two cross-sectional surveys of UK consumers, Diaz-Rainey and Ashton (2009), found that a total of 27% of respondents did not renovate because they lived in either a council property (13%) or a rented property (14%).

To our knowledge, however, the determinants of investment in a context of uncertainty have not yet been studied from the perspective of tenure. In this paper, we model the expenditures on renovations of homeowners and tenants. We seek to explain a household's home renovation decision in a theoretical model. Instead of relying on bounded rationality, (Diaz-Rainey and Ashton 2009; Howarth and Sanstad, 1994) we focus on the characteristics of consumers who decide to renovate their homes when split incentives exist. We explicitly take into account that this decision takes place in an uncertain environment. When we solve the maximization program, we find that tenants are unwilling to invest. The problem of split incentives seems to be partially confirmed. In terms of effectively promoting energy-saving investments, the optimal public policy consists of investment subsidies, but these must be combined with the repercussion of a landlord's investment cost on the rent to obtain higher effect. Finally, the investments of both landlords and tenants are negatively affected by uncertainty.

The remainder of this chapter is organized as follows. Section 2 presents the model with an owner-occupier. In section 3, we present some sensitivity analysis. In section 4, we define the general model with split incentives. Because this model is solved separately for landlords and tenants, we calculate in separate sub-sections the landlord's reaction function and the tenant's reaction function to compute equilibrium. In section 5 we solve the model numerically. We introduce public policies in section 6. In section 7, we solve the model taking into account irreversibility. Section 8 concludes.

2 The model with an owner-occupier (homeowner)

We consider an economy with one type of agent: a homeowner (L) who occupies the dwelling (in order to make the section easier to read, a list of variables is provided in Table 3 in

Appendix A). We set a finite discrete time horizon as $t \in \{0,1\}$. During the two periods, the homeowner has the choice between consuming or investing. The housing quality function represents the value of the dwelling. In period 0, housing quality is a function of the investment level of the homeowner in the dwelling I_0^L, the housing quality when the homeowner moves into the dwelling $\overline{X}$ and a capital depreciation factor δ with $0 < \delta < 1$. We have the same relation in period 1, so we have:

$$X_0 = I_0^L + (1-\delta)\overline{X} \tag{1}$$

$$X_1 = I_1^L + (1-\delta)X_0 \tag{2}$$

The homeowner can consume energy goods C_t^{Le} or non-energy goods C_t^{Lne}. We have the following quasi-linear utility function:

$$U(C_t^{Lne}, C_t^{Le}) = \theta C_t^{Le}\left(\gamma - \frac{C_t^{Le}}{2}\right) + C_t^{Lne} \tag{3}$$

Non-energy goods C_t^{Lne} serves as numeraire in this model. The shape of the utility function implies that the value is measured in terms of the non-energy good C_t^{Lne}, that is to say in "monetary terms". There is an exact correspondence between the utility and its monetary value. Thus, all income is spent at first on energy goods C_t^{Le}. After a point, the expenditure on C_t^{Le} is kept constant, and all additional income is spent on C_t^{Lne}. We can think of good C_t^{Le} as an exemplar of necessity: it has an absolute first claim on income, but once satisfied, all extra income can go toward other goods (see Dixit 1992). Parameter θ is positive and ensures the concavity of the function. Parameter γ is positive too and ensures that consumption of energy good is positive.

We introduce uncertainty on z_1^1 related to the investment costs in period 1. For instance, solar panels for which total construction costs are very hard to predict due to both fluctuating lithium battery prices and silicon cost uncertainties. Moreover, the number of producers can vary, causing a change in the investment cost. There are two possible possible solutions depending on the level of uncertainty. We assume that z_1^H takes the value $z_1^1 = \ z_1^L$ ($z_1^L < 1$) with a probability α_1 and the value $z_1^1 = \ z_1^H$ ($z_1^H > 1$) with a probability $(1-\alpha_1)$.

The problem of the homeowner is to maximize his utility function subject to (1), (2) and:

$$R_1^L = (R_0^L - C_0^{Lne} - p_0(X_0)C_0^{Le} - I_0^L - I_0^{L^2})(1+r) \tag{4}$$

$$R_1^L + \frac{X_1}{1+r} = C_1^{Le} p_1(X_1) + C_1^{Lne} + z_1^1 I_1^L + \left(I_1^L\right)^2 \tag{5}$$

where R_0^L and R_1^L are the income of the owner-occupier in periods 0 and 1. Since we consider a two-period model, this budget constraint takes into account the fact that the owner expects to recuperate the value of his home by selling it at the end of period 1. The homeowner's income return in period 1 is determined by r. The homeowner also can deal with adjustment costs $I_t^{L^2}$. These adjustment costs increase with the volume of investment and are due to hidden costs associated with new equipment (for instance noise, power cut...). They also are due to organizational and maintenance costs. $p_0(X_0)$ and $p_1(X_1)$ represent the energy costs in periods 0 and 1. They depend on housing quality. We assume that the cost function is a linear function. f is the maximum amount of energy expenditures when housing quality is equal to zero.

We set:

$$p_t(X_t) = -\xi X_t + f \tag{6}$$

We can write the homeowner problem as:

$$\max_{I_1^T, C_0^{Te}, C_1^{Te}, I_0^T} U(C_0^{Lne}, C_0^{Le}, I_0^L, C_{1,}^{Lne} C_1^{Le}, I_1^L) = \theta C_0^{Le}\left(\gamma - \frac{C_0^{Le}}{2}\right) + C_0^{Lne} \tag{7}$$

$$+\beta\alpha_1^L\left[\theta C_{1,z_1^1=z_1^L}^{Le}\left(\gamma - \frac{C_{1,z_1^1=z_1^L}^{Le}}{2}\right) + C_{1,z_1^1=z_{1,}^L}^{Lne}\right] + \beta(1-\alpha_1^L)\left[\theta C_{1,z_1^1=z_1^H}^{Le}\left(\gamma - \frac{C_{1,z_1^1=z_1^H}^{Le}}{2}\right) + C_{1,z_1^1=z_1^H}^{Lne}\right]$$

β is the utility discount factor. We have a two-period planning problem. This intertemporal problem in discrete time with a time-separable objective function can be solved using the "principle of optimality" due to Bellman (1957). We work backward to find the optimal sequence of decisions. At the last relevant point, we can make the best choice and thereby find the continuation value. Having optimized the final period (period 1), this solution is substituted into the period 0 problem and then period 0 is optimized. We find two separate solutions for C_1^{Le} in the case where $z_1^1 = z_1^L$ and $z_1^1 = z_1^H$. Using the first order conditions, we get two solutions for C_1^{Le} and I_1^L. Introducing these solutions into the initial program and using first order conditions, we obtain solutions in period 0. In order to understand the effect of each parameter, numerical results are provided in the following section (section 3).

