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# Is France on track for decarbonizing its residential sector? Assessing recent policy changes and the way forward.

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## Abstract

This study assesses the long-term cost-effectiveness and distributional impacts of various energy efficiency policies to decarbonize the French residential sector. It does so using Res-IRF 4.0, a significantly enhanced version of a behaviorally- and technologically-rich model of residential energy demand in France. Our analysis reveals that deep decarbonization targets cannot be achieved with current policies. However, we demonstrate that the progressive implementation of new mitigation policies generates net socio-economic benefits. In particular, newly implemented direct subsidies that direct support toward low-income households and deep renovation outperform precedent attempts. Mandatory renovation for privately rented dwelling and carbon tax, plays a significant role in enhancing socio-economic balance. Finally, we illustrate that banning the adoption of new natural-gas boilers will significantly accelerate the transition to low-carbon fuels with social benefits outweighing additional costs. Our research highlights the importance of a multifaceted approach to reach climate and social objectives. Overall, by incorporating policy frictions in bottom-up modelling, we provide more plausible long-term policy assessments.

**Keywords:** climate change mitigation, energy efficiency, residential sector, building stock models, ex-ante policy assessment, applied policy analysis.

## 1 Introduction

The residential sector is a major contributor to energy consumption and greenhouse gas (GHG) emissions. According to state-of-the-art assessments, around 40% of energy consumption and 95% of GHG emissions could be cost-effectively saved in most EU countries by 2050 compared to 2019 under the joint effect of energy efficiency improvements and the adoption of low-carbon heating systems (Zeyen et al., 2021; Hummel et al., 2023). As a result, these analysis suggest to implement financial incentives for home insulation (Hummel et al., 2023) or policies to overcome market-failures in energy efficiency sectors (Levesque et al., 2021).

This long and widely shared belief has led Western governments to implement myriad energy efficiency policies. France is perhaps where this approach has been the most comprehensive, with nearly 8 billion Euros spent in 2021 on four major energy efficiency subsidy programs (Ledez et al., 2021). In practice, however, energy efficiency policies have had deceptive effects. First, take-up is less significant than anticipated, and hardly additional compared to a counterfactual situation without policies (Gillingham et al., 2018; Giandomenico et al., 2022). In France alone, up to 85% of households would have invested even in the absence of a tax credit program

(Nauleau, 2014; Risch, 2020) and the zero-interest loan program ceased to be effective after two years of operation (Eryzhenskiy et al., 2023). Second, when realized, investment is found to have little impact, with effective energy savings significantly underperforming projections (Fowle et al., 2018). Known as the energy performance gap, this phenomenon has been attributed to a combination of quality defects, over-optimistic engineering predictions, and, to a lesser extent, rebound effects (Christensen et al., 2021).

As a result of these shortcomings, renovation rates remain low across Europe (European Commission et al., 2019). This is especially the case for in multi-family and rental housing, both subject to pronounced barriers (Gillingham et al., 2012). As these building segments tend to be disproportionately occupied by low-income households, this gives rise to fuel poverty, with significant health effects (Charlier et al., 2021). Additionally, among the too few energy renovations in the EU, deep energy renovations that yield significant energy savings occur only sporadically. This situation is a cause for concern, both in terms of the extensive and intensive margins of energy-saving efforts.

Our goal in this paper is to enrich building sector policy modelling in order to reconcile engineering projections and real-world frictions. The ultimate objective is to provide actionable insights for the design of realistic instruments, addressing a noted gap in existing literature (Pollitt et al., 2024). To do so, we develop a significantly enhanced version of Res-IRF, a model of long-term energy demand for residential space heating in France (Giraudet et al., 2021). The model contains granular technological detail of both the performance of the envelope and the heating systems and relies on engineering computation to simulate their joint effect on energy consumption. This feature is crucial to accurately model policies, which typically target specific technical measures, and finely assess their impact. In addition, the model includes energy performance gap and several important barriers to energy efficiency investment. Among them, the landlord-tenant dilemma, decision frictions in multi-family housing, credit-constraints and non-monetary costs that have been parameterized using empirical estimates from discrete choice experiments and state-of-the art policy evaluation. The model also accounts for behavioral anomalies in household investment decisions, including myopic expectations of energy prices and status quo bias, which can limit investments in energy efficiency. Lastly, the model is calibrated using an updated description of the building stock, more deeply intertwining household and dwelling characteristics. The model is open-source and has a modular structure that can easily be adapted to other economies.

Taking France as a case study, we examine at what cost, and with which distribution various energy efficiency policy instruments can contribute to reducing GHG emissions and energy consumption in residential buildings in the long term. We consider the main policies implemented in France, grouped into five categories: subsidy programs for home energy retrofit, including direct public grants and a reduction in value-added tax (VAT); white certificate obligations; zero-interest loan; the carbon tax; and two regulations – a rental ban on the least efficient dwellings, in effect since 2013, and a ban on new natural-gas boiler installation, not yet enforced but envisioned at the EU level. We combine these policies into three contrasted policy packages, spanning past (2018-2021), present (2021-2023) and future periods (2024 onwards). Importantly, running the 2018-2021 package serves as model validation, enabling a direct comparison between actual and simulated outcomes. In the 2024-onwards package, current policies are set to more ambitious levels to elicit the upper bound of the mitigation potential. The policy packages are assessed through comprehensive cost-benefit analysis, factoring in private costs and benefits and the social costs of GHG emissions and adverse health effects experienced by low-income households living in the worst-performing dwellings as well as the opportunity cost of public funds.

We find that none of the packages considered succeeds in achieving the national

targets of reducing energy consumption and GHG emissions. The latest policy package however get close to these targets, reduces GHG emissions by 75% and fuel poverty by 65% and generates net benefits. Our findings highlight how successive implementation of mitigation policies have generate net socio-economic benefits. In particular, newly implemented instruments that direct subsidies toward low-income households and deep renovation outperform precedent attempts. We find that recent modifications in subsidies specifications increase cost-effectiveness, evolving from €0.2/kWh in 2018 to just €0.1/kWh in the latest programs. We also demonstrate that mandatory renovation and current carbon tax both enhance socio-economic balance. Annual investment cost in the latest packages get close to €20 billion in 2030, one third of which are covered by subsidies. Overall, our results highlight that reaching objectives in the residential sector, although technologically feasible, is a challenging and expensive task: a result that is less optimistic than those obtained by less detailed model. Our analysis also illustrates that the ban on new natural-gas boilers could be instrumental to reach climate and social objectives.

Our work seeks to connect two strands of the literature – the economics of energy efficiency and building stock modelling. The economics of energy efficiency is interested in explaining why investment in energy efficiency is so low and ineffective (Gerarden et al., 2017). The most frequently invoked reasons include split incentives between landlords and tenants (Gillingham et al., 2012), hidden costs (Fowlie et al., 2015), a reluctance to switch fuel (Lang et al., 2021), myopic expectations of energy prices (Gillingham et al., 2021) and credit constraints face by low-income households (Albrecht et al., 2021). These problems are typically captured through high implicit discount rates in building stocks (Levesque et al., 2021; Mastrucci et al., 2021). We go beyond this approach by using explicit depictions of them (Schleich et al., 2023). Incidentally, our model contains much heterogeneity and endogenous processes, whereas related assessments of the residential sector tend to rely on a single representative agent (Keppo et al., 2021) and exogenous energy efficiency investment (Knobloch et al., 2021; Berrill et al., 2022). Modelling framework that is closest to ours is perhaps Invert/EE-Lab (Müller, 2015; Camarasa et al., 2022). However, our approach distinguishes itself by incorporating a whole range of barriers to energy efficiency investment. It also offers a thorough assessment of the environmental and social impacts of real-world policies.

The rest of this paper is organized as follows. Section 2 describes the methods used for our analysis. Section 3 presents the assessment methodology. Section 4 presents the main results and Section 5 discusses them. Section 6 concludes. Additional findings, including numerical and sensitivity analyses, are detailed in Appendix 6.

## 2 Methods

### 2.1 Introduction

Res-IRF 4.0 model is a dynamic microsimulation model of energy consumption and long-term energy efficiency improvement of the French residential building sector. It focuses on space heating as the main usage that accounts for 70% of residential energy consumption in France in 2021. The model integrates a detailed description of the energy performance of the dwelling stock with a rich description of household energy-efficiency investment behavior. The great advantage of this model is to evaluate both incentive programs and regulatory instruments in the long run. As a simulation model, it does not optimize at either the micro or macro level, and does not consider macroeconomic feedback. The development of Res-IRF has produced six peer-reviewed articles to this day, of which an overview is provided in Appendix 6.1. Compared to the last version of the model (Giraudet et al., 2021), we have greatly improved the technical detail, the micro-foundations of homeowners investment decisions, and the realism of

individual mitigation policies.<sup>1</sup>

## 2.2 Building stock

Res-IRF 4.0 builds on a detailed representation of residential buildings. We account for the heterogeneity of the dwelling stock through approximately 180,000 individual housing archetypes (see Table 1). A key feature of our approach is the construction of this building stock using a unique French dataset. This dataset notably links insulation quality with tenant income and occupation status, a typically challenging data point to obtain (refer to Appendix 6.8.2 for further details). In contrast to most modelling assessment, our approach represents building’s energy performance by detailing the insulation levels of each component (walls, roof, floor, windows) and the efficiency of its heating system.<sup>2</sup> This method enables a more granular description of both the building energy performance and the available renovation options. Importantly, this granularity is critical for simulating the impact of French subsidies, where rates vary based on specific renovation works (e.g. white scheme obligation).

Dimension	Number	Description
Housing type	2	single-family or multi-family
Main heating system	5	natural gas, oil-fuel, wood-fuel boilers, district-heating and direct-electric and heat-pumps
Wall insulation	5	levels of thermal insulation
Roof insulation	4	levels of thermal insulation
Floor insulation	4	levels of thermal insulation
Windows insulation	3	levels of thermal insulation
Occupancy status	3	owner-occupied, privately-rented, and social-housing
Income of housing owner	5	income quintile
Income of tenant	5	income quintile

**Table 1:** Model dimension. Total number of dwelling-households pair is approximately 180,000. Thermal insulation is represented by the thermal transmittance ( $W/(m^2.K)$ ).

## 2.3 Energy consumption for space heating

It is well-documented that there is a discrepancy between actual energy usage and the theoretical values predicted by engineering methods. Therefore, we calculate energy consumption for space heating through a two-step method.

First, we calculate the theoretical energy consumption based on the dwelling’s structural and thermal characteristics, adhering to EN ISO 13790 standards and employing the TABULA methodology (Loga, 2013) (see further details in the Appendix 6.7). From this consumption, we estimate the Energy Performance Certificates (EPC) of the building.<sup>3</sup>

Second, we calculate the household’s heating intensity, which is influenced by tenants’ income and energy prices. We apply an empirically-derived formula, tailored to French data, to correlate heating intensity with the proportion of theoretical budget allocated to energy expenses (Cayla et al., 2013):

$$\text{Heating intensity} = 0.3564 \times \text{Budget share}^{-0.244}$$

<sup>1</sup>According to the classification developed in Langevin et al. (2020), the Res-IRF 4.0 model is a hybrid model as system dynamics are applied to simulate aggregate stock dynamics, agent-based to calculate market share of energy-efficiency technologies and simplified physics simulation to estimate the energy demand per building archetype. A description following the best practice reporting guideline (Nägeli et al., 2022) of the model is presented in Supplementary materials 6.6.

<sup>2</sup>Earlier versions of Res-IRF characterized building energy performance by its energy performance certificate only.

<sup>3</sup>The 3CL method, France’s official EPC determination method is closely related to the TABULA approach (Arquin et al., 2020).

The formula is in line with the latest estimate of short-term price elasticity of -0.2 determined by Douenne (2020). By calculating the actual energy use before and after energy renovation, this approach effectively captures an energy performance gap (Christensen et al., 2021) that includes the rebound effect.

Finally, we align the model’s simulated energy consumption across different fuels with actual observed data in base year. We do so by calculating coefficients that capture energy usage from secondary heating systems. In particular, the method allocates a share of the electricity consumption to wood fuels, implicitly accounting for the presence of wood stoves in buildings where electricity is the main heating source (see Appendix 6.7 for further details).

## 2.4 Stock turnover

Each year, the model simulates the demolition and renovation of the existing housing stock and the construction of new housing. Demolition targets on the worst-performing dwellings (i.e., those with energy performance certificates of E, F, or G), which also corresponds to the oldest ones. In accordance with the latest Building Code, we assume that all newly constructed dwellings meet the minimum standard requirements. We rely on an exogenous projection of the market share of heating systems in newly built homes (ADEME, 2022).

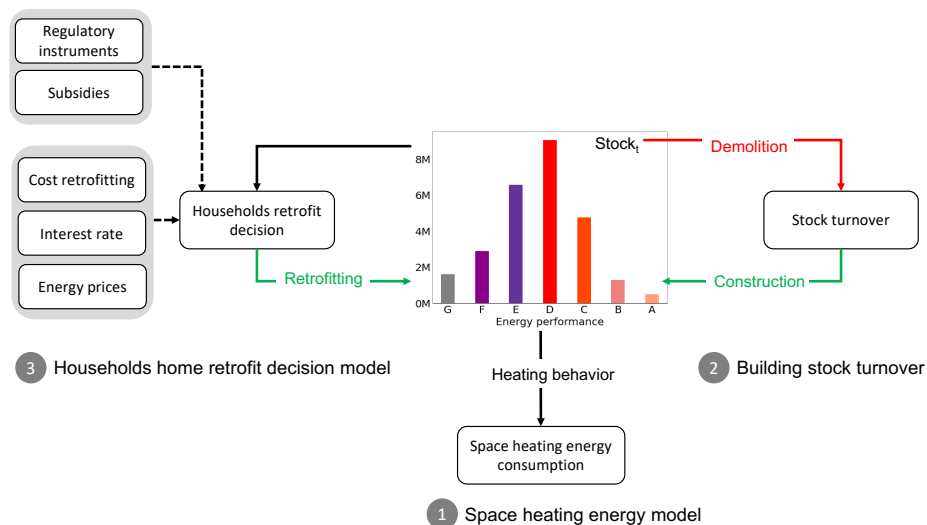


Figure 1: Schema Res-IRF 4.0.

## 2.5 Household energy-efficiency investment

**Investment decision.** The model simulates endogenous energy-efficiency investments, focusing on the replacement of heating systems and insulation of the main components of the building envelope (such as walls, floors, roofs, and windows). The model consists of two steps: first, the replacement of the heating system is triggered by its end-of-life,<sup>4</sup> and subsequently, homeowners decide whether to undertake insulation

<sup>4</sup>We assume that homeowners replace their heating system until it stops working and then decide which heating system to choose. This assumption seems reasonable as a choice experiment conducted by Olsthoorn et al. (2017) in eight countries in the EU found that homeowners prematurely replace their heating system if the payback period is less than three years, with a standard deviation of one year. As a result, our modeling is unsuitable for modeling very aggressive subsidies, but it is well suited for modeling the actual levels of costs and subsidies.

projects.

To model the end of life of a heating system, we should ideally record the vintage of the individual heating system. However, to reduce the number of combination, we only track the vintage on the broader heating system category. Every year, we update the vintage of the heating system and model the failure of systems with an expected useful life of less than one year. Following Knobloch et al. (2021), we begin with a central estimate of expected useful life, which we set to 20 years for all heating systems categories, and we assume an equal distribution of heating system vintage for base year. In addition, we prohibit the installation of heat pumps in worst-performing dwellings, as they are technically incapable of heating the water to more than 55°C with standard-sized radiators.

Regarding insulation investment, homeowners have the option to insulate one or more components of the building envelope (among wall, roof, floor and windows) each year. To simplify the analysis, we consider a single level of insulation for each component of the envelope, which represents the minimum requirement to qualify for subsidies, thereby disregarding partial insulation. Consequently, there are 16 insulation options available, including the option of not insulating, contingent upon the initial performance of the home.

The theoretical foundation for both energy efficiency investment decisions is based on a random utility function representing agents' benefits derived from space heating (Train, 2009). A multinomial discrete choice model is employed to capture the energy efficiency investment decision, assuming agents seek to maximize utility. Specifically, the investment decision is influenced by key economic costs and benefits, namely investment and financing costs, energy bill savings, and subsidy amounts (see Figure 1). Our model assumes that due to imperfect information, homeowners do not consider additional thermal comfort and health benefits when deciding of home retrofitting, but instead focus on energy saving predicted by engineering simulations.<sup>5</sup> Furthermore, we assume that homeowners have myopic expectations regarding energy price growth and the evolution of policies when making investment decisions.<sup>6</sup>

Overall agent  $i$  looks for the energy-efficiency option  $k$  to maximise its gross indirect utility:

$$\max_k U_i(k) = \theta \times (\beta_{i,k} + \text{INV}_k + \text{FIN}_{i,k} + \beta_{\text{SUB},i} \text{SUB}_{i,k} + \beta_{\text{PRESENT},i} \text{SAVING}_{i,k}) + \epsilon_{i,k}$$

- $\text{INV}_k$  is the amount of investment costs,  $\text{FIN}_{i,k}$  financing cost,  $\text{SUB}_{i,k}$  subsidies, and  $\text{SAVING}_{i,k}$  energy bill saving.
- $\beta_{\text{SUB}}$  represents the preferences of the homeowner  $i$  for subsidies compare to investment cost.
- $\beta_{\text{PRESENT}}$  represents the discount factor for time preferences.
- $\beta_{i,k}$  are the alternative-specific constants. It is the mean of the error term and represents the influence of all unobserved factors or non-monetary cost on the investment choice. This constant is found during the calibration process.
- $\epsilon_{i,k}$  is an error term, and represents the unobservable part of the utility.

Building on Train (2009), we assume that the  $\epsilon_{i,k}$  are independently and identically distributed (iid), according to the generalised extreme value law of type I (the standard Gumbel law), and we set the variance of the distribution to  $\frac{1}{\pi^2/6}$  by calibrating the

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<sup>5</sup>Therefore, our model differs from more theoretical studies such as Chan et al. (2023) that employ discrete-continuous models and assume that owners maximize their energy efficient durable investment while considering their expected energy consumption reaction. These models generally assume quasilinear utility resulting in optimal energy consumption that does not depend on homeowners' income. While this assumption is reasonable for theoretical analysis, it does not apply to our applied analysis projecting space heating demand.

<sup>6</sup>This assumption have been confirmed for vehicle purchase by Gillingham et al. (2018).

scale of the utility parameter  $\theta$ . This yields the following close form for the probability of choosing alternative  $k$ :

$$P_{i,k} = P(U_{i,k} > U_{i,j} \forall j, k) = \frac{\exp V_{i,k}}{\sum_j \exp V_{i,j}}$$

Where:  $V_{i,k} = \theta \times (\beta_{i,k} + \beta_{\text{INV},i} \text{INV}_{i,k} + \beta_{\text{SUB},i} \text{SUB}_{i,k} + \beta_{\text{SAVING},i} \text{SAVING}_{i,k})$  represents the observable part of the utility, and is often called the representative utility.

**Discount rate for time preferences.** We distinguish between pure time preferences and financing costs. In our setting, discount rate only represents time preferences as estimated in a discrete choice experiment. In contrast to implicit discount rates estimated by Hausman (1979), this discount rate does not include information about energy-efficiency investment barriers such as market failures or credit-constraint, but only represents the weight of future benefits relative to present costs. We build on a discrete choice experiment conducted by Stolyarova (2016) in France to estimate the discount rate.<sup>7</sup> In line with the findings from the literature, time discount rates are lower for people from higher income households, suggesting that wealthier people exhibit greater patience (Meissner et al., 2023).

