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► To cite this version:

Lucas Vivier, Louis-Gaëtan Giraudet. Energy efficiency policy in an n-th best world: Assessing the implementation gap. 2024. hal-04510798v2

HAL Id: hal-04510798

<https://hal.science/hal-04510798v2>

Preprint submitted on 17 Jul 2024

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Energy efficiency policy in an n -th best world: Assessing the implementation gap

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July 16, 2024

Abstract

The market failures and behavioral anomalies at the source of the Energy Efficiency Gap tend to be studied in isolation, which biases welfare assessment of energy efficiency policies. We develop a dynamic model of home energy retrofit fit for capturing cumulative inefficiencies due to multiple frictions – CO₂ externality, cold-related illness, credit rationing, landlord-tenant dilemma, free-riding in multi-family housing, present bias and status quo bias. Focusing on France, we find that health, rental and multi-family frictions each entail higher deadweight losses than the CO₂ externality alone. Taking all frictions into account implies that energy efficiency subsidies generate net social benefits – at odds with previous findings. In contrast, the benefit-cost balance of regulations is net negative due to ancillary costs. Finally, the French policy portfolio, which blends subsidies, taxes and regulations, only closes half of the energy efficiency gap. Its efficiency could be improved by better targeting low-income families, multi-family housing and rental housing.

Keywords: energy efficiency, public policy, cost-benefit analysis, market failure, behavioral anomaly, housing, health, climate change

JEL Code: D11, H23, Q41

1 Introduction

The energy efficiency gap is a research program examining whether and why actual energy efficiency investment levels fall short of what basic cost-analysis would predict. Initiated in the 1990s by Jaffe et al. (1994b), it focuses on three types of frictions with contrasted welfare implications – unaccounted for market failures, unaccounted for behavioral anomalies and modelling errors. Policy intervention is unambiguously warranted to correct market failures. Correcting behavioral anomalies is more debated, as nudges are criticized on paternalistic grounds. Policy intervention is unwarranted to correct modelling errors – one simply needs to use the right model (Gerarden et al., 2017).

Among the many explanations for the energy efficiency gap, one has been prominent – the carbon dioxide externality. As long as energy use generates a social cost that is not reflected into prices, energy efficiency investment will be too low. This has been the main justification for the numerous energy efficiency policies implemented around the world. Besides this problem, many others have been cited, but only a handful have been empirically estimated. This includes modelling errors (Metcalf et al., 1999), landlord-tenant dilemma (Gillingham et al., 2012), behavioral anomalies

(Allcott et al., 2014), the rebound effect (Chan et al., 2015), moral hazard in quality provision (Giraudet et al., 2018), information asymmetries in energy efficiency capitalization (Myers, 2020) and ancillary value (Wekhof et al., 2023). These frictions are generally studied one-at-a-time, more rarely in interaction with the carbon dioxide externality. To our knowledge, only one paper goes further and assesses three frictions at the same time – modelling errors, information asymmetries and the rebound effect (Christensen et al., 2021). The energy efficiency gap has thus been investigated in second- or third-best environments only, such that the ‘ n -th best’ world underlying Jaffe et al. (1994b)’s framework remains uncharted territory.

The reason for this research gap is a strong emphasis on causal identification in applied microeconomics. Spurred by the ‘credibility revolution’ (Giraudet et al., 2023), several calls have been made to more rigorously estimate the frictions at the source of the energy efficiency gap (e.g., Gillingham et al., 2009; Allcott et al., 2012). This has prompted significant research effort, mostly exploiting administrative and program data (as in most of the references listed above) and randomized control trials on rarer occasions (Fowlie et al., 2018; Allcott et al., 2024). These state-of-the-art approaches have an unparalleled ability to produce internally valid friction estimates (Gillingham et al., 2018; Giandomenico et al., 2022). This benefit comes at the expense of studying one problem at a time. As a result, their conclusions are context-dependent and the welfare implications can be erroneous if accompanying frictions are not properly taken into account.

In this paper, we set out to map the energy efficiency gap resulting from interactions between multiple frictions and study their policy implications. Such a complex environment can only be explored numerically. We do so using a rigorous microsimulation framework, parameterized with the best available friction estimates. We focus on home energy retrofits in France, a good candidate for conducting such an analysis. This market is subject to multiple policy interventions, totalling €7 billion in subsidy costs, the efficiency of which has not been jointly assessed. Meanwhile, the degree of detail contained in public databases has reached the critical mass to enable their assessment.

We develop a structural model of energy demand for space heating with a high level of detail. Each dwelling is specified along five dimensions summarizing the characteristics of the envelope and the heating system, together offering 2,400 upgrading options. Households in turn are described along four dimensions – their occupancy status (owner-occupied, privately rented, social housing), the type of housing (single- or multi-family), the income category of the owner (expressed in quintile) and the occupant’s if different – together offering 75 combinations. The model therefore rests on 180,000 dwelling-household pairs representing a total stock of 27 million principal residences. Energy upgrades result from discrete choices made by the owner. Conditional on investment, households optimize their energy use in a utility framework. The energy performance gap is therefore endogenous to the model. Crucially, investment and utilization decisions are distorted by several frictions parameterized with the best available estimates – uninternalized CO₂ externalities, uninternalized health costs in the worst-performing homes, credit rationing, present bias and status quo bias. We add two more frictions through calibrated coefficients – the landlord-tenant dilemma and free-riding in multi-family housing. Lastly, we take into account the ancillary attributes of renovation (e.g., acoustic or aesthetic benefits, inconvenience costs), estimated as the residual value that rationalizes the gap between observed investment levels and predictions based on an energy-only decision model. Our model thus allows us to assess all relevant welfare dimensions of energy efficiency investment – investment cost, bill savings, increased comfort, reduced health costs, avoided CO₂ emissions, ancillary value and the opportunity cost of public funds. Dynamic runs accurately reproduce recent trends in subsidy spending, thus building confidence in the model’s fitness for purpose.