3 Numerical solutions with an owner-occupier (homeowner)

3.1 Calibration

The discount rate β is set to 0.99. The depreciation rate δ and the rate of return r are set to 0.05. Simulations are first driven with probabilities that event occurs α_1^L set to 0.5. Low outcome for z_1 is set to 0.95 and high income is set to 1.05.

The main difficulty lies in measuring housing quality from an economic point of view. We therefore refer to the hedonic approach[2]. We use average housing prices to appraise dwelling quality. Specifically, it means that an increase in quality (for example, better insulation) increases housing prices. In 2006, the average price of existing homes was 181 066 euros (see INSEE 2010). The average surface area is 90 square meters.

In the equation, we also need to include domestic energy costs. In France, average energy consumption is 195 $\text{kWh}_{ef}/\text{m}^2$/year. Energy cost is on average 0.0967 euros per kWh and therefore 1 697 euros for a dwelling with the average surface area and this average consumption. When a dwelling is renovated, the energy cost decreases to 0.0812 euros. Using equation (6), we compute ξ and we get $\xi = 0.05$. f is equal to 10750. θ is chosen to ensure the concavity of the utility function. γ is calculated to ensure that consumption of goods is positive in 2006.

3.2 Results and sensitivity analysis

Without public policy, we can conclude that the homeowner invests ($I_0^L = 27854$). The higher the energy cost, the higher the homeowner's investment. Uncertainty of investment has a slightly negative effect on the investment. The homeowner's investment is a decreasing function of housing quality but an increasing function of housing depreciation. Results obtained are quite intuitive. For the representative homeowner, public policies are not necessary. However, in the case of slightly more valuable dwellings (210 000 instead of 181 066), the homeowner does not

[2] A detailed methodology is described in Gouriéroux (2009).

renovate. Table 4 is available in Appendix B.2 with the effect of each parameter.

4 The model with split incentives

We consider an economy with two types of agents: a landlord (L) and a tenant (T) who occupies the dwelling. We have two periods of time. We set a finite discrete time horizon as $t \in \{0,1\}$. During the two periods, the agents have the choice between consuming or investing. The housing quality function is the same for both agents. This function represents the value of the dwelling. In period 0, housing quality is a function of the investment level of the landlord in the dwelling I_0^L, the investment level of the tenant I_0^T, the housing quality when the tenant moves into the dwelling $\bar{X}$ and a capital depreciation factor δ with $0 < \delta < 1$. So, we have:

$$X_0 = I_0^L + I_0^T + (1-\delta)\overline{X} \tag{8}$$

$$X_1 = I_1^L + I_1^T + (1-\delta)X_0 \tag{9}$$

The rent (L_t) is also common to both agents. We have again a two-period planning problem. To find the optimal sequence of decisions, we again work backward. At the last relevant point, we can make the best choice providing the corresponding response function and thereby find the continuation value by replacing first period investments by their equilibrium values. Having optimized the final period (period 1), the equilibrium solution is substituted into the period 0 problem an then period 0 is optimized.

Solving the optimization program, we will get two reaction functions. The landlord (tenant) should decide about investment taking into account the investment level of the tenant (landlord). These reaction functions are the best response of each agent. These reactions functions exist for each period. Those of period 1 provide an equilibrium which is then introduced in the program for period 0 of each agent.

$$I_1^L = f(I_1^T) \quad \text{and} \quad I_1^T = f(I_1^L) \tag{10}$$

$$I_0^L = f(I_0^T) \quad \text{and} \quad I_0^T = f(I_0^L) \tag{11}$$

Using these reaction functions, a Cournot Nash equilibrium is obtained.

4.1 The landlord's problem

The landlord consumes goods and we have the following utility function:

$$U(C_t^L) = \theta C_t^L \left(\gamma - \frac{C_t^L}{2} \right) \tag{12}$$

This is a quadratic utility function. Parameter θ is positive and ensures the concavity of the function. Parameter γ is also a positive parameter.

The problem of the landlord is to maximize his utility function (equation 12) subject to (8), (9) and:

$$R_1^L + L_1 + \frac{X_1}{(1+r)} = C_1^L + z_1^1 I_1^L + I_1^{L^2} \tag{13}$$

$$R_1^L = (R_0^L - C_0^L - I_0^L + L_0 - I_0^{L^2})(1+r) \tag{14}$$

where R_1^L and R_0^L are respectively the landlord’s income in periods 0 and 1. The income in period 1 depends on the income in the previous period less the investment, the adjustment costs, and the consumption, and plus the rent. His income return in period 1 is determined by r. In period 1, the landlord’s wealth is due to his income, the rent and the value of the dwelling. But it clearly appears that his wealth in period 1 is determined by the investment of both agents in period 0 and in period 1. Introducing X_1 in the program, we consider that the landlord can sell his dwelling in period 1. He has to deal with adjustment costs $I_t^{L^2}$. We also introduce uncertainty related to z_1^1 the investment costs in period 1. We can write the problem as follows:

$$\max_{I_0^L, C_0^L, I_1^L, C_1^L} U(C_0^L, I_0^L, I_1^L, C_1^L) = \theta C_0^L \left(\gamma - \frac{C_0^L}{2} \right)$$
$$+\beta \left[\alpha_1 \left(\theta C^L_{1,z_1^1=z_1^L} \left(\gamma - \frac{C^L_{1,z_1^1=z_1^L}}{2} \right) \right) + (1-\alpha_1) \left(\theta C^L_{1,z_1^1=z_1^H}) \left(\gamma - \frac{C^L_{1,z_1^1=z_1^H})}{2} \right) \right) \right] \quad (15)$$

Solving the system, I_1^L is not a function of I_1^T. It only depends on income return and investment price. Equilibrium is computed using solutions of I_1^T (see Appendix C). Introducing these solutions into the initial program and using first order conditions, we obtain that I_0^L is an increasing function of I_0^T.