**Financing costs and credit constraints.** Financing costs correspond to the weighted average cost of capital for homeowners. Homeowners choose between their available savings or debt to minimize their financing costs. Based on assumptions from expert groups (Dolques et al., 2022), we use a maximum available savings amount according to income class, ranging from €0 to €10,000 for low- and high-income households. Mathematically, the financing cost,  $\text{FIN}_{i,k}$ , for an agent  $i$ , with a maximum available savings of  $S_i$ , to purchase an option  $k$  that cost  $\text{INV}_k$  is defined as:

$$\begin{aligned} \text{FIN}_{i,k} = \min_d \quad & \text{duration} \times (c_s s + c_d d) \\ \text{s.t.} \quad & d + s = \text{INV}_k \\ & s \leq S_i \end{aligned} \tag{1}$$

Where: duration is the duration of the loan,  $c_s$  is the opportunity cost of savings,  $s$  is the amount of savings used to finance the investment,  $c_d$  is the interest rate of the loan and  $d$  is the amount of debt used to finance the investment.

In France, households with debt ratios over 30% are generally deemed insolvent and are denied to take a loan. To prevent over-indebtedness, we restrict credit use in the model. First, we assume that banks do not count energy savings in debt ratio calculations as extra income. Then, as we do not model whether households have taken out other loans, we propose a lower threshold of debt ratio of 5% (Dolques et al., 2022). Concretely, investments that require debt exceeding 5% of household income are therefore prohibited.

**Subsidy responses.** We use results from Stolyarova's discrete choice experiment to capture the ratio of coefficients associated with subsidy and investment cost (Stolyarova, 2016).<sup>8</sup> Using a similar multinomial logit model, she found that the absolute value of the parameter associated with the subsidy amount, 0.167, is higher than the parameters associated with the investment amount, -0.0964. Thus, the subsidy offsets

<sup>7</sup>We use the average of the four situations described by Stolyarova as a reference value for the discount rate. We extrapolate Stolyarova's results for the choice of a new heating system to the decision to insulate.

<sup>8</sup>In her experiment, Stolyarova specified different models. Among them, we focus on situation 2 that targets the influence of subsidies and financing. The situation represents that "the respondent is in an experimental situation where the heater is broken and a new heater must be chosen". The attributes used in the choice experiment are all significant and have the expected sign.



a part of the investment cost and generates a multiplier effect of more than 1: 1 euro of subsidy. Consequently, subsidies have a greater impact on the probability that a household renovate its building than an equivalent reduction in investment costs.

**Hidden costs.** Importantly, hidden costs, sometimes referred to as non-monetary costs have been shown to drive and explain homeowners’ energy-efficiency investment decisions in their dwelling (Fowle et al., 2015). These costs, often elusive and challenging to quantify, include the time spent gathering information, the inconvenience of undergoing renovations and the cost of temporary relocation during renovations. Additionally, they can encompass ancillary costs not directly related to energy renovation, such as the relocation of pipes or electrical circuits necessary for insulation or new heating system installations. These costs vary between different renovation options and households situations. The decision to insulate becomes much easier, for example, if a roof renovation is already underway.

In our approach, we calibrate these hidden costs to reflect real-world investment patterns, specifically renovation rates and heating system market shares. These hidden costs corresponds to the unobservable part of the utility in our setting, and are therefore distributed among households and over time. This represents the diversity of situations faced by households. Specifically,  $\beta_{i,k}$  represents the mean of the hidden costs distribution for a specific agent  $i$  to make an investment  $k$ . Simultaneously, we estimate the scale of the utility,  $\theta$ , using one additional information.

We calibrate the investment function for heating systems based on the market shares provided by ADEME for the sale of new heating systems (ADEME, 2022). We simultaneously calibrate the scale of utility,  $\theta$ , using estimation of the price-elasticity of the demand for heat-pumps. We build on the research of Nauleau (2014) and Risch (2020) that assess the causal impact of introducing income tax credit in 2005 in France that reduces the investment cost for energy renovation by 30%. Based on their results, we estimate this price elasticity to be around -1. In view of the uncertainty of this estimate, we perform a sensitivity analysis with a lower and a higher estimate in Appendix 6.4.

For the case of insulation, we employ a combination of two data sources to ensure the model’s predictions are grounded in reality. To determine the aggregate number of renovations by housing type, we utilize results from the white certificate obligations program. These data possess a significant advantage in terms of standardization, as the program mandates a minimum performance level to ensure the quality of renovation work.<sup>9</sup> To complement the data on white certificate obligations, we include information from a national survey on the renovation of homes (TREMI), which provides detailed information on combined insulation measures and the proportion of buildings with low energy performance (EPC F and G) that have been effectively renovated (MTE, 2020a).<sup>10</sup> We assimilate the ratio of the constant for homeowners in single-family dwelling and the investment coefficient,  $\beta_{\text{Homeowners, Single-family}}/\beta_{\text{INV}}$ , as hidden cost for insulation. We present calibration results in Table 10 in Appendix.

**Market-failures and behavioral anomalies.** Evidence indicates that homeowners tend to prefer retaining their existing heating systems when considering replacements (Stolyarova, 2016; Lang et al., 2021). To incorporate this statu-quo bias, we draw upon the findings of Stolyarova (2016) and introduce an inertia parameter into our utility function. This parameter enhances the utility derived from keeping the current

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<sup>9</sup>However, it is important to note that these data may not capture all renovation activities. Some renovations may not have received subsidies due to homeowners undertaking the work themselves, employing contractors without the required certification for subsidy eligibility, or simply choosing not to apply for the subsidy, among other reasons. This focus on subsidized renovations is pertinent since the model’s objective is to evaluate the impact of policies on the renovation rate.

<sup>10</sup>This additional information is required to calibrate the scale  $\theta$  of the utility.

heating system, reflecting this observed homeowner preference.

In addition, we address two significant market failures that prevent homeowners from insulating their properties: the public good problem in multifamily buildings and the landlord-tenant split incentive dilemma between landlord and tenant (Gerarden et al., 2017). These issues are incorporated as additional penalties in the utility function in our model. We calibrate these penalties using data on renovation distribution across different occupancy statuses from the TREMI survey and housing types from white certificate obligations data (MTE, 2020a) (see Table 10 in Appendix).

## 2.6 Data

The parametrization of such a detailed model requires to gather considerable amount of different data sources (Table 2). Readers seeking a more detailed description of inputs can refer to the Supplementary materials 6.8. Values of the associated data are available on the model’s GitHub page. In addition, due to the inherent uncertainty of some parameters, we perform a sensitivity analysis of 13 key inputs that we present in the Appendix 6.4.

<b>Inputs</b>	<b>Source</b>
<b>Energy system</b>	
Energy prices projection	Scenario AME 2021 (MTE, 2021)
Energy taxes projection	Scenario AME 2021 (MTE, 2021)
Emission content 2020	Légifrance (2021)
Emission content projection	Scenario BAU (ADEME, 2022)
Amount of renewable gas for space heating	Scenario BAU scenario (ADEME, 2022)
Number of dwelling connected to district heating	Scenario BAU ADEME (2022)
<b>Housing market</b>	
Demolition rate	Scenario BAU (ADEME, 2022)
Number of new buildings	Scenario BAU (ADEME, 2022)
Share of multi-family in new buildings	Scenario BAU (ADEME, 2022)
Market share heating system construction	Scenario BAU (ADEME, 2022)
Surface area of new housing	Fidéli (2018)
<b>Macro</b>	
Household income by decile in 2018	INSEE (2021)
Income growth	DGEC (2023)*
<b>Initial housing stock</b>	
Housing stock in 2018	MTE (2020b)*
Building performance characteristics by certificate	ADEME (2021) and Rogeau et al. (2022)
Landlords income	MTE (2020b)
Wood and oil fuel housing	(MTE, 2018)
Surface area of dwelling by occupation status	Fidéli (2018)*
<b>Technical data</b>	
U-value of renovated envelope components	ADEME (2024)
Cost insulation by envelope component	Effienergie (2019)
Capex heating system	RTE et al. (2020)
Renovation rate	CEE 2017-2018 (MTE, 2020a)
Market share insulation work	TREMI (MTE, 2020a)
Heating system lifetime	Knobloch et al. (2021)
Market share heating system	ADEME (2022)
<b>Behavioral parameters</b>	
Time preferences discount factor	Stolyarova (2016)
Subsidies preferences	Stolyarova (2016)
Status-quo bias	Stolyarova (2016)
Average price elasticity for heat pumps	Own assumption, from Risch (2020)
<b>Financing information</b>	
Maximum upfront cost by income class	Dolques et al. (2022)
Threshold credit constraint	Dolques et al. (2022)
Average interest rate of households savings	Own assumption
Average interest rate of home renovation loan	Dolques et al. (2022)
<b>Indicators</b>	
Health cost due to bad housing condition	Dervaux et al. (2022)
Social value of carbon - Value of climate action	Quinet (2019)
Social discount rate	Ni et al. (2021)
Grey emissions due to home renovation	Siedler (2021)
<b>Thermal module data</b>	Loga (2013) and Arquin et al. (2020)

**Table 2:** List of data sources used in Res-IRF. \* means data are not publicly available.

## 3 Assessment methodology

### 3.1 Scenarios

In this study, we evaluate three distinct policy packages that aim to replicate the policy mixes implemented in France after 2018. These include the ‘2018 Package’ for past policies (2018-2021), the ‘2021 Package’ for current policies (2021-2023), and the ‘2024 Package’ for future policies starting from 2024. To compare these policy mixes, we

maintain all policies until 2050. In the ‘2024 Package’, current policies are set to more ambitious levels to elicit the upper bound of the mitigation potential. In addition, we consider policy package based on ‘2024 Package’, augmented by a ban to sell new gas boilers after 2030, which we refer to as the ‘2024 Package + Ban’. This package reflects the current discussions at both national and European level. We also introduce two counterfactual scenarios. The first scenario projects a future without any mitigation policies in the existing residential sector and is used as a baseline to calculate the effect of the implementation of policy packages. The second scenario is based solely on a carbon tax aligned with France’s social cost of carbon, to illustrate the effect of the first-best solution to reduce GHG externalities. We assume that revenues are entirely and equally redistributed to households as energy bill rebates (see Appendix 6.8.6). Both counterfactual scenarios take into account the already enacted ban on the sale of oil boilers. We describe all individual policies in Table 6. We assume that the instruments work at full capacity, in particular, a household that carries out a renovation receives all the aid for which it is eligible, and that incentives are perfectly passed on to households, without being captured by energy efficiency vendors in the form of an increase in the base price.<sup>11</sup> Finally, due to the lack of specific data, we extrapolate the impact of the policy on social housing. This represents a perfect alignment between mitigation policies for private and social housing stock.

**2018 Package.** In 2018, policy package in France contained an income tax credit (‘CITE’) that were a uniform ad-valorem subsidy reducing the investment cost by 30% capped at €4,800 per household. This package also included a subsidy program, ‘MPR Serenite’, specifically targeting deep renovations and households with lower incomes.<sup>12</sup> White certificate obligations, ‘CEE’, provide subsidies for energy-efficiency investments based on standardized energy savings and an avoided energy price of approximately €7 per MWh of energy saving cumulated and discounted. French authorities also provided a temporary bonus for insulation investment between 2019 and 2021 and for heat-pumps and wood boilers starting in 2019 and ending in 2026. Investments in energy efficiency were favored with a reduced VAT rate of 5.5%, compared to the regular 10% for standard construction activities (‘Reduced VAT’). Additionally, the carbon tax applied to residential energy prices was set at €45 per ton of CO<sub>2</sub>.

**2021 Package.** In 2021, the introduction of two new subsidy programs, ‘MPR’ for single-family dwelling and ‘MPR Multi-family’—for multi-family residences, replaced the income tax credit. In contrast, these programs target specific technical measures and are structured to primarily benefit low-income households. Subsidy amounts are capped between 90% for lower income groups and 40% of total investment costs for higher income groups. The ‘MPR’ program also offered a bonus of €500 for homes improving their energy performance to EPC B or moving out of the worst-performing categories (EPC G and F). In addition, the ‘Loi Climat et resilience’ introduced a mandatory renovation for private homes, which prohibits landlords from renting out properties that do not meet certain performance standards and is due to be enforced from 2025.<sup>13</sup> This agenda is phased, starting in 2025 with EPC G, followed by EPC F in 2028, and EPC E in 2034. We expect landlords to comply with the law after each new lease and to at least meet the 2034 standards (i.e. upgrade their properties to at least EPC D).

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<sup>11</sup>This mechanism is based on an assumption of perfect competition in the energy renovation sector (Nauleau et al., 2015).

<sup>12</sup>Deep renovations are characterized by an upgrade that includes at least two energy performance certificate (EPC).

<sup>13</sup>We perform a preliminary analysis of this measure with an older version of the model (Vivier et al., 2021).

**2024 Package.** In the context of the EU Green Deal, French authorities have introduced a new 2024 reform, which we refer to as the ‘2024 package’. ‘MPR’ will be replaced by ‘MPR Efficacite’, and ‘MPR Serenite’ by ‘MPR Performance’, shifting the focus from subsidizing individual measures for deep renovations. Worst-performing buildings (EPC F and G) are not eligible anymore to subsidy for individual measures and need to perform deep renovation to get subsidies. Others buildings are required to change their heating systems to be eligible for individual measures subsidy. Buildings intended solely for improving building insulation performance now require eligibility for ‘MPR Performance’. Similarly, the subsidy amount is contingent upon the homeowner’s income, ranging from 30% for high-income households and extending up to 80% for low-income households. We assume that the ‘Reduced VAT’ will be discontinued due to its insufficient effectiveness. In addition, we retain the ‘CEE’ bonus for heat pumps and wood boilers in the ‘2024 Package’ until 2050, assuming that the French authorities will maintain this influential incentive to promote the introduction of heat pumps. In addition, we introduce a zero-free loan in the ‘Package 2024’ to renew the policy instrument that has been almost unused for ten years (Eryzhenskiy et al., 2023). Finally, in contrast to the ‘2021 Package’, we assume that the new EU-ETS II will be added to the existing carbon tax, and therefore consider an increase of the residential carbon tax after 2030 (see Table 21 in Appendix 6.8.6).

<b>Policy Package</b>	<b>Main policy</b>
<b>No policy</b>	Ban of oil fuel boilers
<b>2018 Package</b>	Ban of oil fuel boilers, Carbon tax, white certificate obligations (CEE), tax credit (CITE), subsidy targeting deep renovation for low-income households (MPR Serenite), reduced VAT
<b>2021 Package</b>	Ban of oil fuel boilers, Carbon tax, white certificate obligations (CEE), subsidy (MPR), subsidy targeting deep renovation for low-income households (MPR Serenite), subsidy targeting multi-family dwellings (MPR Multi-family), reduced VAT, mandatory renovation for privately-rented dwellings
<b>2024 Package</b>	Ban of oil fuel boilers, Carbon tax (inc. EU-ETS II), white certificate obligations (CEE), restricted subsidy (MPR Efficacite), subsidy targeting deep renovation (MPR Performance), revised subsidy scheme targeting multi-family dwellings (MPR Multi-family), mandatory renovation for privately-rented dwelling stock, zero-interest loan (ZIL)
<b>2024 Package + Ban</b>	Ban of oil fuel boilers, All policies of 2024 Package and ban of natural gas boilers by 2030
<b>Carbon tax</b>	Ban of oil fuel boilers, Carbon tax valued at the social value of carbon with lump-sum recycling

**Table 3:** Description of policy packages implemented in France.

## 3.2 Outcomes

### 3.2.1 Cost-benefit analysis

The key advantage of ex-ante modelling is to quantitatively assess both cost and benefit from the introduction of policy packages or specific policy.

Regarding private value, the model considers home renovation costs, encompassing both heating system and home insulation expenses. It also accounts for the reduction in energy expenditure resulting from these improvements. Our evaluation crucially considers changes in heating comfort, valued through residential energy prices. Therefore any reduction in energy savings from an energy tax is counterbalanced in the cost-benefit analysis by a decline in thermal comfort. Conversely, any reduction in energy-saving due to the rebound effect is offset by an increase in thermal comfort.<sup>14</sup> Identifying hidden costs is challenging due to their varied nature. For our cost-benefit analysis, we have focused exclusively on material costs of energy renovation, treating hidden costs as externalities borne by homeowners. This decision and its implications are further elaborated in Section 5.

In terms of social value, our model also includes health benefits, in particular the avoidance of mortality and morbidity associated with cold indoor environments. These benefits are monetized following methodologies such as the one provided by the Working Group on the Socioeconomic Assessment of the Health Impact of Public Investments (Dervaux et al., 2022). For example, it is estimated that each energy-inefficient dwelling incurs an average annual cost of 7,500 euros, considering medical costs, loss of well-being due to illness, and the social cost of mortality (detailed in Appendix 6.8.5). While there is debate about classifying health costs as an externality, we consider these costs as such, particularly noting their disproportionate impact on low-income households, who often face credit constraints limiting their ability to invest in renovations. Further social values considered include the benefits from avoided GHG emissions, and embodied emissions from renovation and construction activities valued using the social cost of carbon (Quinet, 2019). GHG emissions are calculated using exogenous emission pathways for electricity and district heating. For gas, emissions are calculated on the basis of gas consumption net from the use of renewable gas. Additionally, the model assesses the impact on public spending due to the increase of subsidies expenditures and the decrease of energy taxes revenue. These impacts are quantified in terms of the opportunity cost of public funding, applying a coefficient of 0.2 to the difference in public spending between two scenarios (Stratégie, 2017).

To ensure fair comparison across impacts at different times, a social discount rate of 3.2% is applied over a 30-year period, in line with the guidelines recommended by French authorities for public investment (Ni et al., 2021).

### 3.2.2 Distributional impacts

We identify energy poverty as households whose energy costs amount to more than 10% of their income, as often seen in definitions of fuel poverty in modeling assessment (Charlier et al., 2018). In addition, we offer a broader indicator that includes the costs a household has to pay to replace their heating system or insulate their home. These costs are net of existing subsidies and are annualized over 10 years with a discount rate of 3.9% to simulate realistic financing conditions (MTE, 2020a). Both indicators are calculated using theoretical energy consumption so as not to take into account the behavioral responses of households to reduce their energy consumption when energy prices rise.

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<sup>14</sup>In contrast to thermal comfort, we monetize energy savings with energy price projections excluding taxes to account for the long-term impact of savings on the energy system.

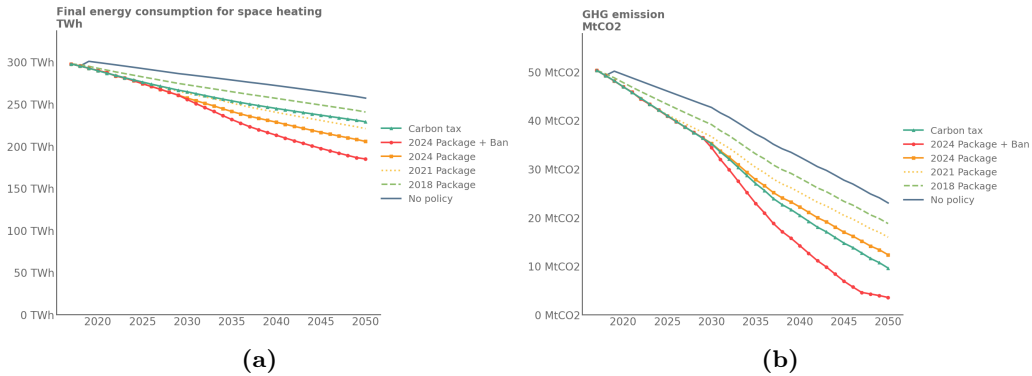
## 4 Results

This section begins by assessing policy packages in terms of their environmental effectiveness, net socio-economic benefits, and distributional impacts. Following this, we delve into the latest policy package and assess the impact of the implementation of stand-alone policies. All numerical results are presented in Appendix 6.3. For the purposes of consistency and to negate the effects of inflation, all monetary values within the paper are standardized to 2018 euros

### 4.1 Assessment of policy packages

#### 4.1.1 Environmental effectiveness

Figure 2a illustrates the trajectory of space heating energy consumption across policy scenarios. In the absence of any mitigation measures, final energy consumption falls by 14% in 2050 compared to 2017 levels. Each of the successively implemented packages of measures enable significant additional reduction in energy consumption. Overall, the model projects that the currently implement policy scenario, the ‘2024 Package’, enables a reduction of 13% by 2030 and 30% by 2050. This strategy fails to reach the new 2030 target presented in the European energy efficiency directives, which ambition to reduce the total primary energy saving by 16% by 2030. On the other hand, Figure 2b displays the evolution of space heating emissions. Similarly, none of the policy scenarios meet the Fit-for-55 objective, which mandates a reduction of emissions by at least 55% by 2030 from 1990 levels (which means reaching 26 MtCO<sub>2</sub> per year by 2030). The model also projects that currently implemented policy package reduce emission by 75% by 2050, but fail to reach carbon neutrality in the residential space heating sector by 2050 (implies limiting emissions to 3 MtCO<sub>2</sub> annually (ADEME, 2022)). Additional measures, such as banning the sale of gas boilers, appear necessary to reach these goals. Remarkably, a scenario based solely on a carbon tax valued at the social cost of carbon outperforms all policy scenarios, except the ban of gas boilers, in term of emission reduction, but still falls short of the target with still 10 MtCO<sub>2</sub> emissions annually in 2050.