We proceed in three steps. First, we compare the deadweight losses implied by

each friction. We find that the landlord-tenant dilemma, free-riding in multi-family housing and uninternalized health costs are all greater market failures than the CO₂ externality. Testing all combinations of frictions, we find interactions between them to be mild. Second, we examine how subsidies can be designed to address the four key market failures. We find that subsidies fail to make renovation investment profitable from the households’ private perspective, but contrary to recent findings (Gillingham et al., 2018; Giandomenico et al., 2022), their benefit-cost balance is net positive from a social perspective. This illustrates the importance of considering all welfare dimensions of home energy retrofits. Third, we take a positive perspective and assess the policies currently in place in France – a public subsidy program, a zero-interest loan program, a utility-sponsored subsidy program, the carbon tax and a rental ban on worst-performing housing, plus a rental ban on new gas boilers (not implemented yet but discussed at the European level). Standalone policy analysis confirms the superiority of subsidies, which fare well on all welfare dimensions, whereas the carbon tax fails to internalize health costs and the bans imply high ancillary costs. Taken together, the policies close about half of the French energy efficiency gap – about two-thirds along the energy savings dimension and one-third along the welfare dimension. Still, with €7 billion, actual subsidy spending exceeds the total welfare gap (€4 billion). This suggests that better targeting cost-effective renovation opportunities could significantly increase the cost-efficiency of subsidies.

Our analysis purports to explore the complexities of a market distorted by multiple frictions. In doing so, it bridges a gap between microeconomic modelling and the building stock models used in numerical assessments of climate policy. In addition to the references listed above, our work therefore relates to that of Levesque et al. (2021), Mastrucci et al. (2021), Knobloch et al. (2021), Berrill et al. (2022), Müller (2015), and Camarasa et al. (2022). These studies all have a broader scope than ours in terms of energy usage and countries represented. They however rely on exogenous, or at best significantly less distorted, renovation processes. They thus produce valuable cost-effectiveness assessments, but are unfit for welfare analysis. Our main contribution to this strand of the literature is to illustrate the frequently invoked, yet little documented, co-benefits to home energy renovation (Vorsatz et al., 2014).

The remaining of the paper is organized as follows. Section 2 introduces the model. Section 3 assesses the welfare impact of frictions. Section 4 assesses actual policies. Section 5 compares normative and positive perspectives and assesses the implementation gap in France. Section 6 discusses the results and Section 7 concludes. Detailed results are provided in an Appendix. An exhaustive description of the model can be found in Supplementary material.

2 Model

We develop a dynamic welfare framework with a detailed representation of retrofit technology. Specifically, we propose a substantially upgraded version of a bottom-up model called Res-IRF, developed since its inception with the goal of improving behavioral realism in energy demand modelling (Giraudet et al., 2012; Giraudet et al., 2021b). The model version used here, Res-IRF 4.1, includes two major improvements. First, the decision framework is now fully micro-founded and enriched with market failures and behavioral anomalies specified with the best available estimates for France. Second, technology is now explicit, whereas all dwelling characteristics were conflated in the previous version into EPC ratings. These improvements are instrumental in finely specifying policy instruments and assessing their impacts. We provide below a concise description of the model, emphasizing its key processes and parameters. The overall structure is illustrated in Figure 1. The key variables and parameters are listed in Table 12. Additional information is provided in Supplementary materials B.

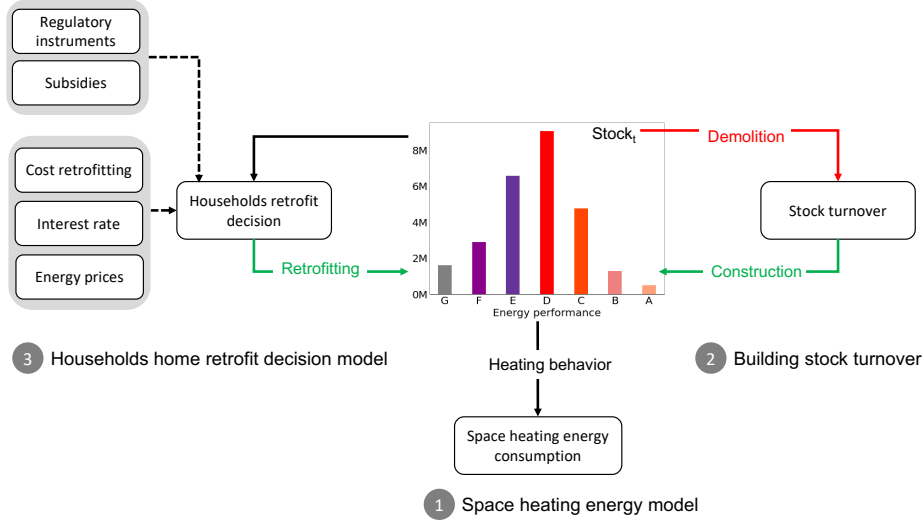


Figure 1: Recursive structure of the model

2.1 Overview

The model simulates energy demand for space heating in 27 million principal residences. As of 2024, this scope contributes 16% of total French energy demand. Energy demand is jointly determined by the thermal performance of the dwellings and their occupant’s behavior. It changes over time through energy efficiency improvements – both exogenous and policy-induced – within a recursive framework initiated in base year 2017. Efficiency improvements result from the penetration of new vintages into the dwelling stock and the renovation of older vintages.

Stock turnover The construction of new dwellings is determined by an exogenous housing demand to fulfill, net of some exogenous dwelling decommissioning, assumed to fall in priority on the worst-performing dwellings. The performance of new vintages is then set to comply with the latest Building Code, assuming current heating system market shares are conserved (based on ADEME, 2022). The renovation of existing dwellings relies on a more comprehensive decision process detailed in the next subsection.

Technology The energy performance of the dwelling stock is determined by the features of the heating system and the performance of the envelope. A heating system is characterized by a technology – electrical heating, heat pump, fuel oil boiler, natural gas boiler, wood furnace and district heating – and a capacity in Watts. Secondary heating systems additionally feature in reduced forms, as detailed in Appendix A. Insulation levels are given by the thermal transmittance coefficients of four components – walls (5 different U-values in $W/m^2.K$), roof (4 values), floor (4 values) and windows (3 values). Heat losses differ between single- and multi-family housing to account for their contrasting geometry. The model is therefore based on 2,400 dwelling archetypes. The resulting theoretical energy use is computed using the EN ISO 13790 methodology, as detailed in Appendix A.

The renovation of existing dwellings consists of improvements on the heating system and/or the envelope. It rests on a two-stage decision. First, the homeowner replaces their heating system if it has reached its end of life. The replacement options here include switching fuel and changing the system capacity. This does not apply to district heating, which is determined by exogenous, centralized decisions. Importantly,

heat pumps cannot be installed in the worst performing dwellings due to the physical challenge of heating water up to 55°C when insulation levels are too low (Terry et al., 2023). Second, the homeowner decides whether to proceed with insulation works and, if positive, picks one among 15 possible options. Each envelope component can be upgraded to a transmittance level aligned with the eligibility requirements included in subsidy programs. Combining binary decisions on all four components therefore provides homeowners with 16 insulation options (including that of not insulating a single component).