4.2 The tenant's problem

The tenant can consume energy goods C_t^{Te} or non-energy goods C_t^{Tne}. We have the following quasi-linear utility function:

$$U(C_t^{Tne}, C_t^{Te}) = \theta C_t^{Te} \left(\gamma - \frac{C_t^{Te}}{2} \right) + C_t^{Tne} \quad (16)$$

The problem of the tenant is to maximize his utility function subject to (8), (9) and:

$$R_1^T = C_1^{Te} p_1(X_1) + C_1^{Tne} + L_1 + z_1^1 I_1^T + I_1^{T^2} \quad (17)$$

$$R_1^T = (R_0^T - C_0^{Tne} - p_0(X_0)C_0^{Te} - I_0^T - L_0 - I_0^{T^2})(1+r) \tag{18}$$

where R_0^T and R_1^T are the tenant's incomes in periods 0 and 1. The tenant also must deal with adjustment costs $I_t^{T^2}$. The rent reduces the tenant's wealth. $p_0(X_0)$ and $p_1(X_1)$ represent the energy cost unit in period 0 and in period 1 (see equation 6 in part 2).

We can write the tenant problem as:

$$\max_{I_1^T, C_0^{Te}, C_1^{Te}, I_0^T} U(C_0^{Tne}, C_0^{Te}, I_0^T, C_{1,}^{Tne} C_1^{Te}, I_1^T) = \theta C_0^{Te}\left(\gamma - \frac{C_0^{Te}}{2}\right) + C_0^{Tne}$$

$$+\beta\alpha_1^T\left[\theta C^{Te}_{1,z_1^1=z_{L,}^1}\left(\gamma - \frac{C^{Te}_{1,z_1^1=z_{1,}^{L,}}}{2}\right) + C^{Tne}_{1,z_1^1=z_{1,}^{L,}}\right] + \beta(1-\alpha_1^T)\left[\theta C^{Te}_{1,z_1^{1,}=z_1^H}\left(\gamma - \frac{C^{Te}_{1,z_1^1=z_1^H}}{2}\right) + C^{Tne}_{1,z_1^1=z_1^H}\right] \tag{9}$$

In order to understand the effect of each parameter and to compute equilibrium, numerical results are provided in the next section.

5 Numerical solutions with split incentives

5.1 Calibration

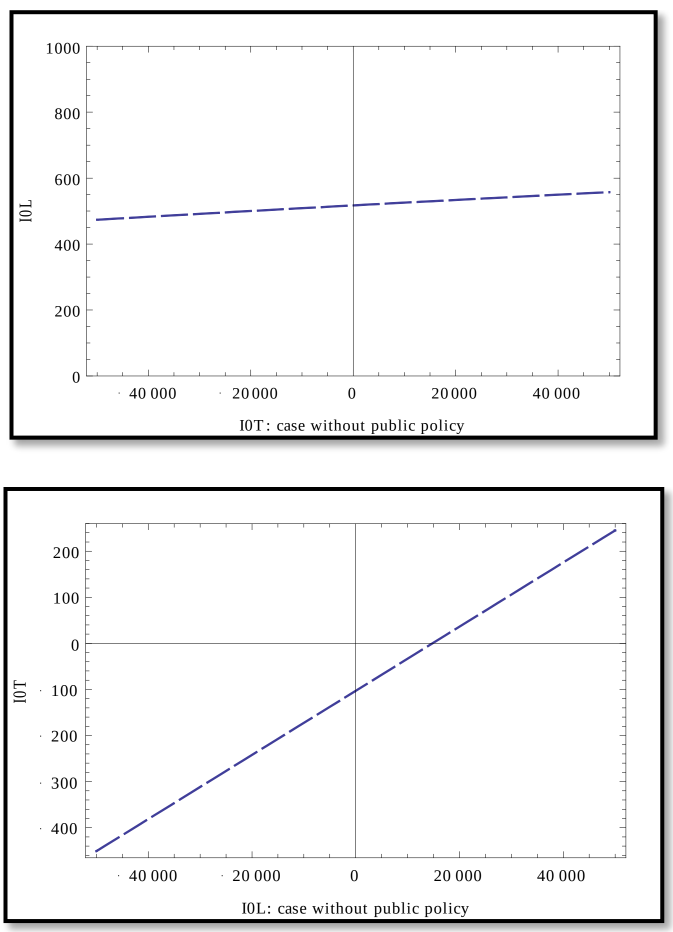
Simulations are driven with the same values as above (see Section 3). However, income and rent values are necessary to compute the equilibriums. The average tenure of a dwelling is 5.9 years (INSEE, 2005). We therefore consider that the length of one period is 3 years. The rate of income growth is 3% per year. The average rent in France is 419 euros. Rent in period 1 is computed taking into account the index of rent reevaluation. So, we have $\bar{L} = 15\ \ 084$ and

$L_1 = 16\ \ 007$. R_0^L is the disposable income of the landlord. Using data from INSEE, we have $R_0^L = 99\ \ 097$.

5.2 Solutions for reaction functions and equilibrium

Landlord investment is an increasing function of tenant investment and tenant investment also is an increasing function of landlord investment. This result suggests that if an agent invests, the second will invest too.