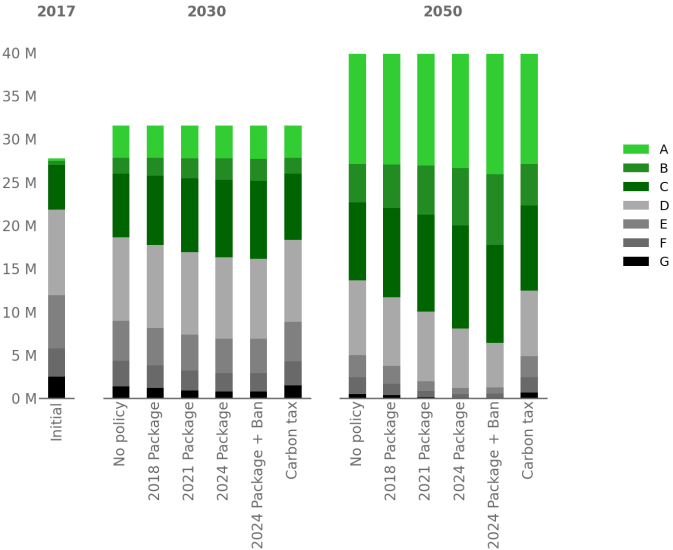


**Figure 2:** Evolution of (a) final energy consumption for space heating and (b) the associated GHG emissions in Scope 2 in France.

Figure 3 depicts the progression of energy efficiency in residential buildings. In our setting, the number of residential dwelling increase from 28 millions in 2017 to 40 million in 2050. Successive upgrades of the policy packages, in particular the ‘2024 Package’, significantly reduces the number of worst-performing buildings (EPC F and G). However, in 2050, there are still 8 millions of dwellings that are D or worst and only 50% of dwelling stock reach B.

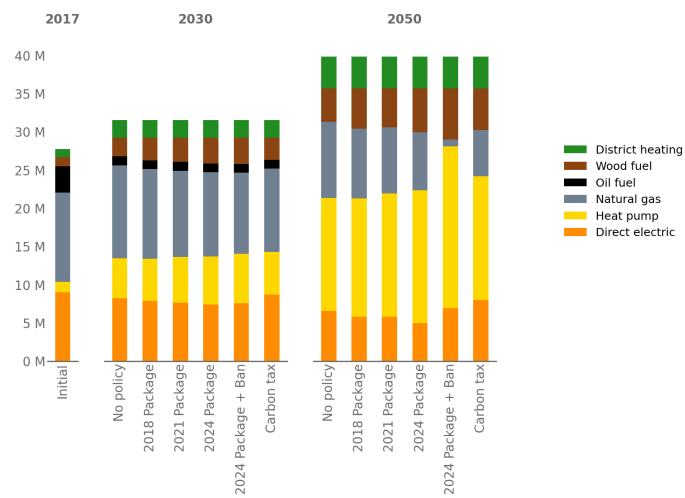
In addition, Figure 4 projects the evolution of the heating system stock. First,

the use of heating oil heating systems drastically reduce all scenarios due to the ban on the sale of new oil boilers that has been in force since 2018. The model projects strong penetration of heat-pumps in all scenarios. In the ‘2024 Package’ scenario, 6 million of heat-pumps are installed in 2030 and 17 million in 2050. The shares of district heating and wood-fired boilers remain relatively unchanged. However, a residual presence of gas boilers remains in every scenario in 2050. By design, the package that implements the ban on gas boilers reaches almost 100% of low-carbon fuels by 2050. The scenario relying on an ambitious carbon tax, incentivizes emission reduction rather than consumption reduction. Consequently, its influence on home insulation is less significant; however, it results in a more adoption of direct electric heating systems compared to other policy packages. As the installation of heat pumps in worst-performing dwellings is technically challenging, direct electric heating systems are increasingly being installed. Despite this shift, the overall increase in electricity consumption remains modest even in the scenario with the carbon tax, with an increase of 20 TWh, which represents 4% of 2024 French electricity consumption (see Figure 14 in Appendix).



**Figure 3:** Evolution of energy efficiency of the housing stock in France in different policy scenarios. The energy performance of residential buildings is characterized by their energy performance certificate, which ranges from G for the worst to A for the most efficient dwellings.

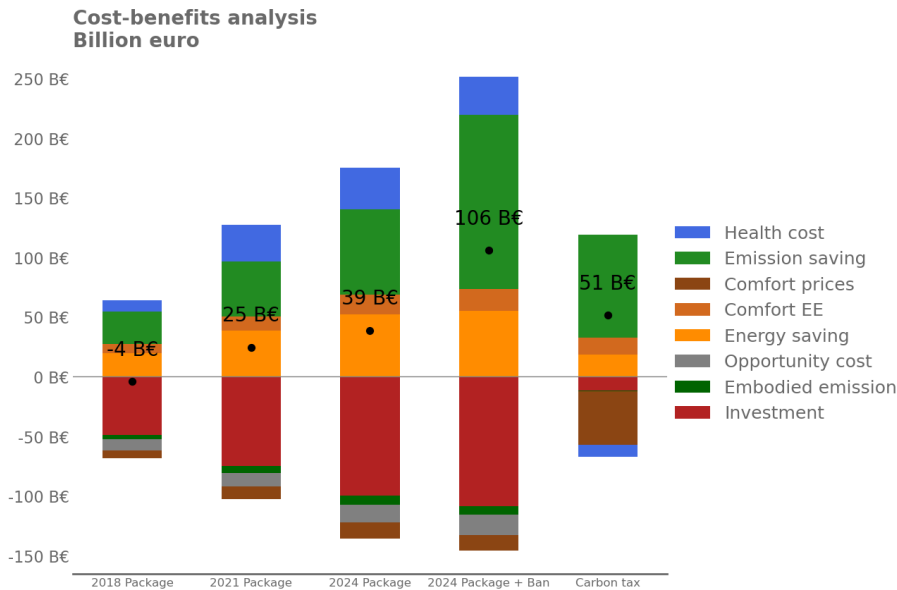




**Figure 4:** Evolution of the main heating systems residential stock in France in different policy scenarios.

### 4.1.2 Cost-benefit analysis

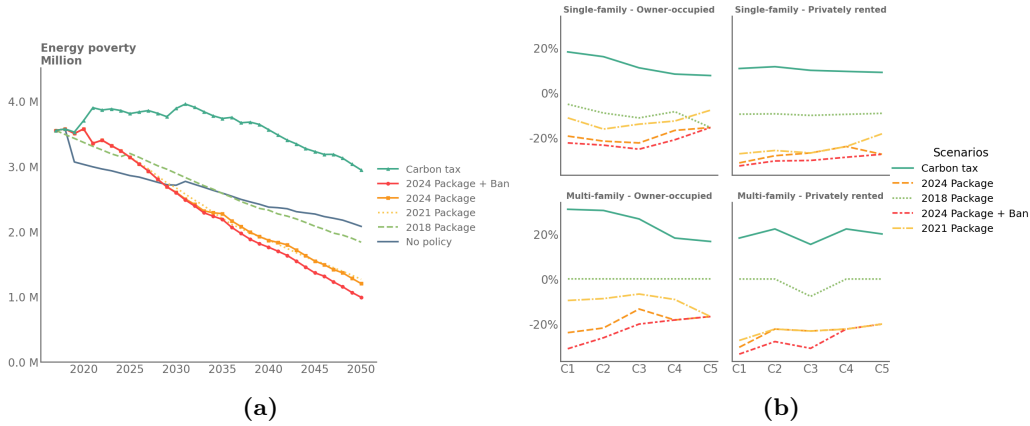
Figure 5 presents a cost-benefit analysis of implementing each policy packages. The ‘No policy’ serves as the counterfactual, and we compare the marginal impact of policy packages encompassing both private and social value (see Section 3.2). There is a significant increase in investment with successive implementation of policy packages. Specifically, the ‘2024 Package’ and the ‘2021 Package’ see an average annual investment of €6 billion each in home insulation and €10 billion in heating system replacement. This represents a yearly increase of €5 billion over the ‘No Policy’ scenario (see Appendix 6.3). Even if the private benefit alone is not sufficient to offset these additional costs, the consideration of societal benefits – including reductions in health costs and GHG emissions – tips the balance favorably. Specifically, the ‘2021 Package’ outperforms both the ‘No Policy’ scenario and the ‘2018 Package’ in terms of health cost reduction. Similarly, the ‘2024 Package’ surpasses the ‘2021 Package’ by promoting more extensive use of heat pumps. This suggests that the extra economic costs incurred by more ambitious policies are more than compensated for by the substantial societal benefits they yield, justifying the implementation of such policies. Conversely, non-targeted approaches like the ‘2018 Package’ fail to enhance socio-economic balance, raising legitimate questions about the rationale behind these policies. In this framework, the implementation of a ban significantly enhances the balance by reducing GHG emissions. Similarly, the ‘Carbon Tax’ scenario, while not diminishing health costs or energy expenditures, generates extensive GHG emission savings that still results in a net positive socio-economic impact.



**Figure 5:** Cost-benefit analysis of all scenarios compared to the ‘No Policy’ scenario, with costs and benefits discounted at a social rate of 3.2%. Long-term impacts, including energy and emission savings, are projected over a 30-year period, corresponding to the lifespan of renovation work. Dots in the figure represent the balance between benefits and costs, where a positive value indicates a favorable net socio-economic outcome.

### 4.1.3 Distributional impacts

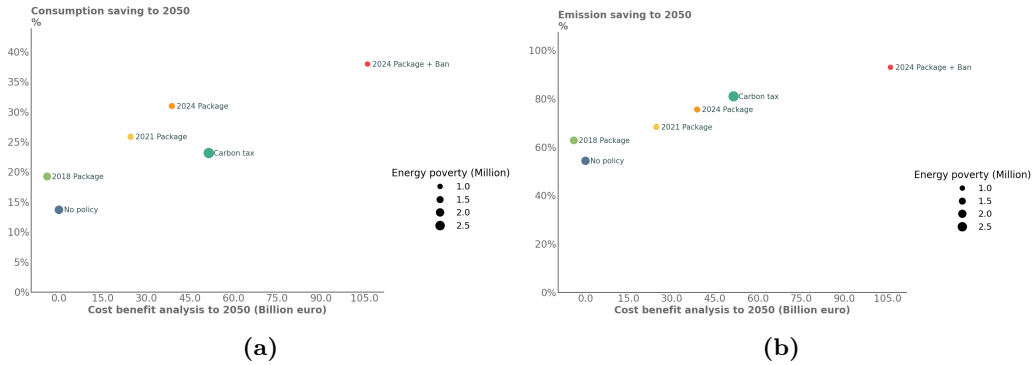
Using a data-driven approach based on comprehensive statistics on France’s residential sector, our study evaluates the distributional consequences of policy packages. Figure 6a reveals a significant decrease in energy poverty linked to the progressive introduction of policy packages targeting low-income. Under ‘2018 Package’, the number of energy-poor households stabilized at around 2 million. This figure dropped to 1.5 million under ‘2021 Package’ and ‘2024 Package’. However, none of these policy packages completely eradicated energy poverty, indicating the need for additional interventions, such as renovation or bill rebates. Despite the redistribution of tax revenues, the ‘Carbon Tax’ scenario fails to diminish fuel poverty. This underscores the imperative for mitigation policies to address not just GHG emissions but also the balance between emissions reduction and distributional impacts. Figure 6b provides a comparative analysis of total energy expenditures, including costs for insulation and heating system investments, after adjusting for subsidies to better represent actual household expenses in 2050. This analysis is carried out at the level of household groups, taking into account differences in housing type, occupancy status and income level. The model indicates that mandatory renovations, as introduced in the ‘2021 Package’, substantially lower the total household costs for tenants in privately-rented dwellings, with the most significant benefits observed among low-income households (around 20 to 25% of cost reduction). In addition, the ‘2024 Package’ reduces the total costs for low-income homeowners by 20% compared to the ‘No policy’ scenario and by 10% compared to the ‘2021 Package’. Remarkably, our model suggests that the implementation of a gas boiler ban could alleviate fuel poverty. This outcome arises from the dual benefits of heat pumps’ increased efficiency and the subsidies that make them more affordable, notwithstanding the higher cost of electricity compared to natural gas.



**Figure 6:** (a) Evolution of energy poverty, and (b) total energy cost on income ratio in 2050 compared to ‘No policy’ scenario by households group.

#### 4.1.4 Trade-offs

Figure 7a summarizes previous findings and illustrates the correlation between consumption savings, cost-benefit outcomes, and energy poverty projections for 2050. Graphically, our analysis shows that the successive implementation of policy packages leads to improvements across all indicators. Policy packages that are both ambitious and focused on the needs of low-income households and the worst-performing dwellings can lead to significant social and environmental gains. The implications for policy-makers are clear: the pursuit of robust climate policies can be synergistically aligned with social equity objectives. Finally, the counterfactual ‘Carbon tax’ scenario leads to significant emissions savings, while energy poverty increases compared to the ‘2024 package’, despite the implementation of lump-sum recycling. This finding reiterates the importance of not limiting GHG mitigation strategies in the residential sector to just the ‘Carbon Tax’ approach.



**Figure 7:** Trade-offs between consumption savings, cost-benefit outcomes, and energy poverty projections.

## 4.2 Assessment of stand-alone policies

In this section, we assess stand-alone policies within the ‘Package 2024’ in term of environmental and social effectiveness, cost-effectiveness and cost-benefit analysis. We group policies into five categories direct subsidies, white certificate obligations, zero-interest loan, carbon tax and mandatory renovation.

### 4.2.1 Comparative cost-benefit analysis of stand-alone policies

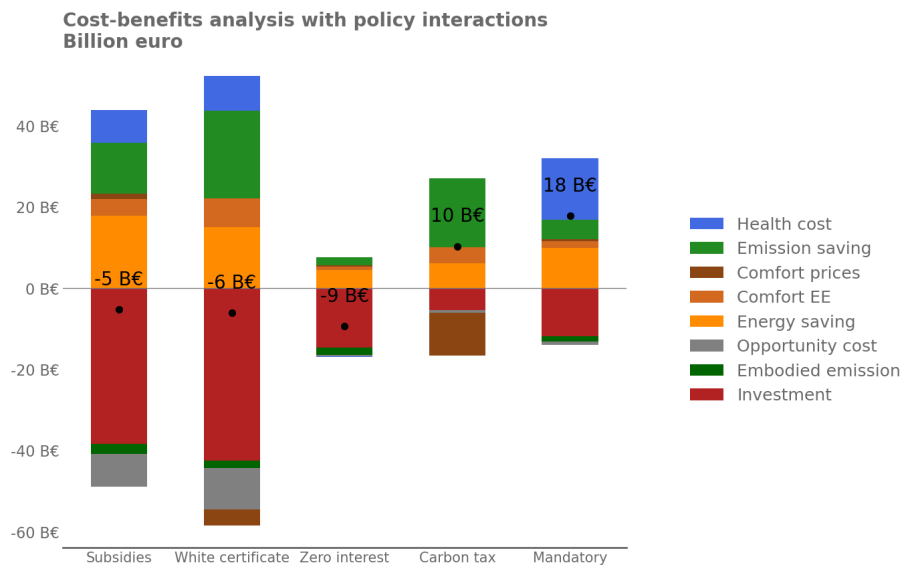
Table 4 shows the marginal impact of stand-alone policies within the current policy framework. This assessment involves a comparative analysis between the reference scenario, which includes all active policies, and a counterfactual scenario in which the policy in question is deactivated. This approach enables an assessment of the impact of the policy in interaction with other policies in play. A detailed assessment of each policy in isolation from the interaction with others can be found in the Appendix 6.5.3. Direct subsidies are shown to decrease energy consumption by 24 TWh and emissions by 2 MtCO<sub>2</sub> in 2050. White certificate obligations achieve similar reductions in consumption and emissions, with both scenarios lifting nearly half a million households out of energy poverty. Mandatory renovations, focused on privately-rented dwellings, reduce energy consumption by 10 TWh and assist 314,000 households in escaping energy poverty. This measure primarily involves insulation without heating system replacement, thus minimally impacting emission reduction. Conversely, the carbon tax, aimed at GHG emissions, leads to a 3 MtCO<sub>2</sub> emission reduction. However, despite lump-sum recycling, it exacerbates energy poverty by nearly 20%

in 2050, highlighting inequalities among low-income households depending on their heating sources.

Outcomes	DS	WCO	ZIL	MR	CT
Consumption saving (TWh)	-17	-12	-4	-10	-7
Consumption theoretical saving (TWh)	-24	-18	-5	-13	-5
Consumption theoretical saving (kWh/m <sup>2</sup> )	-7	-5	-2	-4	-1
Emission saving (MtCO <sub>2</sub> )	-2	-3	0	-1	-3
Cumulated emission saving (MtCO <sub>2</sub> )	-55	-98	-8	-13	-72
Energy poverty (Million)	-0.4	-0.4	0.0	-0.4	0.2
Investment heater (Billion euro)	8	31	-1	0	5
Subsidies heater (Billion euro)	25	56	0	0	4
Investment insulation (Billion euro)	52	40	29	21	4
Subsidies insulation (Billion euro)	41	34	6	9	1

**Table 4:** Marginal impact of stand-alone policies. DS stands for Direct Subsidies, WCO for White Certificate Obligations, ZIL for Zero-Interest Loan, MR for Mandatory Renovation, and CT for Carbon Tax.

Figure 8 presents a cost-benefit analysis of each policy relative to the counterfactual scenario. Both direct subsidies and white certificate obligations demonstrate that social benefits almost offset the additional investments. These measures particularly benefiting low-income households, notably reduce health costs. It underscores the importance of considering co-benefits in policy evaluation for energy efficiency investments. The 'Mandatory renovation' policy shows a clear favorable balance, with benefits surpassing investment costs, despite its modest contribution to GHG emission reductions. The focus on the worst-performing dwellings, predominantly occupied by low-income households, significantly mitigates energy poverty and enhances the cost-effectiveness of insulation measures. In contrast, the 'zero interest loan' available for all home insulation leads to a deterioration of the socio-economic balance. The 'Carbon tax', despite reducing thermal comfort, yields positive socio-economic outcomes. It significantly lowers GHG emissions by encouraging a shift to low-carbon fuels. In Appendix 6.5.3, we detail our assessment conducted without accounting for policy interactions. Interestingly, in this scenario, all policies demonstrates a more favorable net socio-economic impact. This can be attributed to the lower total subsidies selectively funding the most efficient energy-saving projects, and the increased marginal impact of mandatory renovations in reducing health costs without the support of other policies. Our findings underscore the importance of assessing policies in their specific context to avoid overestimating their impact.