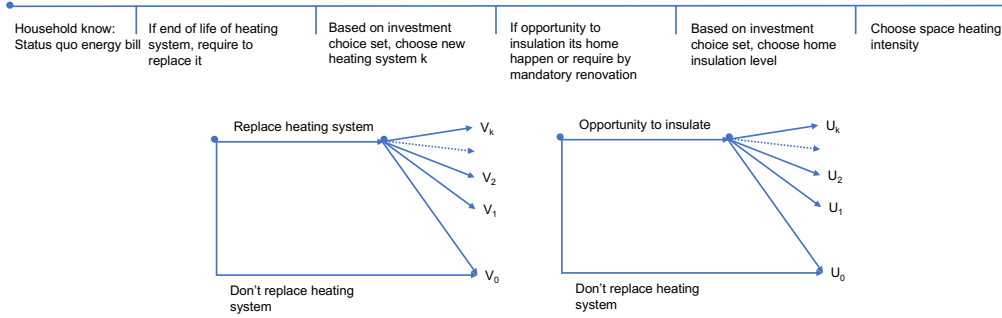


Figure 2: Timing of investment decision

Consumer heterogeneity The physical characteristics of a dwelling are combined with the socio-economic characteristics of their owner and, if the dwelling is rented out, of their tenant. This adds 75 more dimensions to the dwelling stock – 3 occupancy status (owner-occupied, privately rented, social housing), 5 income levels for owners and 5 more for occupants.

Combining all characteristics therefore provides us with 180,000 dwelling-household pairs (see Table 1). These characteristics are specified using a unique dataset provided by French authorities (MTE, 2020), matching dwelling data and fiscal data about their occupants, discussed in greater length in Appendix B.

Dimension	Number of options	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 dimensions. All combinations add up to 180,000 dwelling-households pairs. Thermal insulation is represented by thermal transmittance ($\text{W}/(\text{m}^2\cdot\text{K})$).

2.2 Decision framework

The decision framework builds on the models developed by Allcott et al. (2024) and Chan et al. (2023), enhanced with discrete choices and several additional frictions.

Utility from space heating. Households derive comfort from the consumption of space heating $h(\cdot)$ and a numeraire good x . Space heating is produced using energy,

purchased at price p . Energy use $e(\cdot, \cdot)$ decreases in the energy efficiency $1/\eta$ of the heating infrastructure and increases in the intensity m with which households use it, reflecting varying thermostat settings or heated surface. Parameter η captures the theoretical energy consumption determined by the performance of the heating system and the envelope. Households set their heating intensity so as to maximize utility under the constraint that energy expenditure $p\eta \cdot m$ and consumption of the numeraire do not exceed wealth ω . We make the standard assumption that utility is quasi-linear, which is reasonable given the small budget share of energy expenditure and conveniently allows us to express utility in monetary terms. The constrained optimization program is:

$$\max_{x,m} \quad u(x, m) = x + h(m) \quad (1)$$

$$s.t. \quad \omega = x + p\eta \cdot m \quad (2)$$

We denote $m^*(p, \eta)$ the equilibrium heating intensity, $e^*(p, \eta) = e(m^*(p, \eta), \eta)$ the equilibrium energy demand and $v(p, \eta) = \omega - p \cdot e^*(p, \eta) + h(m^*(p, \eta))$ the indirect utility function.

Energy use Utility $h(m)$ is specified with a constant relative risk aversion function:

$$h(m_i) = A \cdot \frac{m_i^{1-\zeta_i}}{1-\zeta_i} \quad (3)$$

with A a scaling parameter and ζ_i the coefficient of relative risk aversion. This functional form is commonly used to capture diminishing returns while relying on a constant short-term price elasticity (Allcott et al., 2024). The first-order conditions imply $u_m = p\eta_i$ and $x_i = \omega_i - p\eta_i \cdot m_i$, leading to:

$$m_i^* = \left(\frac{A}{p\eta_i \cdot \theta} \right)^{1/\zeta_i}. \quad (4)$$

where θ is the marginal utility of income.

We parameterize this function so as to generate a short-term price elasticity of -0.2, as estimated in France by Douenne (2020). This results in $\zeta = 5$ (see Appendix A). In addition, we assume preferences for space heating are constant and homogeneous across households and thus set the value of A so as to reproduce the energy consumption observed in the initial year. Importantly, by doing so, we explicitly account for the well-documented discrepancy between predicted and realized energy consumption, known as the energy performance gap (Christensen et al., 2021). The performance gap in our model is 61% on average in base year.

Energy efficiency investment Households can improve the energy efficiency of their heating infrastructure by investing in a new heating system and/or insulation works. Upon investing in option k of energy efficiency $1/\eta_k > 1/\eta_0$, Household i reduces their marginal energy expenditure $p\eta$. Meanwhile, utility maximization leads them to increase their heating intensity, as m^* is decreasing in η (see Equation 2.2). Equilibrium energy use is therefore higher than it would have been without this adjustment – a phenomenon known as the rebound effect. With the parameterization introduced above, the rebound effect is 26% in our model, perfectly in line with common estimates (Sorrell et al., 2008; Gillingham et al., 2016).

Unlike Allcott et al. (2024), we assume that households anticipate this adjustment and more generally the energy performance gap – with important implications for our welfare assessment, as we will see below. Household i enjoys gross utility gains $V_{i,k} = v(p, \eta_k) - v(p, \eta_0)$. They will invest if and only if this value and some unobserved

idiosyncratic value $\epsilon_{i,k}$ are together larger than capital cost K , that is if indirect utility $X_{i,k}$ is positive, with:

$$X_{i,k} = V_{i,k} - K + \epsilon_{i,k}. \quad (5)$$

Based on available evidence (Anderson et al., 2013), this decision is made assuming constant energy price.

Capital cost With upfront costs p_k typically in the thousands or tens of thousands of euros, energy efficiency investment entails some financing costs $r_{i,k}$, such that total capital cost is $K = p_k \cdot (1 + r_{i,k})$. Financing costs in turn are the weighted sum of debt, charged at interest rate d , and the opportunity cost of equity, providing returns at rate s , over the duration of investment: $r_{i,k} = \text{duration} \cdot (\gamma_{i,k} \cdot d_{i,k} + (1 - \gamma_{i,k}) \cdot s_{i,k})$, with $\gamma_{i,k}$ the share of investment covered by debt, which typically depends on household income. We compute γ such that households use equity first – with initial endowments ranging from €0 for the bottom 10% of the income distribution to €10,000 for the top 10% – and borrow the remaining amount. Based on available evidence, we set the interest rate to 3.9% and the rate of return on equity to 2.5% (ADEME, 2018; Giraudet et al., 2021b; Dolques et al., 2022), respectively providing an upper and a lower bound of financing costs.