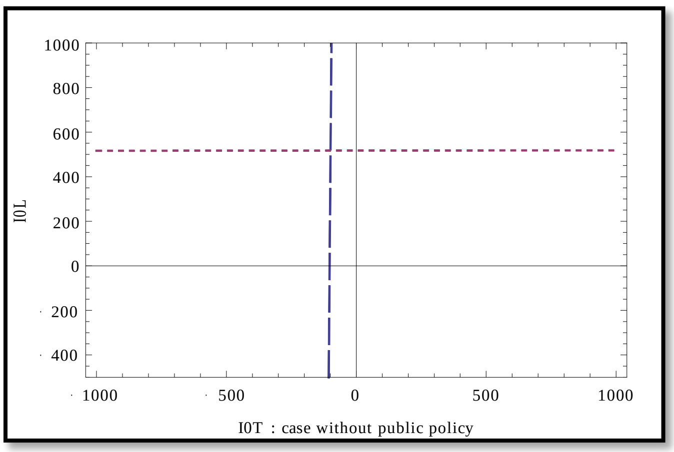
Figure 1: Solutions of reaction functions without public policy



$$I_0^L = f(I_0^T) \text{ and } I_0^T = f(I_0^L)$$

The equilibrium is computed. It is the intersection point of the reaction curves. Without public policy, at equilibrium we have $I_0^T = -99.1874$ and $I_0^L = 517.196$. If we consider that the investment cannot be negative, the solutions are $I_0^T = 0$ and $I_0^L = 517.279$. This result suggests that only the landlord invests in energy efficient systems. Comparing this result with an homeowner situation, the level of investment is higher in a owner-occupied house ($I_0^L = 27854$). In this case, public policies may trigger investment.

Figure 2: Equilibrium without public policy



With regard to the landlord, the higher is the income (R_0^L), the higher is the investment. A similar result is obtained concerning the rent and the initial housing quality. In general, the landlord seems to invest only if the dwelling has "an initial good quality". The higher is the depreciation rate (δ), the lower is the investment. This finding shows that landlords are not concerned if the dwelling is deteriorated. They only want to secure the monetary value of their dwelling if it is good quality but they will not invest to rehabilitate it. The results also show that the more a household is concerned about the future (larger β), the lower is its level of investment. We provide tables 7 and 8 in Appendix E.1 and E.2 to show the effect of each parameter in the case of both the tenant and the landlord. Let us now turn to the effect of uncertainty. The investments of both landlords and tenants are negatively affected by uncertainty. Finally, the tenant invests if the average tenure of a dwelling is 13 years. This result shows that the tenant is sensitive to the time required to make the investment profitable. In this case, $I_0^L = 840.873 \quad and \quad I_0^T = 9.28$. Tenants are responsive to, time horizon over which such savings would be realized (Alberini, 2013).

6 Public policies

In France, there are several public policy mechanisms to encourage households to undertake energy-saving renovations: income tax deduction and subsidies. Another measure is specifically dedicated to landlords: the compensation of investment.

The income tax deduction allows part of renovation expenses to be deducted from a household’s income tax. The deduction rate is a function of equipment (for example double glazing or heating system allows for a 25% deduction rate in average in 2006).

Households that make renovations involving insulation or which choose an efficient heating system can receive a subsidy depending on household income. The subsidy is given to owner-occuppiers and tenants. The subsidy rate is 35%.

Since November 2009, if a landlord invests, he can require a tenant to repay a portion of the energy-savings. This is a means to help the landlord finance the renovations. This is a "win / win" configuration: the tenant’s energy bill decreases and the landlord does not bear the cost of the renovation work alone. The landlord has the choice between two solutions: the repayment of energy-savings or a lump-sum. In the first case, the contribution cannot exceed half of estimated energy-savings. But if the landlord invests, there is no guarantee that the tenant saves energy because of a rebound effect in demand. The rebound effect refers to a behavioral response to the introduction of new technologies that increase the efficiency of a heating system. These responses tend to offset the benefits of the new technology. For example, the tenant can choose to live at a more comfortable temperature. Thus, even if the tenant (or the landlord) invests, this does not necessarily lead to lower energy consumption. The tenant chooses to use more of the resource instead of realizing the energy cost savings. Moreover, the law requires that the landlord must make a preliminary energy audit. In the case of the lump-sum solution, the amount depends on the average surface area of a dwelling. Given that a landlord generally prefers this option, we decided to test the effect of the repercussion of the investment directly on the rent. Finally, the introduction of a carbon tax is considered. The carbon tax was passed by European Parliament in December 2009 only to be cancelled after. The French government has decided not to submit a new proposal, but the effect of the carbon tax in the residential sector is still studied because such a policy still receives attention in the public debate. This measure can limit the rebound effect.

6.1 The subsidy or the income tax deduction

6.1.1 The landlord's problem

We can combine income tax deduction and subsidy. The problem of the landlord is to maximize his utility function subject to (8), (9) and:

$$R_1^L + L_1 + X_1 + S_1 = C_1^L + z_1^1 I_1^L + I_1^{L^2} \qquad (20)$$

$$R_1^L = (R_0^L - C_0^L - I_0^L + L_0 - I_0^{L^2} + S_0)(1+r) \qquad (21)$$

$$S_t = sI_t^L \tag{22}$$

with s the share of subsidies (or income tax deduction) allowed by the investment. This is a function of landlord's investment.

6.1.2 The tenant's problem

We can introduce a similar subsidy in the tenant program. The problem of the tenant is to maximize his utility function subject to (8), (9) and:

$$R_1^T + S_1 = C_1^{Te} p_1(X_1) + C_1^{Tne} + L_1 + z_1^1 I_1^T + {I_1^T}^2 \tag{23}$$

$$R_1^T = (R_0^T - C_0^{Tne} - p_0(X_0)C_0^{Te} - L_0 - I_0^T - {I_0^T}^2 + S_0)(1+r) \tag{24}$$

with

$$S_t = sI_t^T \tag{25}$$

Equilibrium is studied in section 6.1.3.

6.1.3 Numerical solutions

Concerning public policies, the subsidy rate is 35%. So we have $s = 0.35$ in a first time and then we can test several rates. We retain the previous values for the other parameters (see section 5.1). Introducing a subsidy (which is the most efficient measure), the equilibrium is $I_0^T = 0$ and $I_0^L = 517.454$ (see the summary of equilibrium results in the Appendix E.1 table 6). Increasing the subsidy's rate (or the income tax deduction) closer to 1, the tenant does not invest. This measure is not sufficient to trigger a tenant's investment. However, the landlord invests more.