**Figure 8:** Cost-benefit analysis of main policies of ‘Package 2024’.

### 4.2.2 Comparative cost-effectiveness of incentives policies

Figure 9 shows the evolution of cost-effectiveness (CE) of energy-efficiency incentives as part of the ‘2024 Package’. The CE of these policies is quantified as the ratio of policy cost in a given year to the cumulative discounted energy savings over their lifespan generate by the implementation of the policy.<sup>15</sup>

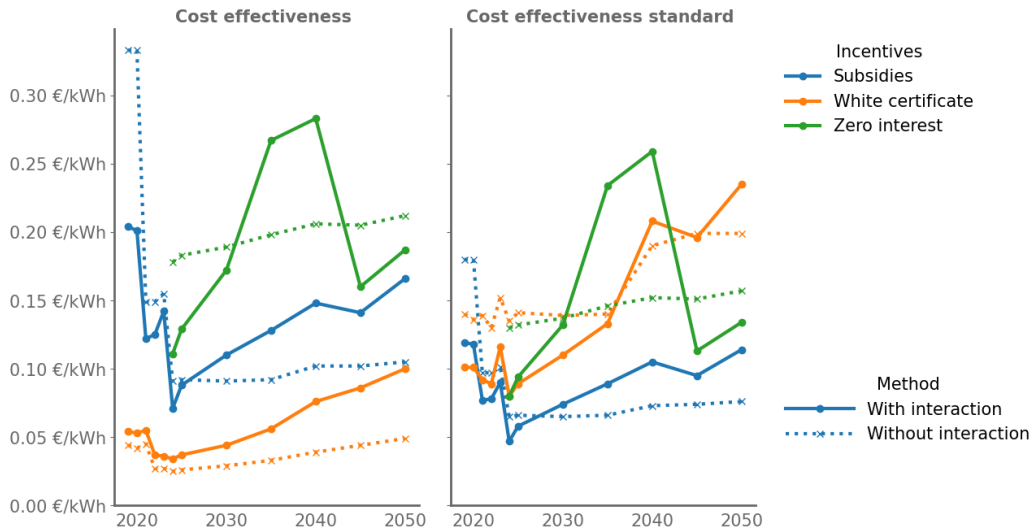
To assess marginal energy savings, we compare the reference scenario encompassing all policies to a counterfactual scenario lacking the specific policy under evaluation. This approach, termed ‘With interaction’, evaluates the policy among other policies in play. Conversely, the ‘Without interaction’ method isolates the policy’s effect by comparing a no-policy scenario against one with the exclusive addition of the targeted instrument. We find that the impact of a policy when combined with others can lead to either over-additive or under-additive effects. For instance, we observed that direct subsidies are less cost-effective when interacting with other policies before 2024, but this trend reverses after that year. A similar pattern is noted for white certificate obligations, where the shift occurs after 2045.

We also compute CE using theoretical rather than actual energy savings to distinctly segregate the subsidy impact from the rebound effect. When CE is estimated using energy savings predicted by engineering simulations, the figures for direct subsidies are almost divided by two. This discrepancy highlights the importance of incorporating realistic heating behaviors in building sector models to not overestimate the impact of energy efficiency policies. Regarding the white certificate obligations, the CE is notably higher when calculated using actual energy consumption. This increase is due to the policy’s energy tax component, which induces a reduction in energy consumption at no direct policy cost.

Specifically, the CE of direct subsidies fluctuates between €0.1/kWh and €0.2/kWh, influenced by yearly variations and subsidy specifications. Notably, CE of direct subsidies have recently declined, starting above €0.2/kWh in 2018 and subsequently improving to approximately €0.15/kWh following the 2021 introduction of ‘MPR’. The most recent reforms, encompassing new subsidy specifications and removal of ‘Reduced VTA’, further reduced CE to €0.1/kWh. These trends confirm that policymakers are increasingly focusing on cost-effective approaches, particularly by targeting low-income households. Targeted incentives alleviate financial constraints for low-income groups that mostly lived in the worst-performing buildings, thereby yielding profitable energy-saving projects. Similarly, incentives for deep renovation address previously unexploited potential due to their inherent high hidden costs, considered as non-monetary barrier in our model. In contrast, white certificate obligations, primarily subsidized individual measures, demonstrate a higher CE, ranging from 0.2 to 0.45 €/kWh. For both policy types, the gradual CE increase post-2025 can be attributed to the diminishing number of profitable projects following the renovation of the least efficient dwellings and the replacement of oil and gas boilers during the previous years. We further examine the CE of individual subsidies in Appendix 6.5.4.

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<sup>15</sup>We use the same discount rate of 3.2% and duration of 30 years as in the calculation of the cost-benefit analysis.



**Figure 9:** Evolution of cost-effectiveness of direct subsidies and white certificate obligations within the ‘Package 2024’.

## 5 Discussion

Our findings corroborate earlier analyses done in France. Giraudet et al. (2021) project that 2012 policy packages, and Charlier et al. (2018) for the 2014 policies, will not achieve emission reduction targets and only partially alleviate fuel poverty. Similarly, and despite recent improvements, we find that further policy measures are essential to fully reach environmental and social objectives. Our research, however, goes a step further by modeling these recent policy changes that required a framework fit to consider fine-tuning policy specifications (Pollitt et al., 2024). Ultimately, the conclusion stands: reaching carbon neutrality in the residential sector, although technologically feasible, is a challenging and expensive task. Our analysis, however, does not consider the impact of energy sufficiency measures or the gradual warming experienced during winter seasons. In terms of energy sufficiency, Gaspard et al. (2023) evaluate a decrease of 3 TWh in France attributable to reduced set-point temperatures, indicating that energy sufficiency plays a relatively minor role in space heating mitigation strategy. As for the impact of winter warming, this aspect represents a potential avenue for further research.

Our analysis also supports the extensive use of cost-benefit analysis in ex-ante assessment to provide guidance to policymakers in evaluating whether a program is socially desirable. We demonstrate that when accounting for health costs associated with living in the worst-performing dwellings and the valuation of GHG emissions, the benefits of ambitious policies generally surpass the costs. Our assessment, however, excludes non-monetary costs, for example arising from inconvenience to undertake renovation work or installation of a new heating system. As a result, the apparent cost-benefit advantages of regulatory actions that trigger non-voluntary actions, such as bans on inefficient rental housing and new natural-gas boilers, may be overstated.

Our study sheds light on the lack of comprehensive understanding regarding investment decisions, particularly with regard to hidden costs and non-monetary costs associated with home energy renovation. The quantification and better understanding of the dynamics hidden costs are essential, as they have a significant impact on the overall investment decision. Similar to Fowlie et al. (2015), our results show significant hidden costs, suggesting that pure profitability modeling approaches are insufficient for investments in energy renovation. Consequently, an important avenue for further



research would be to understand the hidden costs dynamics within the building life-cycle.

It should also be reminded that our analysis rests on partial equilibrium. In particular, we do not model the link between energy demand for space heating and the energy system. This limitation may result in inconsistencies between energy demand projections and the transformations they imply in the supply system. In a companion paper, we fill this gap by coupling Res-IRF 4.0 with EOLES, an optimization model of the French energy system (Escribe et al., 2023). Further research should also link retrofit demand with an explicit model of retrofit supply to examine how retrofit prices might react to a demand shock, as a retrofitting obligation can typically create.

## 6 Conclusion and Policy Implications

We introduce Res-IRF 4.0, a significantly enhanced version of a well-established building stock model. This new vintage drastically improves on technology detail behavioral processes. The resulting model is fit for fine-tuning policy specifications, thus generating valuable insights into the long-term impact of various policy mixes.

We illustrate the model functionalities by assessing France’s decarbonization strategy in the residential sector. We find that, despite significantly reducing GHG emissions and energy consumption, current policies fall short of achieving energy reduction and climate targets. In the current policy scenario, GHG emissions are reduced by 75% compared to the required 95% to reach carbon neutrality. More aggressive measures are therefore needed to simulate the adoption of low-carbon heating systems. In this study, we show that banning new natural-gas boilers could be a potential solution.

Our findings also highlight how successive implementation of mitigation policies have increased net socio-economic benefits. In particular, newly implemented instruments that direct subsidies toward low-income households and deep renovation outperform precedent attempts. Notably, recent modifications in subsidies specifications improve cost-effectiveness from €0.2/kWh in 2018 to just €0.1/kWh in the latest programs. Crucially, in addition to get closer to environmental targets these strategies alleviate energy poverty. Mandatory renovations in privately-rented dwellings substantially decrease health costs by overcoming the landlord-tenant dilemma. Similarly, a carbon tax effectively reduces GHG emissions by promoting a transition to low-carbon fuels. Our findings indicate that individually the implementation of these policies enhances social welfare. We conclude that a multifaceted approach is needed, combining a carbon tax, direct subsidies for low-income households and deep renovation and regulation.

Importantly, this study’s insights extend beyond France, offering valuable lessons for the EU. Particularly in light of discussions around mandatory renovations and gas boiler bans in the new Energy Performance Buildings Directives. We show that such policies, if well-crafted, could significantly contribute to the EU’s broader climate and energy goals while ensuring social fairness. In addition, with its code made fully open-source, our France-focused framework can be applied more broadly to assess national policy packages.

Important areas for further research include the quantification of hidden costs in energy renovation and a better understanding of household investment decisions, both found to critically influence policy effectiveness.

### Code availability

The code of Res-IRF 4.0 is open-source and can be freely accessed at URL/DOI: <https://zenodo.org/doi/10.5281/zenodo.10405491>.

## Data availability statement

The data that support the findings of this study are openly available on the GitHub pages. Simulation results are openly available at the following XX.

## CRedit authorship contribution statement

**Lucas Vivier:** Conceptualization, Methodology, Data curation, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Louis-Gaëtan Giraudet:** Conceptualization, Funding acquisition, Writing - review & editing

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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# Appendix

## 6.1 Previous development

Peer-reviewed publications	Approach	Main results
Giraudet et al., Energy Journal, 2011	Policy analysis	Policy portfolio considered (energy efficiency subsidies, carbon tax, building codes) does not permit attainment of sectoral energy saving targets
Giraudet et al., Energy Economics, 2012	Sensitivity analysis	Business as usual reduction in energy use of 37% to 2050, with an additional 21% if barriers to energy efficiency are removed
Mathy et al., Energy Policy, 2015	Policy analysis	Carbon dioxide emission reductions of 58% to 81% by 2050
Branger et al., Env. Mod. & Software, 2015	Sensitivity analysis	Monte Carlo simulations point to 13% overall uncertainty in model outputs. Morris method of elementary effects identifies energy prices as the most influential variable.
Giraudet et al., working paper, 2018	Policy analysis	Policy interactions imply a 10% variation in policy effectiveness
Glotin et al., Energy Economics, 2019	Backtesting	Model reproduces past energy consumption with an average percentage error of 1.5%. Analysis reveals inaccuracies in fuel switch due to off-model, politically-driven processes
Giraudet et al., Energy Policy, 2021	Policy analysis	Carbon tax is the most effective, yet most regressive, policy. Subsidy programmes save energy at a cost of €0.05–0.08/kWh
Bourgeois et al., Ecological Economics, 2021	Policy analysis	Subsidy recycling saves energy and increases comfort more cost-effectively than lump-sum
Vivier and Giraudet, ECEEE Proceedings, 2022	Policy analysis	A retrofitting obligation for French dwellings – A modelling assessment

**Table 5:** Previous development of Res-IRF.

## 6.2 Description of main policies

Instruments	Type, ‘Scenario’	Details
<b>Reduced VAT</b>	Reduced tax, ‘Package 2018’	VAT 5.5% instead of 10%. Reduced VAT is removed in 2024.
<b>Carbon tax</b>	Carbon tax, ‘Carbon tax’	Carbon tax have been freezed after 2018, and we kept the value constant towards 2050. We only consider the EU-ETS II in ‘2024 Package’. See Appendix 6.8.6 for further details.
<b>Carbon tax SVC</b>	Carbon tax, ‘Package 2018’	Carbon tax aligned with France’s social cost of carbon. Revenues are entirely and equally redistributed to households as energy bill rebates.
<b>CITE</b>	Direct subsidies, ‘Package 2018’	We assume 17% for all insulation costs (except windows) and heating-system (except oil boilers). We limit eligibility to single-family homes, as these account for 85% of subsidies distributed. Subsidy is capped at €4,800. Policy is stopped in 2021.
<b>MPR Serenite</b>	Direct subsidies, ‘Package 2018’	50% and 35% respectively for deep renovation (upgrade of two EPC) only for very low-income and low-income households. Stopped in 2024.
<b>MPR</b>	Direct subsidies, ‘Package 2021’	Amount per unit that depends on the income level. Several bonuses for improving energy performance to EPC B or moving out of the EPC G and F.
<b>MPR Multi-family</b>	Direct subsidies, ‘Package 2021’	25% ad valorem for renovation that save 35% of primary energy in multi-family buildings. Revised in 2024.
<b>MPR Efficacite</b>	Direct subsidies, ‘Package 2024’	Similar to MPR, but prohibited for F and G dwellings and dwelling that have not replaced their heating system.
<b>MPR Performance</b>	Direct subsidies, ‘Package 2024’	60% to 15% for deep renovation depending on households income.
<b>MPR Multi-family</b>	Direct subsidies, ‘Package 2024’	30% and 45% ad valorem subsidy for renovation that save respectively 35% and 50% of primary energy in multi-family buildings.
<b>CEE</b>	White certificate, ‘Package 2018’	The amount of the subsidies corresponds to the white certificate value times the cumulative discounted energy savings. Several bonuses were introduced in 2019. Specifically, a bonus of €4,000 for heat-pumps and wood boilers. This bonus ends as planned in 2026, but we are only extending it in the ‘2024 package’. The energy tax is based on the value of the white certificate times a specific coefficient. We keep the value of the white certificate constant over the time horizon.
<b>Subsidies cap</b>	Subsidies cap, ‘Package 2018’	Cap the total amount of subsidies for each households. Cap depends on the income level and have increased in the ‘2024 package’.
<b>EPTZ</b>	Soft loan, ‘Package 2024’	Zero-interest loan for a maximum loan of €15,000 starting in 2024.
<b>Obligation</b>	Regulation, ‘Package 2021’	Mandatory retrofitting obligation for privately rented buildings if EPC falls below the minimum standard. Minimum standard evolve toward more efficient building following a agenda. We model retrofitting obligation only when a new lease occurs with a rotation rate of 10%.
<b>Oil-fuel ban</b>	Regulation, ‘Package 2018’	Ban to purchase new oil boiler after 2018.
<b>Gas ban</b>	Regulation, ‘Package 2024 + Ban’	Ban to purchase new gas boiler after 2030.

**Table 6:** Description of the main policies implemented in France. Policy packages are a mix of these instruments.

### 6.3 Numerical results

Outcomes in 2030	NP	2018	2021	2024	2024 + Ban	CT
Stock (Million)	32	32	32	32	32	32
Surface (Million m <sup>2</sup> )	2,730	2,730	2,730	2,730	2,730	2,730
Consumption (TWh)	285	273	263	257	256	265
Consumption (kWh/m <sup>2</sup> )	104	100	96	94	94	97
Consumption Electricity (TWh)	43	42	42	41	43	48
Consumption Natural gas (TWh)	136	121	112	106	102	102
Consumption Oil fuel (TWh)	14	13	12	11	11	12
Consumption Wood fuel (TWh)	74	79	80	81	82	85
Consumption Heating (TWh)	18	18	18	18	18	18
Energy poverty (Million)	3	3	3	3	3	4
Emission (MtCO <sub>2</sub> )	43	39	37	35	34	35
Stock G (Million)	1	1	1	1	1	1
Stock F (Million)	3	3	2	2	2	3
Stock E (Million)	5	4	4	4	4	5
Stock D (Million)	10	10	10	9	9	10
Stock C (Million)	7	8	9	9	9	8
Stock B (Million)	2	2	2	3	3	2
Stock A (Million)	4	4	4	4	4	4
Heat-pump (Million)	5	6	6	6	7	6
Direct electric (Million)	8	8	8	7	8	9
Gas boilers (Million)	12	12	11	11	11	11
Oil boilers (Million)	1	1	1	1	1	1
Wood boilers (Million)	2	3	3	3	3	3
District heating (Million)	2	2	2	2	2	2
Carbon value (Billion euro)	11	10	9	9	9	9
Health cost (Billion euro)	5	5	4	4	4	6
Energy expenditures (Billion euro)	29	29	28	28	28	33
Cumulated Emission (MtCO <sub>2</sub> )	1,298	1,183	1,104	1,041	893	1,008
Renovation (Thousand households)	11,809	15,465	17,461	18,635	18,261	12,280
Investment insulation (Billion euro)	101	160	195	232	229	110
Subsidies insulation (Billion euro)	1	36	50	67	66	1
Investment heater (Billion euro)	287	294	302	329	350	302
Subsidies heater (Billion euro)	1	35	31	71	91	1
Renovation (Thousand households/year)	908	1,190	1,343	1,433	1,405	945
Investment insulation (Billion euro/year)	8	12	15	18	18	8
Subsidies insulation (Billion euro/year)	0	3	4	5	5	0
Investment heater (Billion euro/year)	22	23	23	25	27	23
Subsidies heater (Billion euro/year)	0	3	2	5	7	0
Consumption saving (%)	4%	8%	12%	14%	14%	11%
Emission saving (%)	15%	22%	27%	30%	32%	30%
Energy poverty reduction (%)	24%	19%	25%	27%	27%	-9%

**Table 7:** Simulation results in 2030 for all policy scenarios. NP stands for ‘No Policy’, 2018 for ‘2018 Package’, 2021 for ‘2021 Package’, 2024 for ‘2024 Package’, 2024 + Ban for ‘2024 Package + Ban’ and CT for ‘Carbon Tax’.