Ancillary attributes In addition to comfort gains, households attach extra value to the purchased asset, unrelated to energy attributes and unobserved to the empiricist. This value can be positive – think of the acoustic or aesthetic benefits from new windows. It can also be negative – think of the inconvenience due to insulation works, which can be as serious as requiring temporary relocation. The net value varies with idiosyncratic shocks, such as moving to a new apartment, which reduces inconvenience, or unexpected money inheritance, which lowers capital costs.

Including ancillary value is crucial for modelling investment dynamics (Wekhof et al., 2023). On the one hand, ancillary benefits play a critical role in renovation decisions at the margin. On the other, ancillary costs contribute to the slow pace of renovation, constrained by building stock inertia and little responsive to incentives (Aldenhoff et al., 2024).

In our discrete-choice context, we account for unobserved non-energy value through parameter $\epsilon_{i,k}$, a type I extreme value idiosyncratic preference of mean $\theta \cdot \delta_{i,k}$. We define θ as a scaling factor so $\epsilon_{i,k}/\theta$ follows a standard type I extreme value law (Gumble law) of standard deviation $\pi^2/6$:

$$X_{i,k} = V_{i,k} - p_k \cdot (1 + r_{i,k}) + (\delta_{i,k} + \epsilon_{i,k})/\theta \quad (6)$$

We define $\tilde{X}_{i,k}$ as the rescaled indirect utility net of the extreme value error, also called the representative utility. Note that $\tilde{X}_{i,0} = 0$ for the status quo.¹ Given the extreme value error assumption, the probability $P_{i,k}$ of choosing investment option k is the standard logit choice probability (Train, 2009):

$$\tilde{X}_{i,k} = \theta \cdot (V_{i,k} - p_k \cdot (1 + r_{i,k})) + \delta_{i,k} \quad (7)$$

$$P_{i,k} = P(X_{i,k} > X_{i,j} \forall j, k) = \frac{\exp \tilde{X}_{i,k}}{\sum_j \exp \tilde{X}_{i,k}} \quad (8)$$

¹ θ is defined to set the variance of the distribution to $\frac{1}{\pi^2/6}$

Estimating parameters δ_k and θ is inherently challenging. For one thing, the full choice set is rarely observed.² Notwithstanding this difficulty, estimates are typically obtained in specific programs, thereby lacking external validity (Allcott et al., 2024). To circumvent these problems, we compute ancillary value as the residual when the fully specified energy-only model (i.e., reflecting $X_{i,k} - \epsilon_{i,k}$) is calibrated against observed investment patterns. We do this for both heating system decisions and insulation decisions, following a procedure described in Appendix A.

Normalizing the value of not investing to zero, we obtain a mean ancillary value of insulation of $-\text{€}67,132$ in private housing and $-\text{€}82,338$ in social housing. These costs reflect the strong inertia associated with home energy retrofit, which only 3% of households undertake every year. As expected, the values are almost systematically positive (i.e., benefits) to marginal investors. Overall, mean costs are lower for measures that combine several insulation actions, thus pointing to economies of scale, the grouping of measures arguably reducing inconvenience, which essentially is a fixed cost.

2.3 Market and behavioral frictions

We assume all prices – the energy price p , the upfront cost p_k , the interest rate d and the return on capital s – to be competitive. In this well-functioning market environment, we add seven key frictions at the source of the energy efficiency gap (Jaffe et al., 1994a; Gerarden et al., 2017). While market failures unambiguously call for corrective government intervention, the justification of ‘libertarian paternalistic’ interventions to address behavioral anomalies is more debated on normative grounds (Gillingham et al., 2014). In any case, behavioral anomalies do affect traditional interventions and therefore need to be taken into account. We thus focus on five market failures and two behavioral anomalies that are known to seriously deter energy efficiency investment and for which empirical estimates are available in the French context.³ Summarized in Table 2, the seven frictions modify the constrained optimization program as follows:

$$\max_k \tilde{X}_{i,k} = \theta \cdot (\lambda_i \cdot V_{i,k} - p_k \cdot (1 + r_{i,k}) + \delta_{i,k} + \epsilon_{i,k} + \phi_i^{\text{rental}} + \phi_i^{\text{MFH}}) \quad (9)$$

$$s.t : \alpha_{k,i} \cdot p_k \cdot (1 + r_{i,k}) / \text{duration} < b \quad (10)$$

where $\lambda_i < 1$ is a present-bias coefficient, b is a borrowing constraint and $\phi_i < 0$ are reduce forms for distortions in both rental and multi-family housing.

Carbon dioxide externality. Energy use generates CO₂ emissions that contribute to climate change. The associated social cost ζ has been estimated to be $\text{€}150/\text{tCO}_2$ in 2024, $\text{€}250/\text{tCO}_2$ in 2030 and $\text{€}775/\text{tCO}_2$ in 2050 in France (Quinet, 2019b). The externality associated with energy use is partially internalized through the EU-ETS price – fluctuating between $\text{€}60$ and $\text{€}100/\text{tCO}_2$ in the past two years, presumably passed-through onto wholesale fuel prices – and an additional $\text{€}45/\text{tCO}_2$ carbon tax applied to retail natural gas and fuel oil prices.

Credit rationing. Adverse selection in credit markets induce lenders to deny low-income households access to credit (Stiglitz and Weiss, 1981). This little-studied problem typically materializes through a debt-to-income ratio b beyond which prospective borrowers are denied credit. In France, it is customary to set this energy efficiency-specific borrowing constraint to 5% (Dolques et al., 2022).

²Allcott et al. (2024) circumvent this difficulty by using energy audits, but this piece of information is not available to us.

³Another important market failure to account for is moral hazard-induced quality defects, known to significantly contribute to the energy performance gap (Giraudet et al., 2018; Christensen et al., 2021). We implicitly account for them upon calibrating the energy performance gap, but do not consider them in welfare assessment for lack of data about remediation cost .