Then, comparing energy consumption without and with public policies, the quantity of energy consumed is higher with a subsidy (694.959 kWh$_{ef}$/m^2/year with a subsidy and 694.922 kWh$_{ef}$/m^2/year without). There is a rebound effect in demand. This result is consistent with other French data and Giraudet *et al.* (2011). These findings can show that public policy in a landlord/ tenant configuration is irrelevant.

6.2 The repercussion of the investment cost on the rent

6.2.1 The landlord's problem

The function of rent is common to both the landlord and the tenant. On the one hand, the rent in period 1 is an increasing function of the landlord's investment in period 0. On the other hand, the rent is a decreasing function of the tenant's investment in period 0. In France, rents are reviewed annually. In this case, an investment in period 0 has an effect only in period 1. If the landlord invests in period 0, a share of the investment, represented by parameter a, is included into the rent. If the tenant invests, the rent is reduced by a share of the investment represented by parameter b. We consider that a and b are both positives. It is possible to test public policies using these parameters. Finally, the rent is also dependant on an average rent L_0.

$$L_1 = aI_0^L - bI_0^T + L_0 \tag{26}$$

The problem of the landlord is to maximize his utility function subject to (8), (9), (26) and:

$$R_1^L + L_1 + X_1 = C_1^L + z_1^1 I_1^L + I_1^{L^2} \tag{27}$$

$$R_1^L = (R_0^L - C_0^L - I_0^L + L_0 - I_0^{L^2})(1+r) \tag{28}$$

The effect of parameters a and b are analyzed in the numerical section. We also test the effect of a rise in the rent only in a to take into account the existing measure. Finally, it is also possible to test the efficiency on investment if the landlord invests at the beginning of period 0. In this particular case, the initial rent will be higher than without investment in period 0.

6.2.2 The tenant's problem

The problem of the tenant is to maximize his utility function subject to (8), (9) and:

$$R_1^T = C_1^{Te} p_1(X_1) + C_1^{Tne} + L_1 + z_1^1 I_1^T + {I_1^T}^2 \quad (29)$$

$$R_1^T = (R_0^T - C_0^{Tne} - p_0(X_0)C_0^{Te} - I_0^T - {I_0^T}^2 - L_0)(1+r) \quad (30)$$

Solutions for I_1^T are a decreasing function of b. Effects of parameters a and b are analyzed in section 6.2.3.

6.2.3 Numerical solutions

We set $a = 0.01$ and $b = 0.01$. With the repercussion of the investment cost on the rent, we have $I_0^T = 0$ and $I_0^L = 526{,}657$. Now, if $a = 0.01$ and $b = 0$, the equilibrium is $I_0^T = 0$ and $I_0^L = 516.433$. If $a = 1$, we have $I_0^T = 0$ and $I_0^L = 516.905$. This measure is slightly better than a direct repercussion of the investment cost of both agents even if a and b are raised to 1. However, this is not sufficient to trigger the tenant's investment. Finally, it also is possible to test the efficiency on investment if the landlord invests at the beginning of period 0. To study the measure where investment is compensated by a lump sum, we need to compute the new rent with only a repercussion of the landlord's investment. The lump sum depends on the average surface area of a dwelling (a mean of 20 euros per month). Now $L_0 = 15804$ and $L_1 = 17832$. At equilibrium, we have $I_0^T = 0$ and $I_0^L = 518.956$. This measure on the rent is the most effective but it requires the landlord to invest before the tenant moves into the dwelling. This result is not surprising because the landlord seems to invest only if the dwelling has "an initial good quality".

6.3 The carbon tax

6.3.1 The landlord's problem

In the landlord program, we also can introduce a carbon tax. The problem of the landlord is to maximize his utility function subject to (8), (9), and:

$$R_1^L + L_1 + X_1 = C_1^L + z_1^1 I_1^L + I_1^{L^2} + T_1(X_0) \tag{31}$$

$$R_1^L = (R_0^L - C_0^L - I_0^L + L_0 - I_0^{L^2} - T)(1+r) \tag{32}$$

$$T_1 = -t_1 X_0 + T \tag{33}$$

with t_1 the share of tax due to emissions. This is a decreasing function of quality. The effect of the tax is studied in the sensitivity analysis section.

6.3.2 The tenant's problem

The problem of the tenant is to maximize his utility function subject to (8), (9), (33) and:

$$R_1^T = C_1^{Te} p_1(X_1) + C_1^{Tne} + L_1 + z_1^1 I_1^T + I_1^{T^2} + T_1(X_0) \tag{34}$$

$$R_1^T = (R_0^T - C_0^{Tne} - p_0(X_0) C_0^{Te} - I_0^T - I_0^{T^2} - L_0 - T)(1+r) \tag{35}$$

The carbon tax function is the same as in the previous section. Contrary to the landlord, a tax on housing quality can be unfair for the tenant. In France, there is a problem of energy poverty.[3] Tenants are poorer than homeowners. Moreover, the poorest households live in the worst insulated dwellings. In such a situation, it is impossible for them to invest in energy efficient renovations. A tax based on housing quality seems unfair because these households may decide to consume less but they would still have to pay the tax. We consequently introduce a tax based only on the quantity of energy consumed. The problem is the following:

$$R_1^T = C_1^{Te} p_1(X_1) + C_1^{Tne} + L_1 + z_1^1 I_1^T + {I_1^T}^2 + T_1 \tag{36}$$

$$R_1^T = (R_0^T - C_0^{Tne} - p_0(X_0)C_0^{Te} - I_0^T - {I_0^T}^2 - L_0 - T_0)(1+r) \tag{37}$$

with

$$T_t = t_2 C_t^{Te} \tag{38}$$

t_2 is the share of tax due to the quantity of energy consumed.

Instead of taxing only the quantity of energy consumed, the cost of energy also can be taxed. So, we have:

$$T_t = t_3 p_t(X_t) C_t^{Te} \tag{39}$$

t_3 is the share of tax due to the cost of energy. Solutions in period 0 are studied in following section (6.3.3).