<b>Outcomes in 2050</b>	<b>NP</b>	<b>2018</b>	<b>2021</b>	<b>2024</b>	<b>2024 + Ban</b>	<b>CT</b>
Stock (Million)	40	40	40	40	40	40
Surface (Million m <sup>2</sup> )	3,520	3,526	3,513	3,515	3,514	3,520
Consumption (TWh)	257	241	221	206	185	229
Consumption (kWh/m <sup>2</sup> )	73	68	63	58	53	65
Consumption Electricity (TWh)	51	49	49	49	65	63
Consumption Natural gas (TWh)	101	82	71	55	3	39
Consumption Oil fuel (TWh)	0	0	0	0	0	0
Consumption Wood fuel (TWh)	78	84	77	78	93	100
Consumption Heating (TWh)	27	26	25	23	23	27
Energy poverty (Million)	2	2	1	1	1	3
Emission (MtCO <sub>2</sub> )	23	19	16	12	3.6	10
Stock G (Million)	0	0	0	0	0	1
Stock F (Million)	2	1	1	0	0	2
Stock E (Million)	3	2	1	1	1	2
Stock D (Million)	9	8	8	7	5	8
Stock C (Million)	9	10	11	12	11	10
Stock B (Million)	4	5	6	7	8	5
Stock A (Million)	13	13	13	13	14	13
Heat-pump (Million)	15	15	16	17	21	16
Direct electric (Million)	7	6	6	5	7	8
Gas boilers (Million)	10	9	9	8	1	6
Oil boilers (Million)						
Wood boilers (Million)	4	5	5	6	7	5
District heating (Million)	4	4	4	4	4	4
Carbon value (Billion euro)	18	15	12	10	3	7
Health cost (Billion euro)	3	3	1	1	1	4
Energy expenditures (Billion euro)	33	32	30	29	27	36
Cumulated Emission (MtCO <sub>2</sub> )	1,298	1,183	1,104	1,041	893	1,008
Renovation (Thousand households)	11,809	15,465	17,461	18,635	18,261	12,280
Investment insulation (Billion euro)	101	160	195	232	229	110
Subsidies insulation (Billion euro)	1	36	50	67	66	1
Investment heater (Billion euro)	287	294	302	329	350	302
Subsidies heater (Billion euro)	1	35	31	71	91	1
Renovation (Thousand households/year)	358	469	529	565	553	372
Investment insulation (Billion euro/year)	3	5	6	7	7	3
Subsidies insulation (Billion euro/year)	0	1	2	2	2	0
Investment heater (Billion euro/year)	9	9	9	10	11	9
Subsidies heater (Billion euro/year)	0	1	1	2	3	0
Consumption saving (%)	14%	19%	26%	31%	38%	23%
Emission saving (%)	54%	63%	68%	75%	93%	81%
Energy poverty reduction (%)	41%	48%	64%	66%	72%	17%

**Table 8:** Simulation results in **2050** for all policy scenarios. NP stands for ‘No Policy’, 2018 for ‘2018 Package’, 2021 for ‘2021 Package’, 2024 for ‘2024 Package’, 2024 + Ban for ‘2024 Package + Ban’ and CT for ‘Carbon Tax’

## 6.4 Sensitivity analysis

Table 9 illustrates the variation on energy consumption, emissions and energy poverty in 2050 when varying main inputs of the model. In particular, household income growth rates significantly impacts energy poverty levels. Lower income growth exacerbates fuel poverty, while higher growth alleviates it. Similarly, changes in energy prices also play a decisive role. Higher energy prices lead to a decrease in consumption and emissions, but also escalate energy poverty. The emission content of electricity is key; constant emission rates significantly increase overall CO<sub>2</sub> emissions. The availability of renewable gas and the extent to which district heating is used also prove to be influential factors affecting greenhouse gas emissions. Fluctuations in the turnover rate of existing buildings, the use of heat pumps in new buildings and the proportion of buildings that cannot be renovated have a notable impact, particularly on emissions and energy poverty. Cost reductions in heat pumps and insulation are powerful levers affecting both emissions. Finally, financing costs and the price elasticity of heat pumps are identified as crucial elements that mainly affect energy consumption. Overall, the results reveal expected variations, confirming the operational capability of the model.

Parameters	Consumption (TWh)	Emission (MtCO <sub>2</sub> )	Poverty (Million)
<b>2024 Package</b>	<b>206</b>	<b>12</b>	<b>1.2</b>
<b>Income rate</b> (ref = 1.2%)			
low: 0%	195	11	2.2
high: 2%	222	14	0.2
<b>Energy prices annual growth rate</b>			
low: -20%	210	13	1.1
medium: +20%	201	12	1.3
high: +50%	194	11	1.7
<b>Emission content</b> (ref = 0 by 2050)			
constant emission content electricity	206	16	1.2
<b>Renewable gas</b> (ref = 14 TWh by 2050)			
low: 0 TWh	206	16	1.2
high: 25 TWh by 2050 (S3)	206	10	1.2
<b>District heating</b> (ref = 5 M (S2))			
low: 3.5 M dwellings (S1)	203	13	1.2
high: 8 M dwellings (S3)	210	11	1.1
<b>Stock turnover</b> (scenario TEND)			
low: 0.15% demolition rate by 2050 (S1)	204	12	1.4
high: 0.6% demolition rate by 2050 (S3)	188	11	0.7
<b>Heat-pumps in construction</b>			
low: S1	213	13	1.2
high: S4	199	12	1.2
<b>Share of buildings that cannot make renovation</b>			
medium: 5%	211	13	1.3
high: 10%	216	15	1.5
<b>Reduction cost heat-pumps</b> (ref = -20% by 2035)			
low: no cost reduction	206	12	1.2
high: -50% by 2035	199	11	1.1
<b>Reduction cost insulation</b> (ref = 0%)			
high: -30%	195	12	0.8
<b>Financing cost</b>			
low: interest: 2.5%/year, saving: 1%/year	202	12	1.0
high: interest: 10%/year, saving: 5%/year	213	13	1.4
<b>Price-elasticity heat-pumps</b>			
low: -0.8	208	13	1.3
high: -1.2	202	11	1.1

**Table 9:** Sensitivity analysis of the most important inputs in 2050. Consumption in TWh, GHG emission in MtCO<sub>2</sub>, energy poverty in millions of households and cumulated investments in billions of euros. The scenarios ‘Tend’, ‘S1’, ‘S2’, ‘S3’ and ‘S4’ are taken from the official French transition scenarios (ADEME, 2022). Details on the input can be found in the GitHub repository.

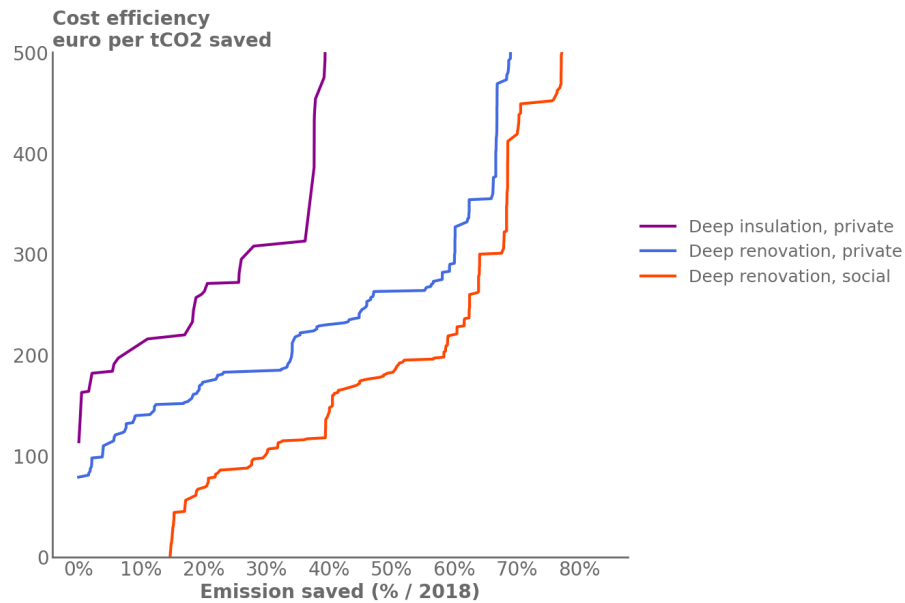
## 6.5 Additional results

### 6.5.1 Calibration results

Housing type	Occupancy status	Hidden cost	Landlord-tenant dilemma	Multi-family friction
Single-family	Owner-occupied	-67,132		
Single-family	Privately rented	-67,132	-20,639	
Single-family	Social-housing	-82,338		
Multi-family	Owner-occupied	-67,132		-15,691
Multi-family	Privately rented	-67,132	-19,506	-15,691
Multi-family	Social-housing	-82,338		-3,522

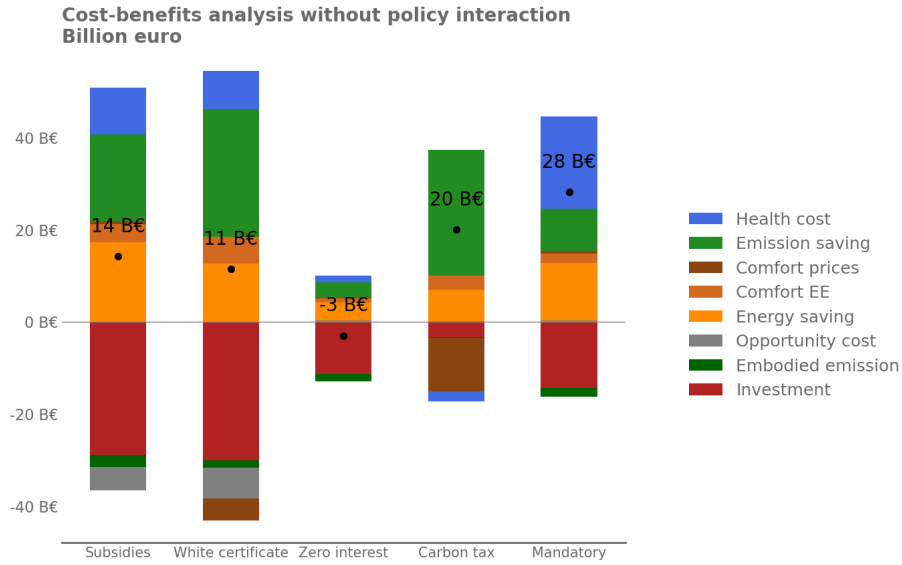
**Table 10:** Calibration results. Hidden cost found to align with observed renovation rate. All values are in euros.

### 6.5.2 Abatement curve of carbon



**Figure 10:** Abatement curve residential stock.

### 6.5.3 Comparative cost-benefit analysis of stand-alone policies without interaction



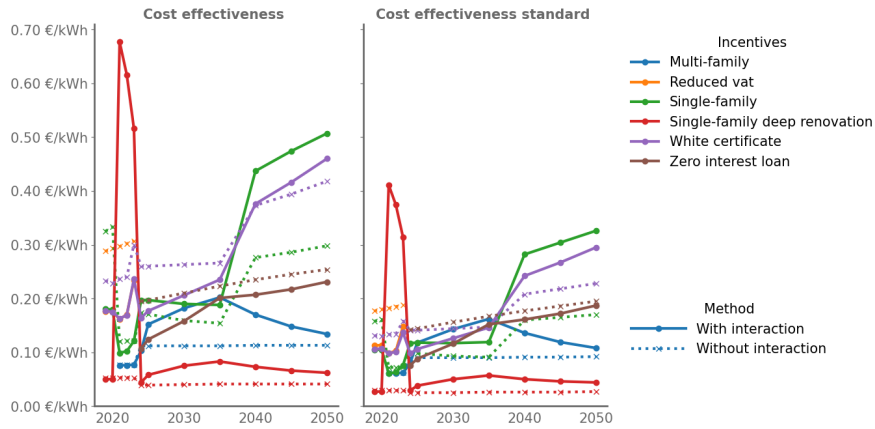
**Figure 11:** Cost-benefit analysis of main policies of ‘Package 2024’ without policy interactions. We compare a no-policy scenario against one with the exclusive addition of the targeted instrument.

Outcomes	DS	WCO	ZIL	MR	CT
Consumption saving (TWh)	-18	-11	-4	-12	-10
Consumption theoretical saving (TWh)	-24	-14	-6	-17	-6
Consumption theoretical saving (kWh/m <sup>2</sup> )	-7	-4	-2	-5	-2
Emission saving (MtCO <sub>2</sub> )	-3	-4	0	-1	-4
Cumulated emission saving (MtCO <sub>2</sub> )	-55	-97	-9	-20	-88
Energy poverty (Million)	-0.4	-0.2	0.0	-0.4	0.4
Investment heater (Billion euro)	6	28	0	0	4
Subsidies heater (Billion euro)	14	42	0	0	0
Investment insulation (Billion euro)	42	25	23	27	2
Subsidies insulation (Billion euro)	28	19	0	0	0
Performance gap	73%	77%	74%	71%	

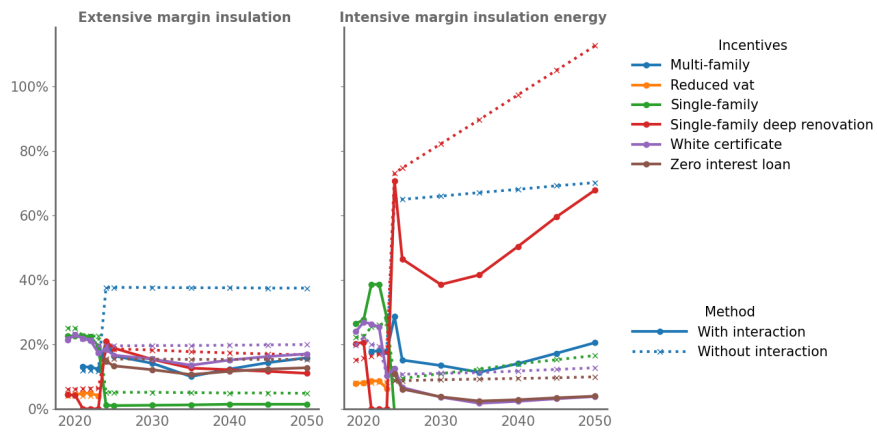
**Table 11:** Marginal impact of stand-alone policies. DS stands for Direct Subsidies, WCO for White Certificate Obligations, ZIL for Zero-Interest Loan, MR for Mandatory Renovation, and CT for Carbon Tax.

### 6.5.4 Evolution of cost-effectiveness of individual incentives

This section details the individual cost-effectiveness of each incentive under the ‘Direct subsidies’ category, as outlined in Section 4.2.2. We apply the same methodological approach to evaluate the effectiveness of these incentives, both in isolation and in interaction with other policies. To isolate the effects of the policy, we run the simulation with constant income and energy prices over time. The subsidies are categorized by their target: multi-family households, single-family households, and a combined category for single-family households undergoing deep renovation. Figure 13 illustrates the varying cost-effectiveness of these incentives within the ‘Package 2024’, ranging from €0.05/kWh to €0.7/kWh, highlighting significant disparity in effectiveness among the different incentives. Specifically, subsidies aimed at single-family homes, either for individual measures or deep renovations, show a strong anti-correlation in cost-effectiveness due to their non-cumulative nature. The 2021 reform significantly enhances the effectiveness of subsidies for individual measures, adversely affecting the deep renovation subsidy. Conversely, the 2024 reform reversed this effect, greatly improving the cost-effectiveness of deep renovations. An analysis excluding policy interactions confirms that focusing on deep renovations enhances subsidy effectiveness. The 2024 ‘Multi-family’ reform, despite targeting more comprehensive renovations, deteriorates cost-effectiveness. This is due to the increase in subsidy amounts, which lead to more but less profitable energy-efficient projects. The ‘Reduced VAT’ measure demonstrates lower cost-effectiveness relative to other direct subsidies, justifying the rationale to reallocate its funds to more effective policies.

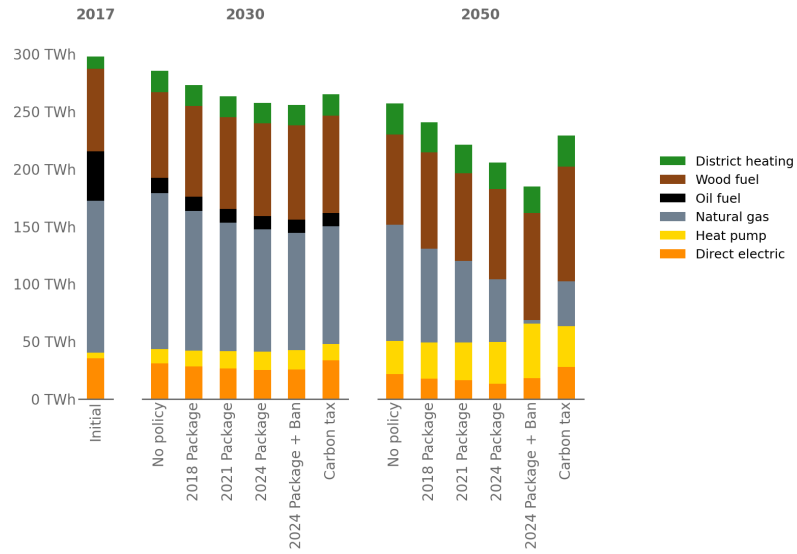


**Figure 12:** Cost-effectiveness of incentives policies in ‘Package 2024’.

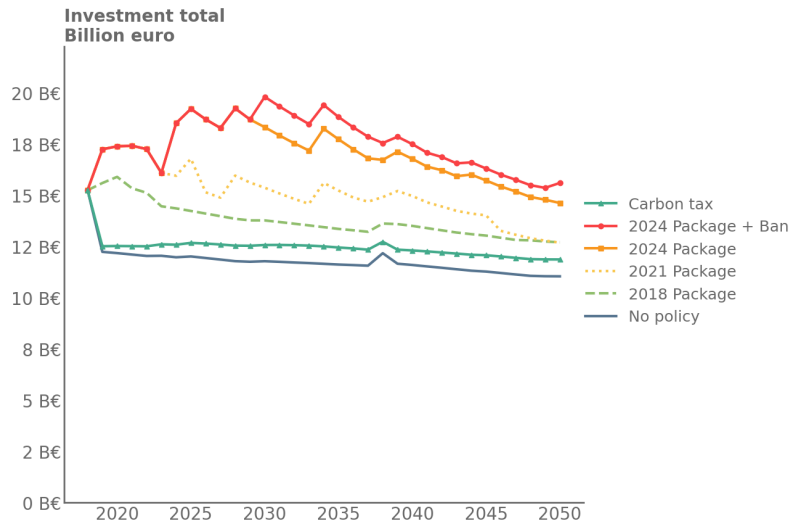


**Figure 13:** Extensive and intensive margin of incentives policies in ‘Package 2024’.

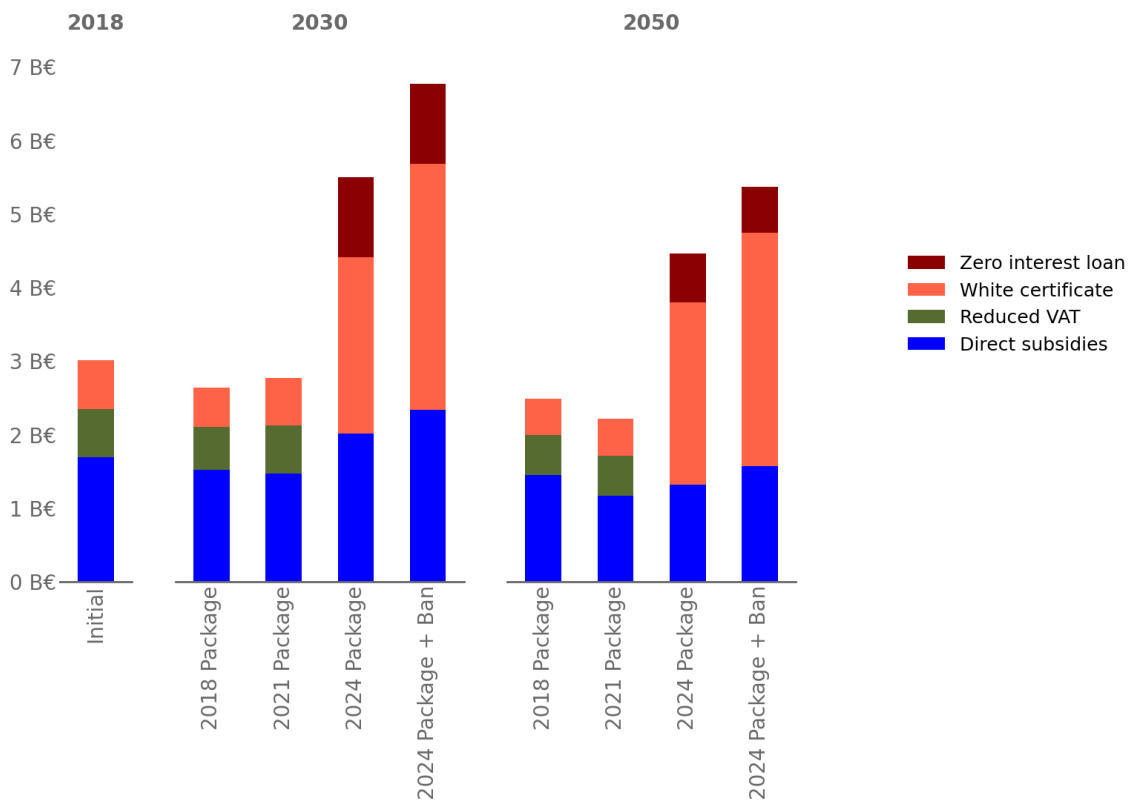
### 6.5.5 Additional figures



**Figure 14:** Evolution of residential space heating consumption in France.



**Figure 15:** Evolution of total investment in home renovation and heating system in France.



**Figure 16:** Policy cost. To simplify the figure we aggregate all subsidies under the name ‘Direct subsidies’. The calculation of the public cost of the zero-interest loan is based on an interest rate of 1.5% paid by the authorities to the bank (Eryzhenskiy et al., 2023).