Category	Friction	Parameterization	Source	No-friction counterfactual
Market failure	CO ₂ externality	SCC of €150/tCO ₂ in 2024, €250 in 2030 and €775 in 2050, only partially internalized through a €45/tCO ₂ tax on natural gas and fuel oil	Quinet (2019b)	Carbon fee aligned with the SCC
	Credit rationing	Credit denied (making investment impossible) if repayment annuity exceeds 5% of household income	Dolques et al. (2022)	No credit restriction
	Low EE capitalization into rents	Penalty of €20,639 per rented house and €19,506 per rented apartment	Own estimation	No penalty
	Free riding in MFH	Penalty of €15,961 per multi-family dwelling in the private sector and €3,522 in social housing	Own estimation	No penalty
	Health externality	€7,500 annual social cost in worst-performing, low-income occupied dwellings, uninternalized	Dervaux et al. (2022)	Tax on problem-prone segments, fully internalizing the social cost
Behavioral anomaly	Present bias	Rate of pure preference for the present ranging from 3% for the top 20% of the income distribution to 19% for the bottom 20%	Stolyarova (2016)	Uniform 3.2% rate of pure preference for the present
	Status quo bias	€8,600 benefit for keeping existing system	Stolyarova (2016)	Benefit removed

Table 2: Summary of the market and behavioral frictions contained in the model.

Low capitalization of energy efficiency into rents Growing evidence suggests that energy efficiency is well capitalized into home sales, but not into rents (Giraudet, 2020). This results in under-investment in energy efficiency in rental housing (Gillingham et al., 2012; Melvin, 2018; Lang et al., 2021b; Petrov et al., 2021). We assess this market failure using the same approach as that used to compute unobserved value. Our reduced-form estimate ϕ_i^{rental} is a penalty of €20,639 per rented house and €19,506 per rented apartment.

Free-riding in multi-family housing Energy efficiency decisions in multi-family housing may be subject to two public-good problems. First, most energy efficiency decisions in multi-family housing are the homeowner’s association’s responsibility, and individual members’ benefits may not be commensurate with their contribution.⁴ Second, heat transfers across adjacent dwellings create heating externalities which mitigate the incentives to renovate. These problems are remarkably understudied. Our reduced-form estimate ϕ_i^{MFH} of it is a penalty of €15,961 per multi-family dwelling in the private sector and €3,522 in social housing.

Positive health externalities Space heating does not only provide comfort, it contributes the material prerequisite for decent living. Low-income households living in the worst-performing homes typically cannot afford heating. The resulting exposure to cold temperatures causes respiratory and cardiovascular diseases (Gillingham et al., 2021; Symonds et al., 2021). In France, the annual social cost c_{health} of cold-related illness has been assessed to be €7,500 (Dervaux et al., 2022). Detailed in Appendix B, this estimate includes care costs, morbidity costs and mortality costs. While one

⁴While Lindhal pricing could address the issue, as is the case for financing an elevator, this does not apply to roof insulation, for instance.

might interpret it as a behavioral anomaly,⁵ the prevalence of the problem among low-income points to financial constraints as a strong determinant. We therefore interpret it here as an uninternalized externality. Note that it can be seen as the recipient of other market failures – credit rationing, frictions in rental and multi-family housing – which primarily affect low-income households.

Present bias There is robust evidence that consumers fail to weigh the future benefits of energy efficiency investment rationally (Schleich, 2019; Schleich et al., 2023). This so-called present bias tends to decrease with income, even after controlling for the lower financing cost enjoyed by wealthier households. Based on choice experiments conducted in France by Stolyarova (2016), we set the value of parameter λ to 3% for the top 20% of the income distribution, increasing up to 19% for the bottom 20%, with an average value of 9.6%.

Status quo bias Moreover, households tend to stick to their current technology when considering heating system, despite the higher profitability of some alternatives (Stolyarova, 2016; Lang et al., 2021a). This is captured in our framework by an intangible benefit of €8,600 for keeping the same system (Stolyarova, 2016).

2.4 Cost-benefit analysis

Our microfounded framework allows us to perform comprehensive cost-benefit analysis of energy efficiency programs.

Social welfare function We consider a utilitarian social welfare function that treats all individuals the same and factors in financial outcomes (energy expenditure and investment cost), non-financial outcomes such as comfort and ancillary benefits, environmental and health outcomes, and the opportunity cost of public funds. The social welfare function reads:

$$W = \sum_{i=1}^N \alpha_i \cdot [P_{i,k} \cdot (\underbrace{-c_k}_{\text{investment cost}} + \underbrace{E[\epsilon_{i,k}|k = \operatorname{argmax}_j V_{i,j}]}_{\text{ancillary value}})] \quad (11)$$

$$+ \gamma \cdot (- \underbrace{\eta_i p \cdot m_i^*}_{\text{energy expenditure}} + \underbrace{h(m_i^*)/\theta}_{\text{thermal comfort}}) \quad (12)$$

$$- \underbrace{\gamma \cdot \zeta \cdot Q}_{\text{carbon externalities}} - \underbrace{\gamma \cdot c_{\text{health}}}_{\text{health externalities}} + c_{\text{public money}} \quad (13)$$

where α_i is the weight of household group i , γ is the social discount factor, $P_{i,k}$ is the probability that type- i households make an energy efficiency investment k , Q is aggregate energy demand and $c_{\text{public money}}$ the opportunity cost of public funds. Welfare streams are then accumulated over lifetime horizon T and discounted at the rate of interest γ . In cost-benefit analysis, we compare lifetime discounted welfare streams between two scenarios s and s^{ref} as follows:⁶

$$\Delta W = \frac{\sum_{t=1}^T W_t(s) - W_t(s^{\text{ref}})}{(1 + \gamma)^t} \quad (14)$$

$$(15)$$

⁵Supporting evidence is provided by a recent survey showing that, regardless of income levels, only 6.3% of respondents considered health effects in their energy retrofit decisions (Benites-Aguilar et al., 2024).

⁶Under our quasi-linear utility assumption, income remains constant, thus being irrelevant to utilitarian welfare variation. We therefore ignore it in our social welfare function.

While most inputs have already been detailed, we clarify some of them here.

Ancillary attributes The unobserved non-energy value discussed above is calibrated so as to rationalize observed choices. An integral part of consumer surplus, it must be included in welfare analysis (Train, 2009). For option k to household i , we compute it as the expected value of the error term, conditional on investment being made, $E[\delta_{i,k} + \overline{\epsilon_{i,k}} | V_{i,k} > V_{i,j}, \forall j \neq k]$.