6.3.3 Numerical solutions

The French government wanted to set the carbon tax to 32 euros per ton of GHG emissions. We know that the average GHG emission is 4397 kg.C0 $_2$. The corresponding amount of tax payment per dwelling is then 140.5. If a household decides to improve its dwelling, the

[3] A household is in energy poverty when the dwelling energy bill represents more than 10% of its disposable income.

amount of the tax will decrease to 134.9. Using equation (33), we compute t_1 and we can set $t_1 = 4.6.10^{-4}$. T is the carbon tax corresponding to the lower quality for a dwelling: $T = 223.8$. In the case where the tax is introduced on energy consumed and on energy cost, $t_2 = t_3 = 0.01$. We keep the same value for other parameters as before (see section 5.1).

Taxes have an disincentive effect on investment (except for the sensitivity to investment to carbon tax t_1). However, the tenant diminishes the quantity of energy consumed because the tax reduces his wealth. Taxes are the only measure which lead to a reduction in energy consumption. This result is consistent with Giraudet *et al.* (2011).

6.4 The mix of public policy instruments

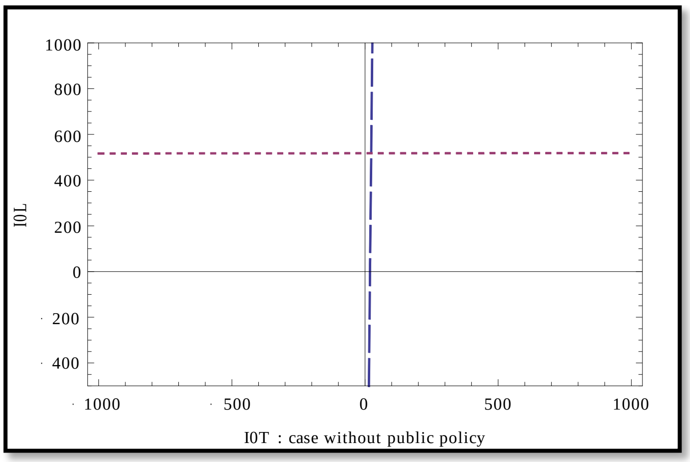
Considering the results, we test a combination of public policies, in other words, a higher initial rent and the subsidy/income tax deduction. Analytical solutions are the same as in the case with the subsidy but we use the following values for the rent $L_0 = 15804$ and $L_1 = 17832$. Both of these measures have a positive effect on agents' investments. When public policies are combined, the effect of the mix is lower than the sum of each public policy. The amount invested by adding each public policy is higher $(+1.852)$ than the effect of the combination of public policies (+0.87). The combination of public policies is not sufficient to trigger the tenant's investment. Moreover, this result also shows a problem of free-ridership.[4] This free-ridership may undermine the effectiveness of environmental public policy.

Moreover, agents can invest if the energy cost sensitivity to investment (ξ) rises only

[4] "Free-riders" are households who would have made energy efficiency investments even in the absence of public policy. For more information, the free-ridership was studied in the literature by Malm (1996) and Grösche and Vance (2009).

slightly. This result suggests that energy prices are clearly key variables in the model. Savings in euros associated with a renovation vary according to energy prices. For instance, if $\xi = 0.055$, the equilibrium is positive. This result is consistent with Amstalden *et al.* (2007) who draw the same conclusions in empirical studies. Expecting high energy prices triggers investment even without policy.

Figure 4: Equilibrium without public policy and xi=0.055



Finally, in the case with an owner-occupied dwelling, public policies are not necessary. This means that public policies to encourage homeowners to invest in energy efficient systems appear inappropriate. The homeowner always is interested in investing.

7 Irreversibility

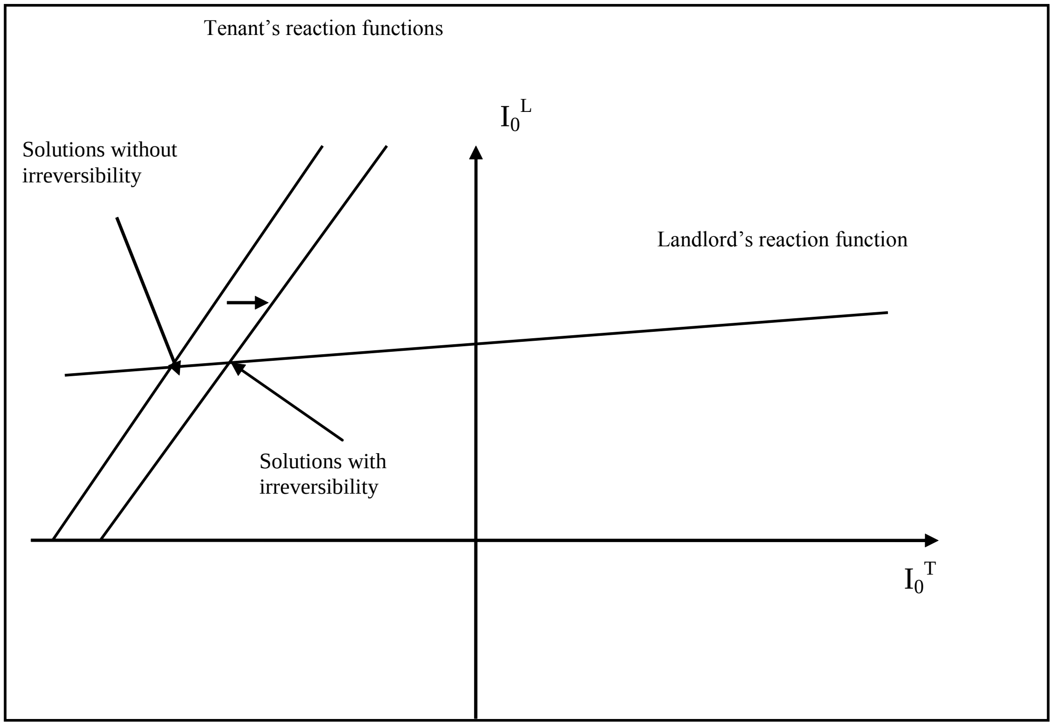
Under uncertainty, it becomes interesting to postpone an irreversible investment. In fact, changing a heating system or type of fuel contains a large element of irreversibility on costs (sunk costs, depreciation in the long run) especially when the use of renewable energy in heating systems remains imperfect. Even if a tenant had no aversion to risk, he prefers to postpone his decision to invest in energy-saving equipment and wait for an improvement in the technology to minimize costs. If he invests today, his investment may be irrecoverable. While the tenant (or the landlord) is waiting, he can take advantage of an opportunity to invest, which is similar to a financial option. Therefore, an option value of the investment project exists that is killed at the time of investment (Henry, 1974; Dixit, 1994). This option value represents an opportunity cost of investment that must be taken into account. These costs would be such that the investor would prefer to continue to exploit his old technology, even if the decision turns out to sub-optimal in period 1, instead of changing to an expensive technology.