## Supplementary materials

### 6.6 Best practise description

Subtopic	Res-IRF
<b>Overview</b>	
Aim and scope	The main objective is to develop forward-looking scenarios for the energy performance of the French building stock, focusing on the assessment of climate change mitigation measures in the residential sector. The aim is to understand and forecast how different energy efficiency and decarbonization strategies can impact energy consumption, greenhouse gas emissions and fuel poverty in France's residential buildings.
Modelling approach	The model uses a bottom-up approach anchored in a detailed representation of the French housing stock. It consists of three core components: A thermal-behavioral module calculates the energy consumption of the building stock at the household level. It takes into account detailed thermal characteristics and behavioral patterns of households to estimate the energy demand for heating. A stock transformation model that takes into account the natural evolution of the building stock over time, including factors such as demolition and new construction. It updates the composition of the building stock taking into account changes in building characteristics and numbers. A decision model module simulates households' decisions regarding energy renovations and the choice of heating system. It captures how households respond to various factors, including policy incentives, energy prices and technological advances, which influence their decisions on energy efficiency improvements and heating upgrades.
System boundary	The model is specifically tailored to the analysis of space heating in the residential sector in France. It examines the dynamics of energy consumption, efficiency improvements and the conversion of heating systems in residential buildings, focusing on the space heating aspects. The model projects all results up to 2050, a long-term time horizon that allows a comprehensive assessment of the impact of different policy measures and technological changes on energy efficiency and GHG emissions in the residential sector over a longer period.
Spatio-temporal resolution	The model was developed to calculate annual space heating consumption at the level of individual buildings. The results are usually given in the form of energy consumption broken down by different heating fuels. This granularity allows a detailed analysis of how the different types of heating systems (such as gas, electricity, wood, etc.) contribute to the total energy consumption for space heating in residential buildings.
<b>Model components</b>	
Building stock	The building stock is represented with the following attributes: housing type (single or multi family), thermal transmittance of wall, roof, floor and windows, heating system (gas, oil and wood boiler, direct-electric and heat-pump), occupancy status (privately owned, rented or social housing) and income of the owner and tenant.
People	Occupants are described by their occupation status and their income. Households attribute influence the heating and the energy-efficiency investment decision behavior.
Environment	The model primarily uses heating degree days (HDD) as a measure of the climatic conditions that are important for estimating heating demand. The economic context is included through an exogenous assumption about income growth. This allows the model to take into account the potential impact of economic changes on energy consumption and household investment decisions. The model explicitly represents the influence of different policy measures on household investment decisions. This includes how different energy efficiency incentives and regulatory measures affect decisions to renovate and upgrade heating systems. The model does not take into account spatial or geographical differences within France. It provides an analysis at the national level without distinguishing between different regions or local climate variations.
Energy	Energy consumption is determined at household level using a two-stage method. First, the theoretical energy consumption is calculated on the basis of the structural and thermal characteristics of the dwelling. The EN ISO 13790 standards are followed and the simple but detailed TABULA method is used. Then we take into account the heating intensity of the households, which depends crucially on their income. Greenhouse gas emissions are estimated based on actual energy consumption and assessed using the exogenous carbon content of heating energy.
Costs	The model evaluates the capital costs of the energy renovation and the heating system. The cost of the energy retrofit is the sum of the cost of insulating each component of the building envelope. The energy expenditure is calculated by multiplying the energy consumption by the energy prices.
Dynamics	The evolution of the building stock takes into account the demolition of the least energy-efficient buildings at a constant annual rate and the construction of new buildings. The evolution of the energy performance of the buildings is determined endogenously by the agents' decision to renovate or not.

**Table 12:** Description of the model following Nägeli et al. (2022)

Subtopic	Res-IRF
<b>Input and output</b>	
Data sources	The model uses building stock libraries to provide a detailed description of the French building stock in the base years. These libraries provide a detailed and accurate representation of the different types of dwellings, their thermal characteristics and heating systems. The investment decision component of the model is underpinned by data from household renovation surveys, which provide real insights into renovation behavior and trends. In addition, the model integrates findings from the economic literature, in particular discrete choice experiments and causal inference analysis.
Data processing	The housing stock in the model is constructed by integrating two primary data sources: the database of energy performance certificates, which provides a broad overview of the energy characteristics of different dwellings, and a detailed description of housing archetypes, which provides additional depth and specificity. In addition, the model relies on national survey data and records of the number of beneficiaries of energy efficiency measures to estimate retrofit numbers in order to provide a realistic picture of retrofit activity in the residential sector.
Key assumptions	Rule of thumb were used to estimate the number of retrofits (used in the calibration) for multifamily buildings based on a national survey of single-family housing stock.
Scenario	All parameters can be changed to describe a scenario. Scenarios are usually described by their packages of measures.
Output parameters	The model outputs include energy consumption and Scope 2 emissions for space heating and tracks the development of the energy efficiency of the housing stock. It also quantifies the number of retrofitted dwellings and the total investment costs. In addition, the model facilitates the cost-benefit analysis of specific policy packages by assessing the impact of these measures on distribution. The results are broken down by various attributes and aggregated at a national level, with all results formatted as CSV files for ease of use and analysis.
<b>Quality assurance</b>	
Calibration	The energy consumption was calibrated to the national data for heating energy from 2018. Renovation rates and market shares for insulation and heating systems were adjusted to existing data based on household renovation surveys.
Validation	First, we check the consistency of renovation costs and energy savings with the established literature using the marginal abatement curve. Next, we evaluate and compare the actual and simulated public sector costs. Finally, we examine the cost-effectiveness and scope of subsidy programs and compare them with econometric studies.
Limitations	The model focuses exclusively on space heating and excludes other uses such as cooling. Due to computational limitations, the analysis is limited to fewer combinations and technologies (only one boiler efficiency type). Several factors influencing renovation, such as risk aversion, environmental preferences and others, are not considered due to quantification issues and problems in matching the attributes of the model. The impact on other sectors such as energy systems, industrial bottlenecks and real estate markets is also not considered.
Uncertainty	We assess uncertainty in the key variables by examining space heating consumption or emissions under different assumptions. This includes testing the results using different values for factors such as the share of single-family homes in new buildings, district heating connections and the availability of renewable gas, to name a few.
Sensitivity	In a previous version, the model was subjected to a global sensitivity analysis using the Morris method (Branger et al., 2015), which showed a remarkable sensitivity to calibration parameters. In the current version, we evaluate the model's response to energy price fluctuations by estimating the long-term energy price elasticity. In addition, a scenario analysis was performed to further assess the sensitivity of the model under different potential future conditions.
<b>Additional information</b>	
The model was developed in Python 3.8 and primarily uses the Pandas library for data collection, cleansing and processing, leveraging its robust features for efficient handling and analysis of large data sets.	
Ecole National des Ponts et Chaussées (ENPC). GPL License.	
Currently financed by ANR Premoclasse.	
Applied for policies evaluation in the residential sector in France.	
Documentation online: <a href="https://cired.github.io/Res-IRF/">https://cired.github.io/Res-IRF/</a> + (Giraudet et al., 2021)	

**Table 13:** Description of the model following Nægeli et al. (2022).

## 6.7 Calculating energy consumption

### 6.7.1 Theoretical space heating energy consumption

Res-IRF calculates the yearly space heating energy consumption for distinct dwelling types. The cumulative energy demand is ascertained by aggregating the final consumption figures for various building archetypes. The estimation of annual space heating requirements is accomplished through the utilization of the seasonal method, adhering to the guidelines outlined in EN ISO 13790 (Loga, 2013). Our approach shares similarities with the TABULA calculation methodology, encompassing a realistic representation of pertinent parameters that exert influence over a building's energy consumption, while striving to maintain methodological simplicity. The seasonal method relies on archetype-specific attributes, such as the dwelling's structural characteristics, thermal properties of the building envelope (comprising wall, roof, floor, and window u-values), and the heating system's efficiency. In the event of unavailability, standardized values are employed as substitutes. The assessment of envelope component loss areas relies on an average geometry. This modeling approach effectively mitigates energy consumption discrepancies among individual dwellings within the building stock such as excluding large window areas. Nevertheless, it adequately captures the substantial heterogeneity of energy consumption ranging from G (least efficient) to A (most efficient), thereby enabling a comprehensive evaluation of potential energy-saving prospects.

The detailed calculation can be found in the TABULA project documentation (Loga, 2013). In a nutshell, the energy needed for heating is the difference between the heat losses and the heat gain. The total heat losses result from heat transfer by transmission and ventilation during the heating season respectively proportional to the heat transfer coefficient  $H_{tr}$ , and  $H_{ve}$ . The total heat losses,  $Q_{ht}$ , is equal to:

$$Q_{ht} = Q_{ht,tr} + Q_{ht,ve} = 0.024 \times (H_{tr} + H_{ve}) \times F_{nu} \times (T_{int} - T_e) \times d_{hs}$$

$F_{nu}$  is the dimensionless correction factor for non-uniform heating,  $T_{int}$  is the internal temperature [°C],  $T_e$  is the average external temperature during the heating season [°C] and  $d_{hs}$  is the length of the heating season expressed in days.

The equations for the heat transfer coefficient  $H_{tr}$  and  $H_{ve}$  are explained below:

$$H_{tr} = \sum_i A_{env,i} \times U_i \times b_{tr,i} + \sum_i A_{env,i} \times U_{tbr}$$

$b_{tr,i}$  is the adjustment factor soil equal to 0.5 for the floor to account for the higher outdoor temperature of the soil,  $A_{env,i}$  is the area of the envelope element  $i$  [m<sup>2</sup>],  $U_i$  is the U-value of the envelope element  $i$  [W/(m<sup>2</sup>.K)], and  $U_{tbr}$  is the surcharge on all U-values, taking into account the additional losses caused by thermal bridging [W/(m<sup>2</sup>.K)].

$$H_{ve} = cp_{air} \times (n_{air,use} + n_{air,infiltr}) \times A \times h_{room}$$

$cp_{air}$  is the volume-specific heat capacity of air in Wh/(m<sup>3</sup>.K),  $n_{air,use}$  is the average air change rate during the heating season, related to the utilization of the building in 1/h,  $n_{air,infiltr}$  is the air change rate by infiltration in 1/h,  $A$  is the area of the building in m<sup>2</sup>,  $h_{room}$  is the room height in m.

The energy consumption is then estimated by dividing total heat losses,  $Q_{ht}$  by the efficiency of the heating system. Efficiency of the heating system refers to the product of distribution, storage and production efficiency.

### 6.7.2 Energy performance certificate

Our objective is to devise a methodology for determining the Energy Performance Certificate (EPC) by leveraging observed dwelling characteristics, which in turn facilitates

the implementation of targeted measures. Notably, the retrofitting obligation follows an incremental agenda based on the EPC. The French calculation method, known as the 3CL method, is utilized to ascertain theoretical energy consumption specifically for space heating. This method draws directly from the guidelines outlined in EN ISO 13790. A study conducted by Pouget Consultant identified a favorable correspondence between the TABULA calculation and the 3CL method, enabling the estimation of a conversion coefficient to translate results from one method to the other (Arquin et al., 2020).<sup>16</sup> The current version of our model does not consider energy usage for cooling purposes, while the estimation of water heating is based on default requirements and the heating system’s efficiency. All parameters not directly observed have been obtained from the TABULA project documentation or default values derived from the 3CL method, and are meticulously outlined in the provided reference spreadsheet.

### 6.7.3 Actual space heating energy consumption

The heating behavior function remains close from Res-IRF 3.0 (Giraudet et al., 2021). The actual energy consumption for space heating differs from the theoretical energy consumption calculated by method 3CL. This is mainly due to the default assumption used in the method. In the model, we consider heterogeneous heating behavior that depends on the income of the tenant. We use an empirical estimation performed by Cayla et al. (2013):

$$\text{Heating intensity} = 0.3564 \times \text{Budget share}^{-0.244}$$

Here, the income share is the energy expenditure - the energy price times the theoretical energy consumption of the dwelling (as indicated in the EPC label) - divided by the income of the occupant.<sup>17</sup> Heating intensity is an indicator of thermal comfort in the dwelling. This leads to a price elasticity of energy demand of 0.23 in the short term and a direct rebound effect of 20% - in line with the recent Douenne, 2020 results for France.

### 6.7.4 Calibration at the aggregated level

The total energy consumption across different energy sources is calibrated in accordance with observed data, taking into account corrected weather data (CEREN). Our findings indicate that we possess reliable estimates for natural gas and oil energy consumption, albeit with an overestimation in electricity consumption and an underestimation in wood fuel energy consumption. This discrepancy primarily arises from our decision to record only the primary heating energy source in each dwelling, thereby neglecting the presence of secondary wood boilers in certain dwellings.

To align the modeled energy consumption with the observed data, we employ a two-step calibration process. Firstly, we apply an aggregated coefficient factor denoted as:

$$C_{global} = \frac{\text{Modeled consumption}}{\text{CEREN consumption}}$$

This factor facilitates the adjustment of the modeled consumption figures. Secondly, we determine an allocation coefficient that allocates a portion of the aggregate

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<sup>16</sup>Notably, modifications were made to the energy certificate calculation methods in July 2021, subsequently corrected in October 2021. Prior to these revisions, the certificate was primarily based on the primary energy consumption associated with three usage categories in dwellings: heating, cooling, and water heating. However, as of 2021, the revised approach incorporates five usage categories (with the inclusion of lighting and auxiliary equipment) and employs a classification system based on both primary energy consumption and greenhouse gas emissions.

<sup>17</sup>We note that energy consumption depends on household income and cannot be represented by the outcome of an agent maximising a quasi-linear utility.

consumption for each energy source to wood fuel, thereby aligning it with the observed data. This coefficient implicitly captures the consumption associated with a secondary wood boiler. Specifically, for example:

$$\text{Consumption}_{DirectElectric} = C_{DirectElectric} \times \overline{\text{Consumption}_{DirectElectric}}$$

$$\text{Consumption}_{WoodFuel,DirectElectric} = (1 - C_{DirectElectric}) \times \overline{\text{Consumption}_{DirectElectric}}$$

Here,  $\overline{\text{Consumption}_{DirectElectric}}$  represents the consumption before calibration,  $\text{Consumption}_{DirectElectric}$  signifies the consumption after calibration, and  $\text{Consumption}_{WoodFuel,DirectElectric}$  corresponds to the additional wood fuel consumption resulting from the allocation process.

It is worth noting that we do not consider an implicit secondary wood heating system for dwellings heated with a heat pump.

## 6.8 Data

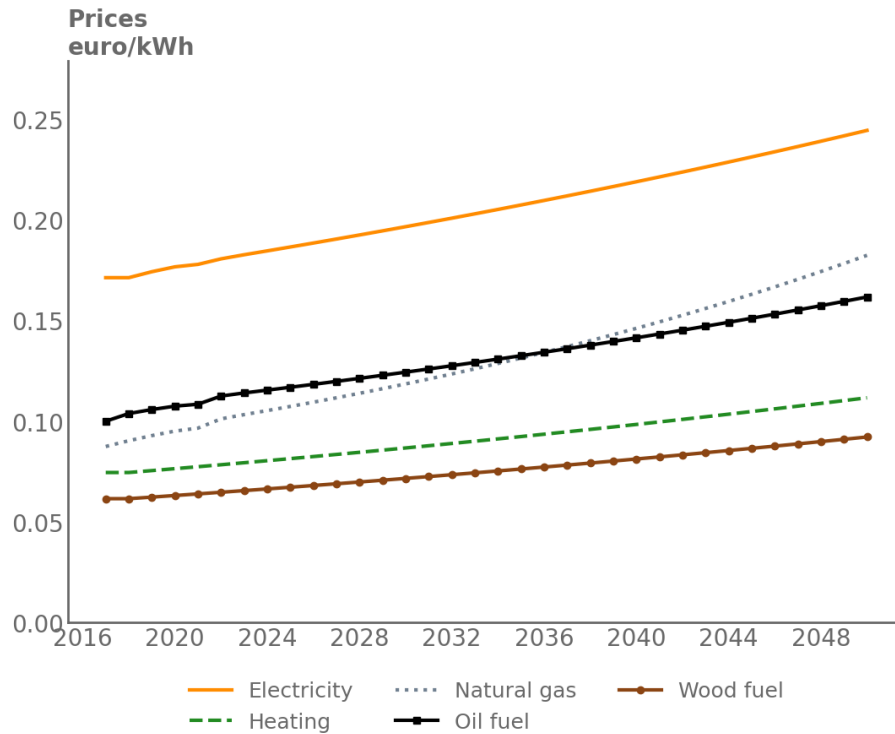
### 6.8.1 Overview

All data sources are comprehensively listed in Table 2, and the corresponding values are accessible on the model’s GitHub pages. For every policy scenario, we project a uniform annual growth of 0.8% in household income across all income brackets, extrapolated from assumptions of Directorate General for Energy and Climate (DGEC). For residential energy pricing (exclusive of taxes) and energy taxes, we also refer to data from the DGEC, as shown in Figure 17. It is crucial to recognize the inherent uncertainty in predicting future fuel prices for consumers, which are important inputs to our forward-looking model. Government measures such as the subsidization of energy prices after the Ukraine crisis, where price increases were withheld, underline this unpredictability. We have therefore decided to base our analysis on the latest officially available data and to carry out sensitivity analyzes on the fluctuations in fuel prices. The projections for the housing market, including demolition rates, construction of new buildings and their specifications (such as housing type, heating system and energy efficiency), are derived from the national reference scenario of ADEME (2022). We also use this scenario to configure the parameters of the energy system, including the share of renewable gas available for space heating of residential buildings and district heating connections. Our model assumes that the emission content of electricity decreases from 2030 and reaches 0 gCO<sub>2</sub>/kWh by 2050. In our reference scenario, we use business-as-usual data and critically examine the impact of key variables through sensitivity analysis.

### 6.8.2 Initial building stock

The 2018 building stock was derived by merging two distinct sources of housing data. The first source comprises a comprehensive overview of the building stock’s characteristics, including occupancy status and income details of owners and tenants. This information was obtained from the French National Energy Renovation Observatory, which combines data from the French energy performance certificate database (Base DPE ADEME) and occupancy attributes from fiscal data (Fidéli). It is important to note that these data are currently not publicly available.