Opportunity cost of public funds The government collects tax proceeds from renovation expenditure at rate τ_k and from energy expenditure at rate τ . In addition, it subsidizes energy efficiency investment at rate s_k . This results in net government expenditure G :

$$G = \sum_{i=1}^N \alpha_i \cdot P_{i,k} \cdot (s_k - \tau_k \cdot p_k) - \tau \cdot Q. \quad (16)$$

We assume that every euro of net government expenditure causes μ euro of deadweight loss, typically equal to 20% (Stratégie, 2017). The opportunity cost of public funds therefore is:

$$c_{\text{public money}} = \mu \cdot G. \quad (17)$$

2.5 Model validation

A sensitivity analysis of the model is provided in Appendix E. In addition, we assess here its overarching behavior.

Long-term elasticity As detailed earlier, energy demand is calibrated in the model using short-term price elasticity (conditional on theoretical energy performance). In contrast, long-term elasticity is not an input of the model, but an output from it, resulting from endogenous renovation processes. Comparing it to empirical estimates is one way in which the model’s accuracy can be appraised. To compute the long-term price elasticity derived from the model, we conduct hundreds of simulations with varying energy price growth rates. We find long-term elasticities of -0.54 for electricity and -0.41 for natural gas. These values are consistent with average long-term elasticities of -0.61 calculated by Labandeira et al. (2017) and estimated with the U.S. NEMS model – respectively -0.48 and -0.21 (EIA, 2021).

Reproduction of recent trends Assessing the model’s ability to reproduce past trends is another possible approach to appraising its validity (Glotin et al., 2019). We compare simulated versus observed policy costs over the 4-year period spanning from the model initial year (2018) to the best-documented recent year (2021). Specifically, we feed the model with energy price records and introduce five subsidy programs that were in operation during this period. Policy specifications are detailed in Appendix D. Some of these instruments are discussed in greater length in Section 4.

The results displayed in Figure 3 reveal systematic understatement of aggregate policy costs, by as much as 30% in 2021 and as little as 4% in 2020. Looking more closely at cost decomposition, the error does not affect all policies in the same way. Several considerations can help explain the errors. First, policy parameters have typically been adjusted several times a year by French authorities, which is inherently difficult to keep track of. It is however unclear whether not capturing all changes results in under- or overstatement. Second, the model ignores some technologies which only play a modest role in heating energy consumption yet which are eligible in subsidy programs, such as ventilation, heat regulation systems and secondary heating systems. This omission undermines subsidy costs. Third, apart from the multiple

barriers considered in the model, it is assumed that households systematically receive the subsidies they are entitled to. This assumption tends to overstate subsidy costs. Finally, the significantly understated cost simulated in 2021 can be attributed to the peculiar circumstances of that year, in particular the exceptionally high number of home sales – a strong determinant of home renovation, not accounted for in the model – that occurred in the immediate aftermath of the first COVID-19 outbreak.

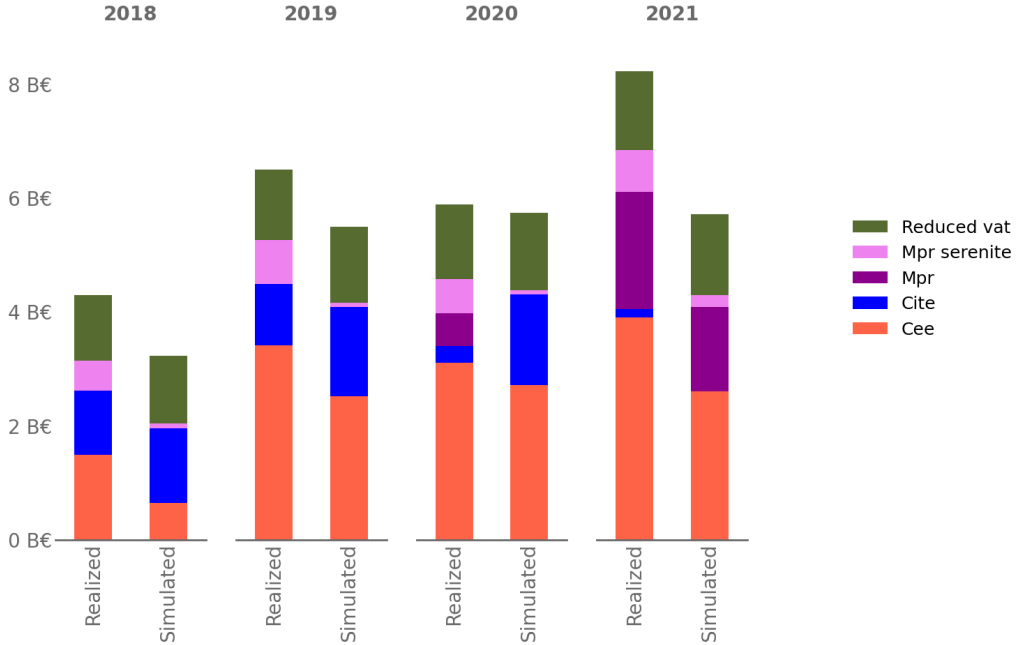


Figure 3: Comparison of simulated (‘Simulated’) and actual evolution (‘Realized’) of public expenditure in France between 2018 and 2021. Policy specifications are detailed in Appendix D.

In addition, we compare simulated policy effects on both the extensive and intensive margins of insulation investments to empirical estimates when available (see Figure 34). We find a proportion of infra-marginal participants in the MPR program of 78% in 2018, similar to the 80% estimated by Nauleau (2014) and Risch (2020) in 2005. As for the zero-interest loan program, we find a 20% effect on the extensive margin in 2024, in line with the estimates of Eryzhenskiy et al. (2023) of 20-22% in 2009.

Overall, these results give confidence in the ability of the model to accurately simulate policy impacts.

3 Mapping the energy efficiency gap

We now proceed with model runs. In this section, we take a normative approach and endeavour to map the energy efficiency gap. Building on Jaffe et al. (2004), we want to assess the individual and joint contribution of each market and behavioral friction to suboptimal outcomes along three dimensions – energy use, CO₂ emissions and social welfare.

3.1 Exogenous inputs

Energy prices grow at an annual rate of 1.35% for electricity, 1.04% for natural gas, 1.27% for fuel wood, 1.73% for fuel oil and 1.04% for district heating, based on the assumptions embedded in France’s nationally-determined contribution to the Paris Agreement. The carbon content of electricity falls from 0.079 gCO₂/kWh to 0

gCO₂/kWh by 2050, that of district heating from 0.101 gCO₂/kWh to 0.033 gCO₂/kWh. 14 TWh of gas consumption for space heating is covered by renewable gas. Aggregate income grows at 0.8% per year. As discussed earlier, the interest rate is constant at 3.9% per year and the return on savings is 2.5% per year. Lastly, outdoor temperature is held constant, thereby ignoring global warming.