To take into account irreversibility, we solve both models (the model with a homeowner, also refered to here as an owner-occupier, and the model with split incentives) numerically.

First, in the owner-occupier situation, there is no irreversibility effect in this case. The value of investment in period 1 is positive. The homeowner is always interested in investing. This is due to the housing quality variable.

Second, in the model with split incentives, in period 1, the landlord investment is negative in the case where $z_1 = z_1^H$ and the tenant investment is negative in both cases. The method is the same as when irreversibility is not taken into account. The value of the tenant's investment is higher than without taking into account irreversibility. This is due to the interaction of both agents. Results are summarized in Figure 5. The results obtained are different from those that normally would be expected. The effect of irreversibility is different than usual.

Figure 5: Equilibrium with and without irreversibility



8 Conclusion

In France, split incentives are an important barrier to reducing energy consumption in the housing sector. While a landlord wants to minimize the cost of installing an energy system, and has no return on this investment, a tenant wants to minimize his energy bill. This paper examines the home renovation decision of households in a theoretical model where there are split incentives. In particular, we explicitly take into account that such a decision takes place in an uncertain environment in which households must choose between consumption and investment in home renovation. Solving the program, we obtain that tenants are not willing to invest. The optimal public policy is an investment subsidy. When public policies are combined, the effect of the mix is lower than the sum of each public policy. Public policies have a stronger impact on the landlord's investment than on the tenant's. At the equilibrium point, even with public policy, the tenant does not want to invest. The problem of split incentives seems to be partially confirmed. Moreover, public policies lead to a rebound effect in demand. The results show that the expectation of high energy costs triggers investment even without policy support. Moreover, the investments of both landlords and tenants are negatively affected by uncertainty. The effect of irreversibility is different from usual.

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Appendix

A. The list of variables

Table 3: List of variables

Variables	Description
X_t	Housing quality in time t
I_t^L	Landlord's investment in time t
I_t^T	Tenant's investment in time t
δ	Capital depreciation factor
C_t^{Le}	Landord's energy goods consumption
C_t^{Lne}	Landord's non energy goods consumption
C_t^{Te}	Tenant's energy goods consumption
C_t^{Tne}	Tenant's non energy goods consumption
θ	Parameter to ensure the concavity of the utility function, positive
γ	Parameter in the utility function, positive
z_1^1	Uncertainty related to the investment cost in period 1
z_1^H	High value of uncertainty realization related to the investment cost in period 1
z_1^L	Low value of uncertainty realization related to the investment cost in period 1
α_1	Probability that uncertainty occurs
ξ	Sensitivity of energy cost to housing quality
f	Maximum amount of energy expenditures when housing quality is equal to 0
β	Utility discount factor
$p_t(X_t)$	Energy cost (depending on housing quality)
L_t	Rent in time t
r	Income return
S_t	Amount of the subsidy or income tax deduction in time t
s	Share of subsidy or income tax deduction allowed by the investment
a	Share of investment included into the rent
b	Share of investment deducted into the rent
T_1	Carbon tax in period 1
T	Initial value of the carbon tax
t_1	Share of tax due to emissions
t_2	Share of tax due to quantity of energy consumed
t_3	Share of tax due to energy cost

B. The model with an owner-occupier

B.1 The solutions in the model with an owner-occupier

When $z_1^1 = z_1^L$:

$$I_1^L = \frac{\theta(-(r+1)z_1^L + \gamma(r+1)\xi + 1) - (r+1)\xi(f + X_0(\delta-1)\xi)}{(r+1)\left(2\theta - \xi^2\right)}$$

$$C_1^{Le} = \frac{-2f(r+1) + 2\gamma\theta(r+1) - (rz_1^L + z_1^L + 2(r+1)X_0(\delta-1) - 1)\xi}{(r+1)\left(2\theta - \xi^2\right)}$$

When $z_1^1 = z_1^H$:

$$I_1^L = \frac{\theta(-(r+1)z_1^H + \gamma(r+1)\xi + 1) - (r+1)\xi(f + X_0(\delta-1)\xi)}{(r+1)\left(2\theta - \xi^2\right)}$$

$$C_1^{Le} = \frac{-2f(r+1) + 2\gamma\theta(r+1) - (rz_1^H + z_1^H + 2(r+1)X_0(\delta-1) - 1)\xi}{(r+1)\left(2\theta - \xi^2\right)}$$

B.2 The sensitivity analysis in the model with an owner-occupier

Table 4: Sensitivity analysis in the owner-occupied situation

Parameters	$\mathbf{I}_0^L$
r	+
θ	-
γ	-
δ	+
X	-
f	+
ξ	+
Uncertainty 1 ($z_1^L z_1^H$)*	-
α_1	-

Note: *senstivity analysis on uncertainty is measured in increasing (or decreasing) the means preserving spread.