While the energy performance certificate provides valuable insights into the energy efficiency of dwellings, it does not suffice to determine their renovation potential and associated costs. To address this limitation, we enriched the dwelling descriptions by incorporating additional information regarding the thermal performance of the primary components of the building envelope and the main heating systems. This

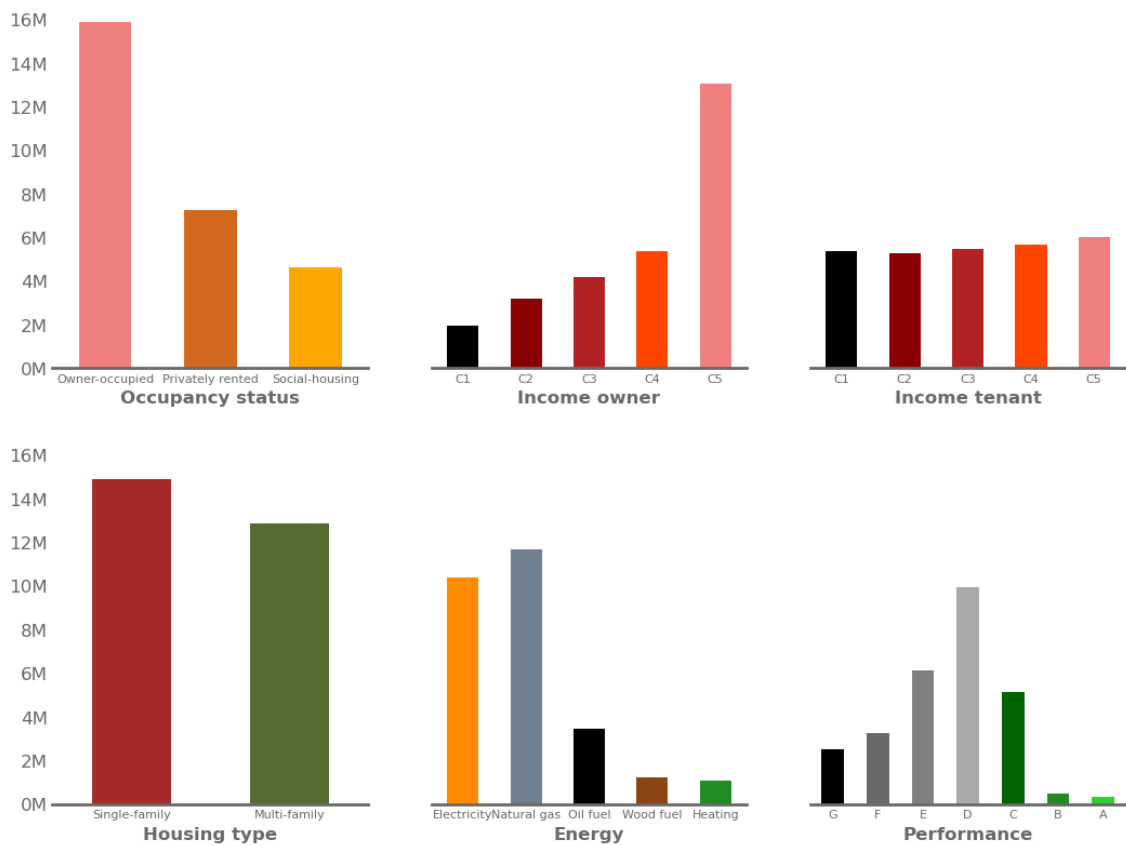


**Figure 17:** Energy prices with taxes used in the reference scenario in Res-IRF 4.0. Source: DGEC.

supplementary data was sourced from the Building Energy model. To identify the most representative dwelling archetypes for each energy performance certificate and heating energy, hierarchical clustering techniques were employed. Subsequently, we merged these enhanced dwelling archetypes with the representative housing stock to establish the original building stock within Res-IRF. This integration process augmented the dataset with information pertaining to the heating systems and the U-values of walls, floors, roofs, and windows.

To minimize the number of combinations, and therefore the computational burden, the following approaches were employed:

- Average living surface areas were calculated based on housing type and occupancy status.
- Standardized geometries were applied to single-family and multi-family dwellings, leading to standardized thermal envelope areas for each building component.
- U-values were limited to the available possibilities prescribed by thermal regulations.
- The heating system options were constrained to encompass standard and efficient boilers for oil, natural gas, and wood, along with direct electric, water-air, and air-air heat pumps.
- We also do not consider information on the construction period of the dwelling, the location of the dwelling (climate zone), the year of move-in, the age and composition of the household. However, the model is designed and code in such a way that it is modular and can be easily extended by the user with new dimensions.



**Figure 18:** Description of the building stock in France in 2018. To simplify the presentation, the energy performance levels are described with EPC, but Res-IRF 4.0 uses the level of insulation for each component of the building envelope.



### 6.8.3 Technical data

Insulation component	Cost (euro/m <sup>2</sup> )	U-value (W/(m <sup>2</sup> .K))
Wall	160	0.2
Floor	53	0.3
Roof	83	0.2
Windows	542	1.3

**Table 14:** Cost analysis from Observatoire BBC field study (Effienergie, 2019). The costs for the wall insulation correspond to exterior insulation. For the roof, the costs correspond to an average value for the insulation costs of converted attics, lost attics and crawl spaces. Costs are consistent with findings from ADEME (2020) and Enertech et al. (2022) studies. Model excludes ventilation costs, audit and accompanying expenses, and non-energy related renovation costs.

Building on ADEME (2022), we integrate an exogenous technical progress that reduces the costs of the heat pump by 20% by 2035. We test the impact such assumption in the sensitivity analysis in Appendix 6.4.

Heating system	Cost (euro)	Lifetime installation
Heat-pump	13000	20
Natural gas boiler	6000	20
Wood boiler	12500	20
Direct electric	3600	20

**Table 15:** Data derived from RTE et al. (2020). It includes costs related to domestic hot water systems as part of heating system costs, but do not consider other costs, such as those associated with heat emitters (radiators).

Material type	Work	Carbon content (kgCO <sub>2</sub> /m <sup>2</sup> )
Traditional material	Construction	500
Traditional material	Retrofit	120
Bio material	Construction	200
Bio material	Retrofit	60

**Table 16:** Carbon content of renovation from Siedler (2021) consistent with ADEME, 2022. We decompose embodied emission of energy renovation by individual insulation component assuming an equi-partial footprint of the surface by component of the envelope.

#### 6.8.4 Flow of renovation and heating-system installation

	Owner-occupied	Privately rented	Social-housing
Single-family	3.1%	1.2%	1.6%
Multi-family	1.8%	0.7%	1.6%

**Table 17:** Aggregate insulation rate for the base year 2018. The insulation rate is the ratio between the number of households that insulate at least one component of the building envelope and the total number of households. Sources: Own calculation from MTE (2020).

Insulation Type	Market Share (%)
All Walls	2.92%
Floor and Roof	0.28%
Wall and Floor	0.13%
Wall and Roof	7.38%
Only Wall	6.86%
Only Roof	65.10%
Floor Only	0.14%
All Insulated	2.67%
Floor, Roof, Windows	3.50%
Wall, Floor, Windows	0.92%
Wall, Roof, Windows	0.48%
Wall, Windows	0.24%
Roof, Windows	0.73%
Floor, Windows	4.99%
Only Windows	3.64%

**Table 18:** Share of insulation measures in total renovation in 2019 in France. Own calculation from MTE (2020).

### 6.8.5 Health cost

Through an extensive literature review, a working group developed a formal methodology to assess health costs attributable to residential energy poverty in France. The analysis identified the likelihood resulting from exposure to cold environments by household group, focusing mainly on households in the first to third income deciles living in buildings rated F and G on the Energy Performance Certificate (EPC). The reason for selecting this metric was its accessibility: both EPC ratings and household income levels are commonly available data points for evaluators. However, the current approach uses an older version of the energy performance certificate, which is not only outdated, but also ignores the potential fluctuations in energy prices. An increase in energy costs may indeed result in additional households being unable to adequately heat their homes. To address this issue, our study integrates the probabilities described in the methodology above with our heating intensity metric, which serves as a proxy for energy costs. A specific heating intensity threshold is set for the base year that . It is assumed that all households operating below this threshold will suffer from cold-related problems.

Energy performance	Share of buildings with health risk
G	34%
F	22%
E	0%
D	0%
C	0%
B	0%
A	0%

**Table 19:** Share of buildings with health risk by energy performance certificate (Dervaux et al., 2022)

Income class tenant	Probability health risk	Cost (EUR)
D1	14.29%	19232
D2	14.29%	19232
D3	14.29%	19232
D4	0.31%	421
D5	0.31%	421
D6	0.31%	421
D7	0.31%	421
D8	0.31%	421
D9	0.31%	421
D10	0.31%	421

**Table 20:** Probability of heath-risk and social cost by income class of the tenant(Dervaux et al., 2022)

### 6.8.6 Carbon tax and carbon value

	Carbon tax '2021 Package'	Carbon tax '2024 Package'	Social value of carbon
2018	45	45	54
2030	45	50	250
2040	45	85	500
2050	45	160	775

**Table 21:** Carbon tax and carbon value. In the 'Carbon tax' policy scenario, the carbon tax is levied on the social value of carbon (Quinet, 2019)

## 6.9 Calibration

From a modelling perspective, estimating behavioral parameters in household investment decision models presents significant challenges, primarily due to the absence of long-term panel data and limited statistical variation in the key determinants (e.g. technology cost). To address these challenges and thus enhance the accuracy of estimations, we adopt a combined approach incorporating empirical evidence from causal inference literature and applied behavioral research. On the one hand, policy evaluations carried out in France allow us to quantify the overall response of households to the reduction in purchase costs. On the other hand, discrete choice experiments enable us to quantify the impact of the determinants under investigation through stated preferences. By creating diverse investment options and soliciting choices from respondents, a broad range of relevant factors can be considered. However, a significant drawback of stated preference data is the potential discrepancy between individuals' stated choices and their actual behavior. Therefore, our combined approach uses stated preference findings to more easily vary attributes, while revealed preference data grounds the predicted proportions in real-world scenarios. This hybrid approach draws upon established methodologies detailed in the discrete choice literature (Ben-Akiva et al., 1994; Train, 2009). The estimation procedure entails an initial estimation of the ratio of coefficients using stated preference data, thereby providing insights into the relative importance of attributes. Subsequently, the alternative-specific constants,  $\beta_{i,k}$  in our setting, and the overall scale of parameters  $\theta$  are identified based on revealed preference data. Notably, these parameters capture unobserved factors that may differ between the discrete choice experiment and real-life contexts. Overall, the integration of data from stated and revealed preferences offers a robust strategy to address the challenges posed by limited data availability and potential discrepancies between stated choices and actual behavior.

## 6.10 Model validation

This section assesses the model's accuracy by contrasting our findings with other modeling outcomes and, crucially, with empirical data. Given the uncertainty of the inputs, this step is of utmost importance for the evaluation of such models, even if this is rarely done in the literature (Mundaca et al., 2010).

### 6.10.1 Energy saving potential

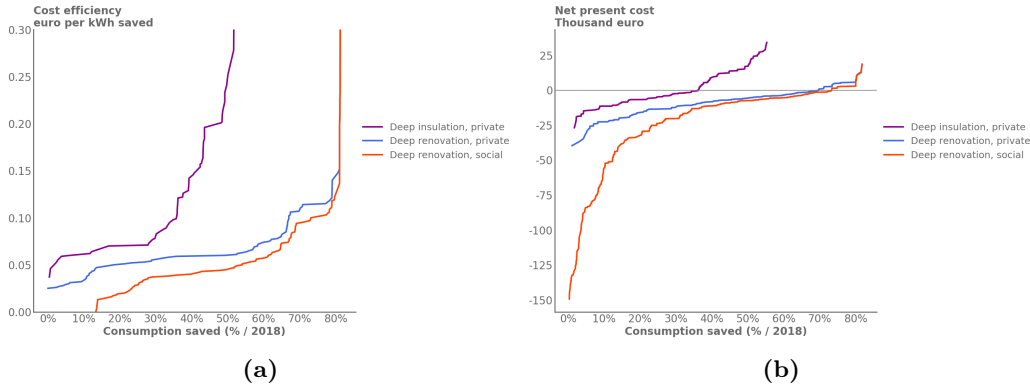
First, in order to assess the consistency of energy savings calculations based on a physical approach and investment cost assumptions, we compute marginal abatement curves that result from model assumptions (Figure 19a). We define three different scenarios that differ in terms of the renovation options available and the benefits included. In all scenarios, energy-savings are calculated with a discount rate of 5% and a lifetime of 30 years. First, the 'Deep insulation, private' scenario evaluates the potential if all households will invest in the more cost-effective insulation measures that allow to reach a low-consumption performance level (EPC B). The 'Deep renovation, private' scenario considers the potential of both 'Deep insulation' and the switch from fossil fuel heating system (i.e. oil-fuel and natural gas boilers) to a heat pump, which is more efficient and thus reduces final energy consumption.<sup>18</sup> In a final scenario 'Deep renovation, social' we consider additional co-benefits such as the value of avoided emissions and health benefits that outweigh the total investment costs. To facilitate a comparison with engineering models, we use theoretical energy saving into our analysis. Our findings reveal a significant heterogeneity in the profitability of different renovation projects, ranging from €0.05/kWh to €0.3/kWh, illustrating the

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<sup>18</sup>As mentioned above, we do not consider the switch to heat pumps in the buildings with the worst efficiency (e.g. EPC label F and G).

granularity in the description of homes and available renovation choices. Moreover, our results are consistent with those documented in existing literature. Hummel et al. (2021) produce the marginal cost of renovation packages on the building envelope for 6 countries in Europe, and find that "the costs for reaching savings of 40–60% are remarkably cheaper than for reaching higher savings". Our closest scenario, ‘Deep insulation, private’ on Figure 19a shows the same trend.<sup>19</sup> In addition, the full potential of energy saving in space heating when also considering the deployment of more efficient heating system such as heat pumps reach a technical potential of 80% which is consistent with figures in the literature (Cabeza et al., 2022).

Second, Figure 19b displays the net present value of home retrofitting projects ordered from the most profitable project to the least profitable one and the associated cumulative standard energy saving. We consider the same scenarios and parameterizations as in the previous figure. The figure illustrates that the optimal reduction falls within the range of 30-40% when only considering insulation work. These results align well with the research conducted by Mandel et al. (2023) and Zeyen et al. (2021), which identified optimal savings from insulation work ranging from 29% to 47% between 2019 and 2050. Additionally, Figure 19b demonstrates that almost a 65% saving may be feasible without incurring any costs. Interestingly, this figure illustrates the calculation of the energy efficiency gap resulting from engineering assessments. First, this method overestimates the energy savings and does not account for financing costs or non-monetary considerations, among others. Second, it does not consider market-failures such as the landlord-tenant dilemma or credit-constraint.



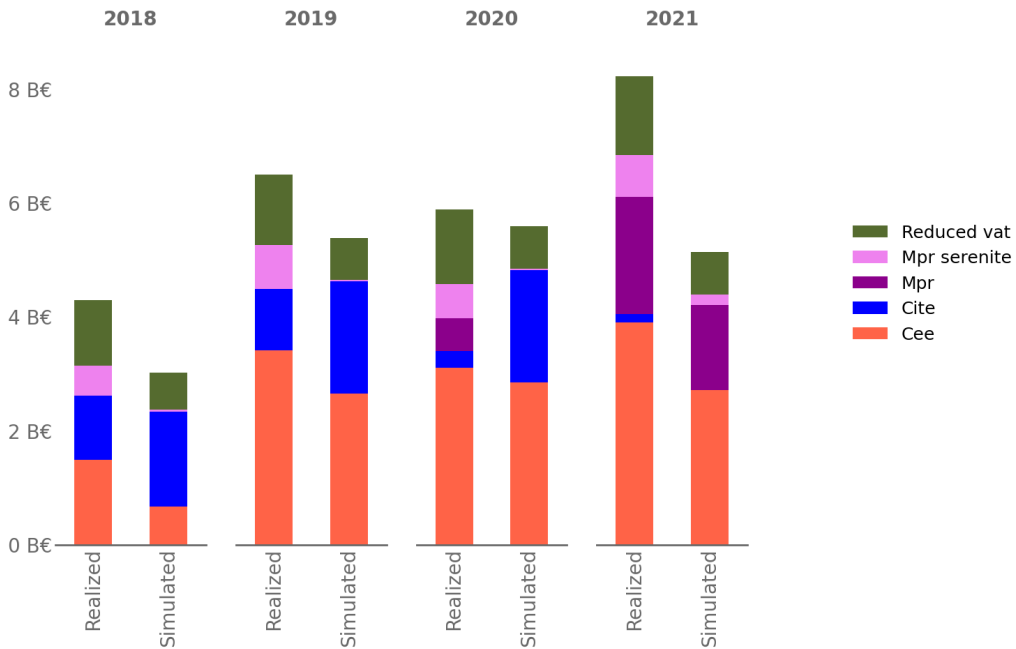
**Figure 19:** (a) Marginal abatement cost curve in euro per kWh saved and (b) Net present value of home retrofitting projects in thousand euro. Energy saving are calculated compare to base year, here 2018. ‘Deep insulation’ stands for insulation only, ‘Deep renovation’ for insulation and switch to heat pumps for homes powered by fossil-fuel. Marginal abatement cost curves show the cumulated potentials for energy-saving options on the horizontal axis and the related costs of option on the vertical axis, ranked from the cheapest to the most expensive.

### 6.10.2 Dynamic sensitivity

We conduct hundreds of simulations with varied energy price rates and analyze the relationship between simulated consumption and energy prices. Our research results reveal long-term energy price elasticities of -0.54 for electricity and -0.41 for natural gas. These findings are in agreement with, albeit slightly above, the estimates provided by the NEMS model, which reported elasticities of -0.48 for electricity and -0.21 for natural gas EIA, 2021.

<sup>19</sup>Note that contrary to Hummel, our cost curve display total costs and not display additional costs of energy saving actions that are generally calculated by subtracting the costs of a maintenance action from the full costs of each renovation action.

We assess the predictive capabilities of our model in the short-term by comparing simulated against actual trajectories of public expenditures over the 2018-2021 windows. Figure 20 shows the comparison between our model results and the realized public money spent for home energy renovation by policy. Overall, our model effectively projects public expenditures and illustrates that Res-IRF 4.0 is aptly tailored for assessing complex policies. However, some modelling simplifications contribute to the discrepancy between simulated and actual evolution. First, the frequent modifications made by French authorities to policy designs make it challenging to precisely track all changes over time. Consequently, the partial explanation for divergent results lies in the parametrization of policies. Second, the model does not explicitly incorporate all technologies such as ventilation, heat regulation systems, hot-water systems, and secondary heating systems. These omissions are intended to reduce the number of segments and computation time. Although we argue that these systems have a relatively a small impact on final energy consumption trend, they account in total public expenditure, given that they are subsidized. Third, as previously discussed, the model assumes that every household receives all available subsidies. While our scope only consider eligible insulation work, we represent all installation of new heating systems, particularly heat pumps. This approach leads to the assumption that all heat pumps receive subsidies, potentially resulting in an overestimation of public expenditure. In addition, as heating systems and building envelope insulation investment decision are treated successively, we only attribute deep renovation subsidies to insulation investment. Consequently, ‘MPR Serenite’ do not support heat pumps and is therefore underestimated. Finally, a significant disparity is observed between the model and realized data in 2021. This divergence can be attributed to the exceptional circumstances of that year, including the conclusion of the COVID-19 crisis, which resulted in a high number of real estate transactions and home renovation.



**Figure 20:** Comparison of simulated (‘Simulated’) and actual evolution (‘Realized’) of public expenditure in France between 2018 and 2021.

In the Appendix 6.5.4, we evaluate the extensive margin of incentives policies. Specifically, we find a similar proportion of non-marginal participant for the income tax credit in 2019, 80%, as identified in (Nauleau, 2014; Risch, 2020) for the same instrument but in 2005. Overall, these results give confidence in the consistency of the

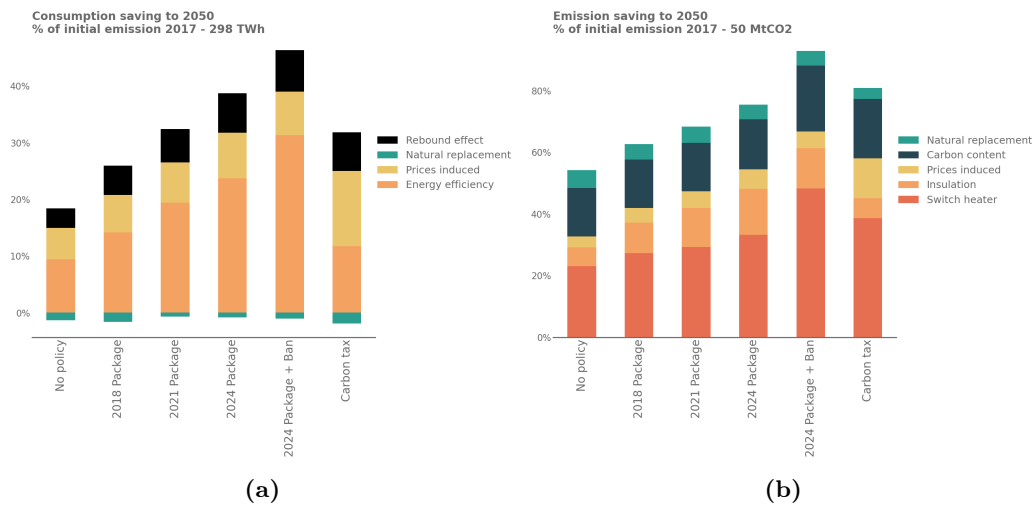
model for capturing fine policy specification. In addition, we calculate an extensive margin of 20% for the zero-interest loan in 2024, which is in line with the findings of (Eryzhenskiy et al., 2023)



## 6.11 Additional results

### 6.11.1 Decomposition analysis

Figures 21a and 21b provide a detailed breakdown of the factors contributing to energy consumption and emission reductions, respectively. Notably, for all policy packages, energy-efficiency is a major factor in reducing consumption, accounting for a 30% reduction in the ‘2024 Policy Package’. However, in the case of the carbon tax, the reduction in energy consumption is largely driven by the increased prices resulting from the tax. In terms of emissions, the successive policy packages achieve reductions through a combination of insulation improvements and a shift to low-carbon heating systems. By 2050, within the ‘2024 Policy Package’, the transition to different heating systems and improvements in insulation contribute to emission reductions of 30% and 20%, respectively. The remaining reductions are attributed to factors such as price-induced changes, reductions in the carbon intensity of energy sources, and the natural replacement of older, less efficient dwellings by newly constructed, more efficient ones.