3.2 Contribution of individual frictions

To assess the joint contribution of the seven frictions reported in Table 2, we compare a baseline that includes all frictions with a first-best counterfactual that ignores them all, i.e., that combines all ‘No friction’ specifications. To assess the individual contribution of each friction, we compare specifications with and without it. In parallel, we consider all possible combinations of frictions, which provides us with 128 intermediate scenarios, fit for exploring interactions between frictions.

Figure 4 displays the marginal impact of each friction, computed by comparing outcomes with and without it along all dimensions of social welfare. By inducing under-investment in home renovation, all frictions reduce investment cost compared to the ‘No friction’ counterfactual. Against these gains are the costs of forgone benefits from home renovation, namely avoided emissions, bill savings, improved comfort, improved health and ancillary benefits. One preliminary observation is that each friction affects all welfare components, which suggests that interactions between frictions are significant.

The figure displays the net cost-benefit balance along three perspectives – private (where only investment cost, bill savings, improved comfort and ancillary value are considered), social (where all costs and benefits are considered) and social without ancillary value. The private value is negative under all frictions, which suggests that each one alone is sufficient to make renovation privately unprofitable. From the social perspective, free-riding in MFH appears as the largest friction, followed by the landlord-tenant dilemma and the CO₂ externality. The ranking changes dramatically when ancillary benefits are ignored, making the CO₂ and health externalities the two most critical problems. This highlights the crucial role played by frictions in rental and multi-family housing, which deny occupants significant benefits. The CO₂ externality exhibits a peculiar welfare profile, as fully internalizing it would imply reduced comfort on the one hand and more tax proceeds on the other.

Figure 5 plots social welfare against cumulative energy savings so as to produce the so-called Jaffe-Newell-Stavins diagram (Jaffe et al., 2004).⁷ In addition to individual frictions, the figure includes all combinations of them. The shape of the scatter plot confirms that energy savings and social welfare tend to go hand in hand. Overall, the combination of all frictions implies an annual deadweight loss of €4 billion per year on average, equivalent to half of support for energy renovation in France in 2021. In Figure 6, we produce the same diagram in the welfare-CO₂ space.

3.3 Interactions

The vast area covered by interactions in Figure 5 motivates closer examination. We examine one-to-one interactions in Figure 7. We find that most interactions are mild and almost systematically under-additive, with notable exceptions. Credit constraints entail over-additive interactions, especially when combined with health cost externalities or present bias – two frictions that disproportionately impact low-income households. This highlights underscores the need for a holistic approach of frictions. In Supplementary Figure 21, we go further and plot all-order interactions, which essentially confirms the insights derived from one-to-one interactions. Supplementary Figures 22, 24 and 23 display Sobol indices, which measure the total influence of a certain variable

⁷This is the ultimate version of a diagram first sketched by Jaffe et al. (1994b).

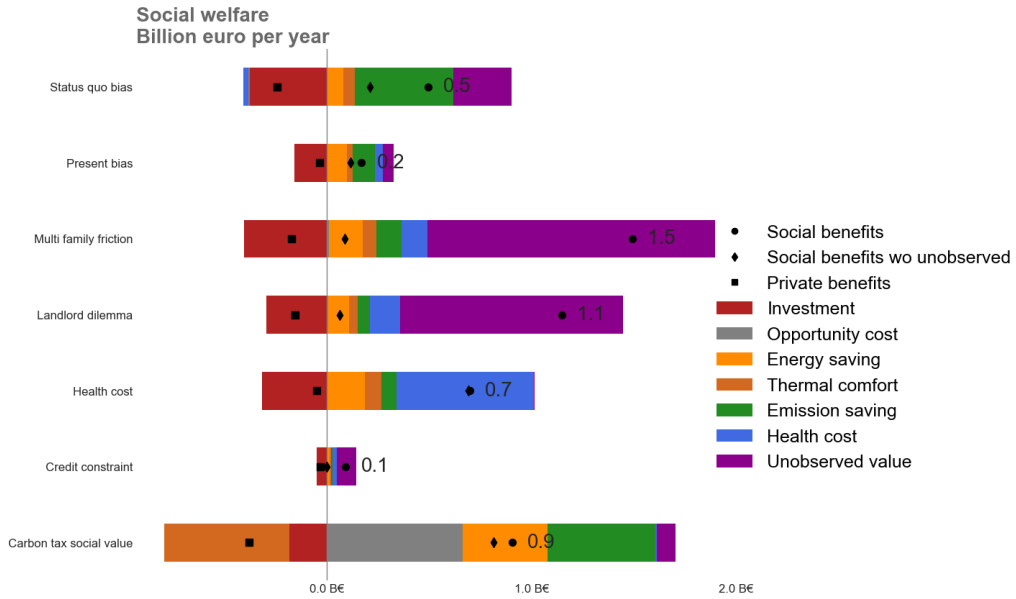


Figure 4: Marginal impact of standalone frictions on costs and benefits. The round marker represents net benefits, including all private and social benefits. The diamond marker shows the same benefits, net of ancillary value. The square marker represents private benefits, simply balancing investment costs and bill savings plus comfort gains.

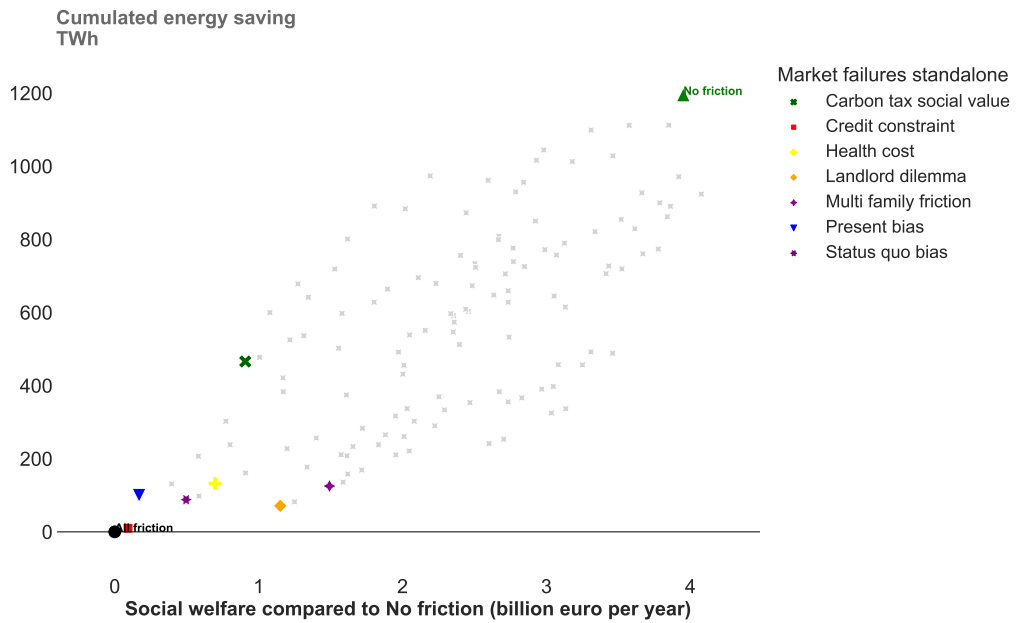


Figure 5: The Energy Efficiency Gap. Each dot represents a combination of frictions. Special markers in the legend refer to the standalone effect of removing each friction, as shown in Figure 4.