C. The equilibrium solutions in period 1 in the model with split incentives

When $z_1^1 = z_1^L$:

$$I_1^T = -\frac{2(r+1)z_1^L\theta + \xi(2f(r+1) - 2g\theta(r+1) + (rz_1^L + z_1^L + 2(r+1)X_0(\delta-1) - 1)\xi)}{2(r+1)\left(2\theta - \xi^2\right)}$$

$$I_1^L = \frac{1}{2}\left(\frac{1}{r+1} - z_1^L\right)$$

When $z_1^1 = z_1^H$:

$$I_1^T = -\frac{2(r+1)z_1^H\theta + \xi(2f(r+1) - 2g\theta(r+1) + (rz_1^H + z_1^H + 2(r+1)X_0(\delta-1) - 1)\xi)}{2(r+1)\left(2\theta - \xi^2\right)}$$

$$I_1^L = \frac{1}{2}\left(\frac{1}{r+1} - z_1^H\right)$$

D. Description of public policies tested

Table 5: Description of public policies tested

Measure	Description	Rate and/or Amount
Subsidy	A subsidy, for household, depending on household income Extension: measure tested on landlord in the model	35% of renovation expenditures
Income tax deduction	A part of the expenses in energy saving renovation can be deducted. from the household income tax (or refunded if the household pays no income tax). Cumul with subsidy in the model	Percentage or renovation expense and depending on the type of renovation.
Repercussion in the rent	Landlord may require the tenant to repay a portion of the energy-savings Extension to the tenant (a share of the investment can be deduced in the rent)	1% of the investment is deduced. 100% is tested.
Repercussion in the rent at the beginning of period 0	The rent in period 0 and in period 1 is higher.	Lump sum depending on the average surface area. (20 euros in means) by month
Carbon tax	The tax is a decreasing function of housing quality Tested on landlord and tenant	t=0.00046 T=223.8
Tax on energy consumed	The tax is an increasing function of the quantity of energy goods	0.01
Tax on energy cost	The tax is an increasing function of the energy cost	0.01

E. Numerical results

E.1 Numerical equilibrium results

Table 6: Summary of equilibrium results

Scenario	I_0^T	I_0^L	C_0^{Te}
Without public policy (1)	(-99.1874) 0*	(517.196) 517.279	(694.922) 694.931
With subsidy (2)	(-99.0082) 0	(517.371) 517.454	(694.959) 694.968
Compared to (1)	(+0.1792) 0**	+0.175	+0.037
With carbon tax (3)	(-99.1897) 0	(516.847) 516.929	(694.886) 694.894
Compared to (1)	(-0.0023) 0	-0.35	-0.037
With tax on energy consumed (4)	(-99.1889) 0	(517.196) 517.279	(694.901) 694.91
Compared to (1)	(-0.0015) 0	0	-0.6
With tax on energy cost (5)	(-103.677) 0	(517.191) 517.278	(650.199) 650.209
Compared to (1)	(-4.4896) 0	-0.01	-44.722
With repercussion on the rent (6)	(-98.1168) 0	(516.352) 516.433	(737.518) 737.527
Compared to (1)	(+1.0706) 0	-0.846	+43.026
With repercussion on the rent with $b = 0$ and $a = 1$ (7)	(-98.1168) 0	(516.352) 516.433	(737.518) 737.527
Compared to (1)	(+1.0706) 0	-0.374	+42.596
With a mix of public policies (9=8+2)	(-99.0034) 0	(518.067) 518.149	(695.032) 695.04
Compared to (1)	(+0.184) 0	+0.87	+0.109

*The tenant's investment is negative, so we set it equal to 0. But it is interesting to know negative values in order to understand the magnitude of public policies.

**The difference between the tenant's investment with the subsidy and the tenant's investment without public policy is equal to 0.1792.

E.2 Sensitivity analysis on landlord's investment at equilibrium

Table 7: Sensitivity analysis on landlord's investment at equilibrium

	Without public policy	**Subsidy**	**Repercussion of investment in the rent**	**Carbon tax**	**Tax on energy**	**Tax on energy cost**	**Mix of public policies**
	$\mathbf{I}_0^T$	$\mathbf{I}_0^T$	$\mathbf{I}_0^T$	$\mathbf{I}_0^T$	$\mathbf{I}_0^T$	$\mathbf{I}_0^T$	$\mathbf{I}_0^T$
r	-*	-	-	-	-	-	-
θ	+	+	+	+	+	+	+
γ	-	-	-	-	-	-	-
δ	-	-	-	-	-	-	-
X	+	+	+	+	+	+	+
f	-	-	-	-	-	-	-
R_0^L	+	+	+	+	+	+	+
ξ	+	+	+	+	+	+	+
L_0	+	+	+	+	+	+	+
L_1	+	+	+	+	+	+	+
$z_1^L z_1^H$ **	-	-	-	-	-	-	-
α_1	+	+	+	+	+	+	+
β	-	-	-	-	-	-	-
s		+					+
t_1				+			
T				-			
t_2					-		
t_3						-	
a			+				
b			+				

Note: *The landlord's invesment in a decreasing function of income return (r).
**Senstivity analysis on uncertainty is measured in increasing (or decreasing) the means preserving spread.

E.2 Sensitivity analysis on tenant's investment at equilibrium

Table 8: Sensitivity analysis on the tenant's investment at equilibrium

	Without public policy	**Subsidy**	**Repercussion of investment in the rent**	**Carbon tax**	**Tax on energy**	**Tax on energy cost**	**Mix of public policies**
	$\mathbf{I}_0^L$	$\mathbf{I}_0^L$	$\mathbf{I}_0^L$	$\mathbf{I}_0^L$	$\mathbf{I}_0^L$	$\mathbf{I}_0^L$	$\mathbf{I}_0^L$
r	+*	+	+	+	+	+	+
θ	+	+	+	+	+	+	+
γ	+	+	+	+	+	+	+
δ	-	-	-	-	-	-	-
X	+	+	+	+	+	+	+
f	-	-	-	-	-	-	-
R_0^L	+	+	+	+	+	+	+
ξ	+	+	+	+	+	+	+
L_0/L	+	+	+	+	+	+	+
L_1	+	+	+	+	+	+	+
$z_1^L z_1^H$ **	-	-	-	-	-	-	-
α_1	+	+	+	+	+	+	+
β	-	-	-	-	-	-	-
s		+					+
t_1				+			
T				-			
t_2					-		
t_3						-	
a			+				
b			+				

Note: *The tenant's invesment in a increasing function of income return (r).
**Senstivity analysis on uncertainty is measured in increasing (or decreasing) the means preserving spread.