**Figure 21:** Decomposition analysis of space heating consumption (a), and GHG emission (b) savings in France in all scenarios. Figure illustrates the decrease of household energy consumption, highlighting the impacts of energy-saving improvements, higher energy costs, and the ‘rebound effect’. It includes calculations of energy savings without the rebound effect, analysis of the rebound effect under constant prices, and the influence of fluctuating energy prices and newer homes replacing older ones. Additionally, it examines factors leading to lower emissions in homes, like energy-efficient renovations, fuel switching, advanced heating systems, and reduced GHG emission intensity.

6.11.2 Additional figures

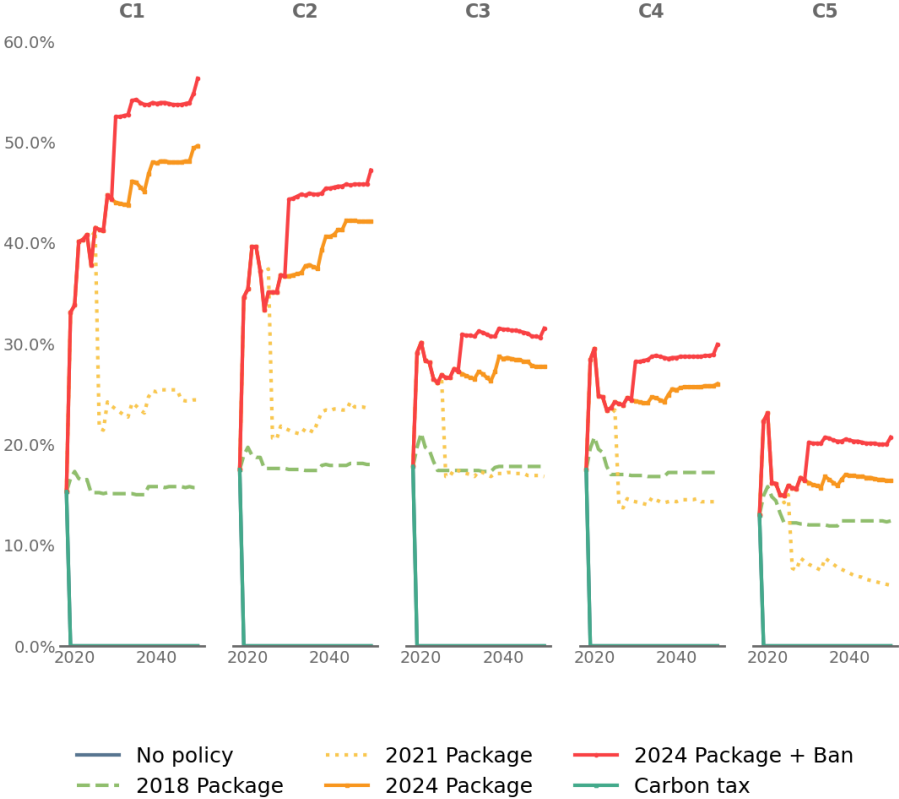
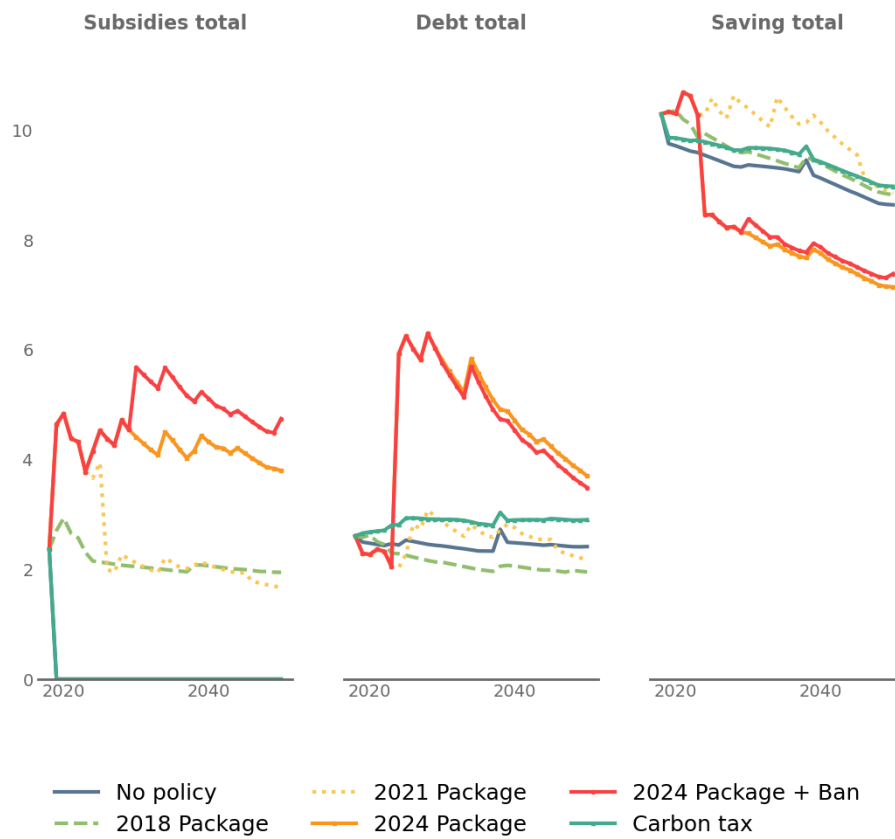
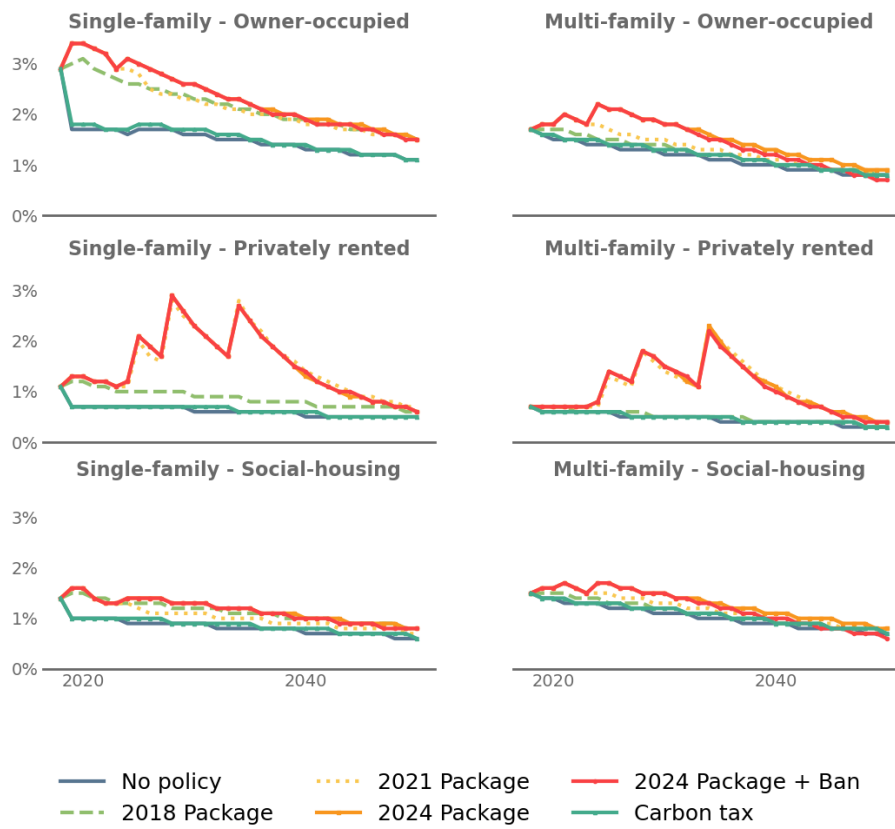


Figure 22: Share of subsidies in total cost by income group.



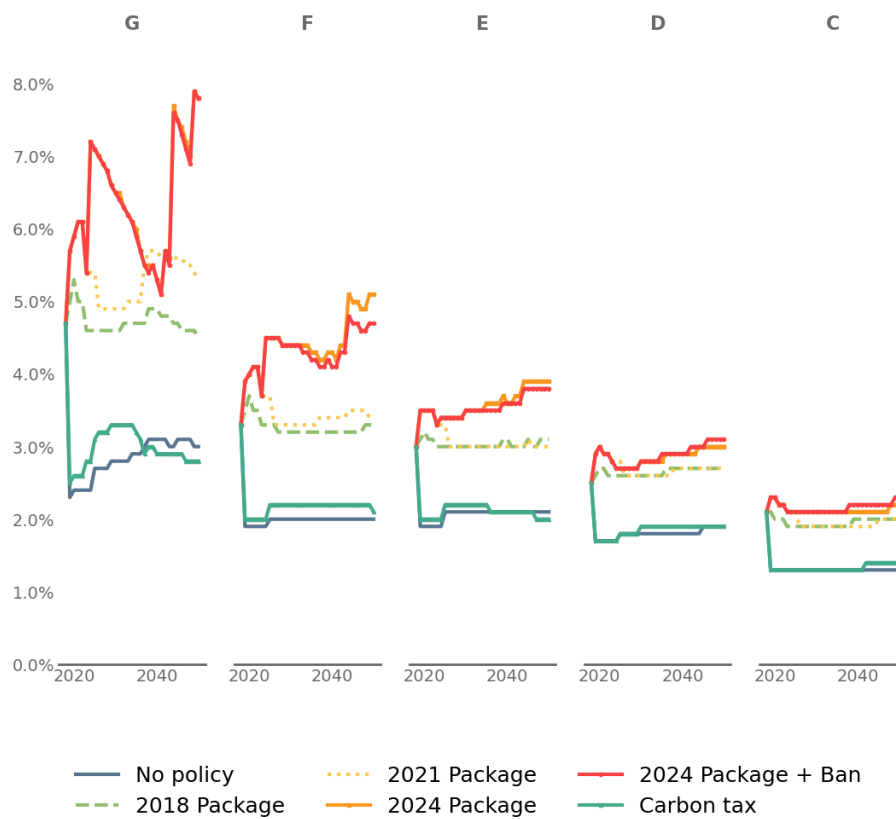
**Figure 23:** Financing of investment in home insulation and heating system replacement.



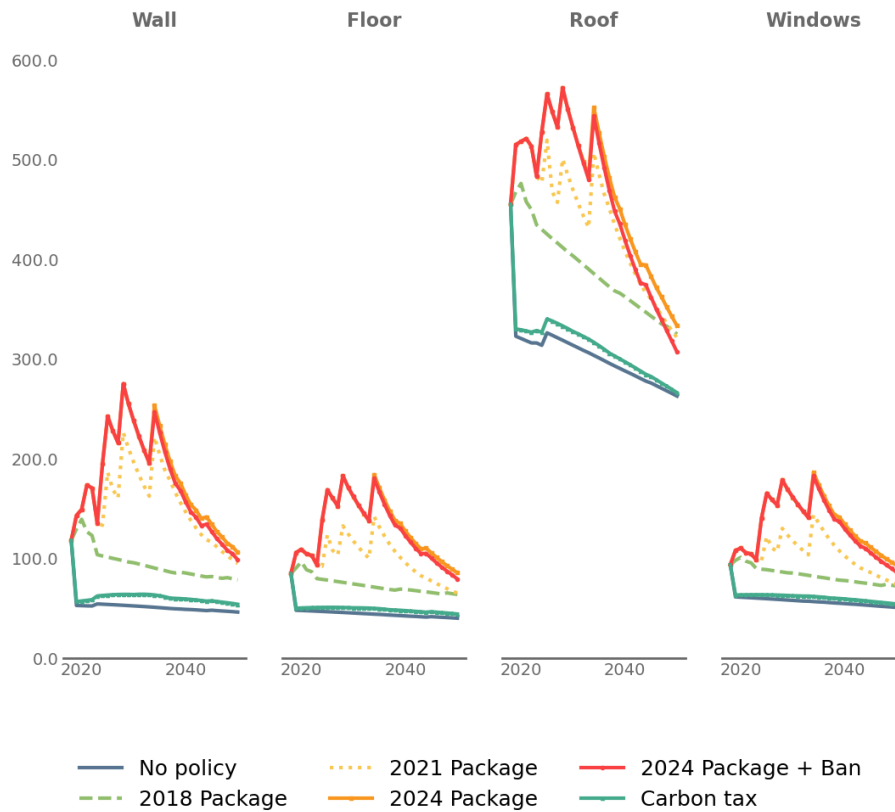
**Figure 24:** Insulation rate by occupation-status.



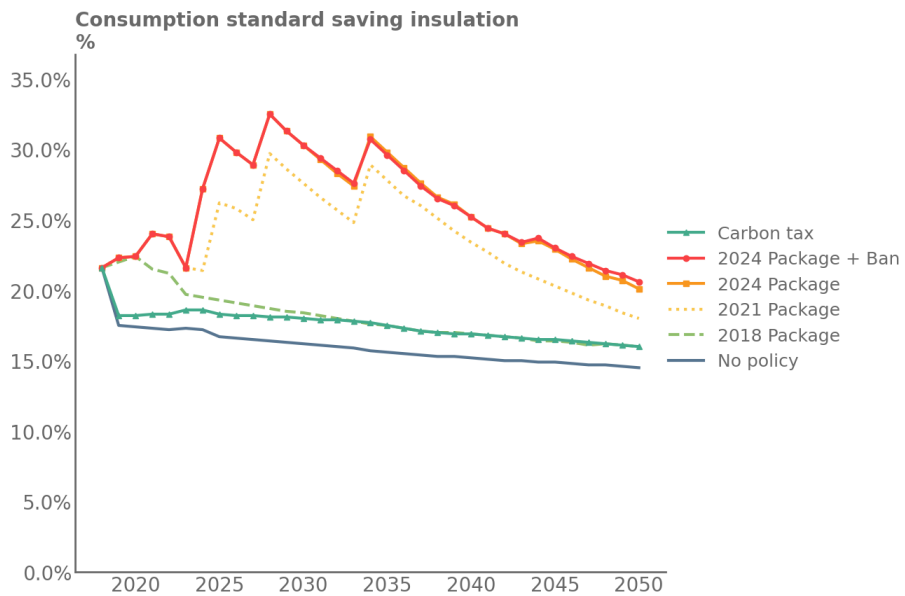
**Figure 25:** Insulation rate for owner-occupied single-family homes by income group.



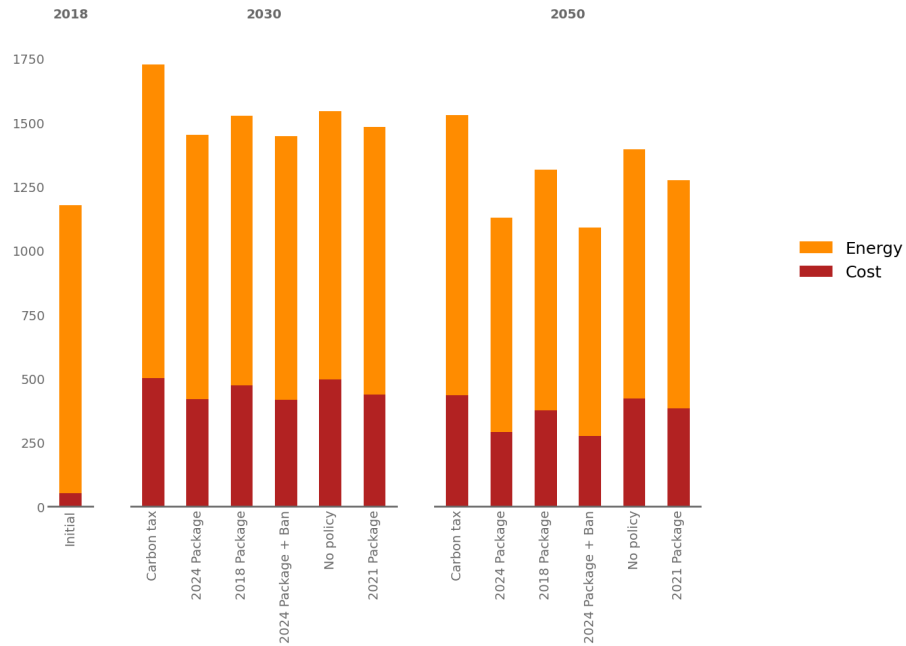
**Figure 26:** Insulation rate for owner-occupied single-family homes by energy performance certificate.



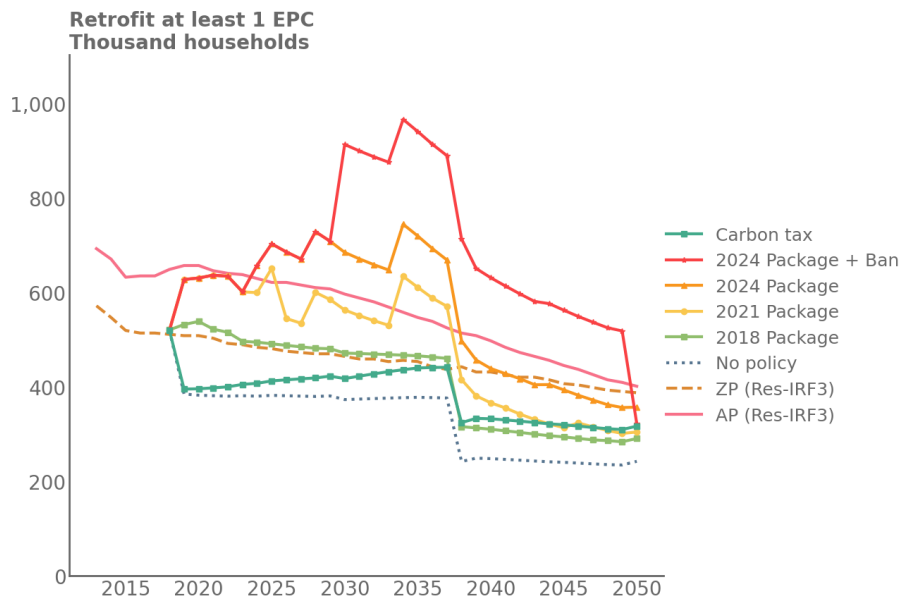
**Figure 27:** Insulation of building envelope component.



**Figure 28:** Average theoretical consumption saving by home insulation.



**Figure 29:** Evolution of energy cost for homeowners breakdown between investment cost and energy expenditures.



**Figure 30:** Comparison of the projection of the number of renovations between the results of Giraudet et al. (2021) and this paper.



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