on an outcome of interest, with interaction with others (total order) and without them (first order) (Sobol, 2001). The lengths of the bars confirm the friction rankings that appear in Figure 5 in terms of both social welfare and emissions reductions. The small wedge between first-order and total-order metrics confirm that interactions are mild.

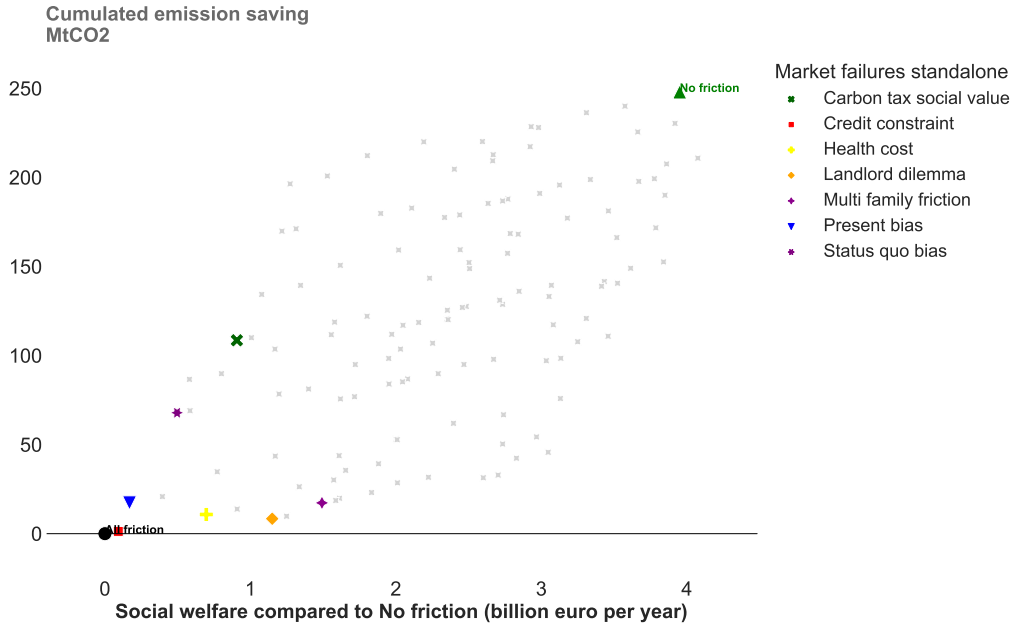


Figure 6: Mapping Emission Efficiency Gap. Each dot represents a combination of frictions. Special markers in the legend refer to the standalone effect of removing each friction, as shown in Figure 4.

3.4 Stylized subsidies

Under the textbook Tinbergen rule, each friction should be addressed by a dedicated policy instrument. In the market environment considered here, the optimal policy mix would thus include: a carbon fee to internalize the CO₂ externality; a tax on worst-performing dwellings if they are occupied by a low-income household; subsidies to eliminate free-riding in MFH; contract provisions that allow landlords and tenants to share the value of energy efficiency investment; and subsidies to overcome credit constraints. Tackling behavioral anomalies is more debated on paternalistic grounds (Gillingham et al., 2014), but energy efficiency subsidies are known to provide an effective nudge against investment inertia (Allcott et al., 2014).

In practice, however, policy departs from first-best prescriptions. This is especially the case in the French residential sector, where the carbon tax has been strongly opposed in 2018 (Douenne et al., 2022). Meanwhile, energy efficiency subsidies have long been the preferred approach, since as early as 1999 with the reduced value-added tax (see Appendix D). It is well known that energy efficiency subsidies are less cost-effective than energy taxes at reducing energy-use externalities, due to the rebound effect they generate (Goulder et al., 2008; Giraudet et al., 2008; Chan et al., 2023). Yet they are considered more acceptable (Blanchard et al., 2023). Moreover, they can be an effective solution to accompanying frictions, thereby motivating their use for addressing multiple problems at the same time.

In this spirit, we examine a stylized policy mix that combines four subsidies, each tailored to address one of the four main market failures – the CO₂ externality, the health externality, the landlord-tenant dilemma and multi-family frictions. Figure 8 exhibits patterns relatively similar to those of Figure 4 for the four considered market failures, with the important difference that social costs now include the opportunity cost of subsidies. Otherwise, the net benefit-cost balance is still positive from a social perspective and negative from a private perspective. Supplementary Figures 25 and 25 also confirm the under-additivity of policy solutions and simply results from the marginally decreasing returns from renovation. This emphasizes the impact overstate-

Policies	In interaction with						
	Carbon tax social value	Credit constraint	Health cost	Landlord dilemma	Multi family friction	Present bias	Status quo bias
Carbon tax social value	0.9	1%	-3%	-1%	-5%	0%	-21%
Credit constraint	9%	0.1	130%	8%	3%	146%	-3%
Health cost	-4%	17%	0.7	-34%	-26%	-13%	1%
Landlord dilemma	-1%	1%	-20%	1.1	-4%	1%	-2%
Multi family friction	-3%	0%	-12%	-3%	1.5	-0%	-2%
Present bias	1%	79%	-56%	10%	-4%	0.2	-50%
Status quo bias	-37%	-1%	1%	-5%	-7%	-17%	0.5

Figure 7: One-to-one interactions. Diagonal values refer to the marginal welfare impact of standalone policies. Other cells refer to the percentage change compared to this value due to interactions.

ment that may result from failing to take into account subsidy interactions (Gillingham et al., 2018). Supplementary Figure 27 displays the Sobol indices. It shows that subsidies have a comparable effect in welfare terms. However, interactions are now strongly over-additive.

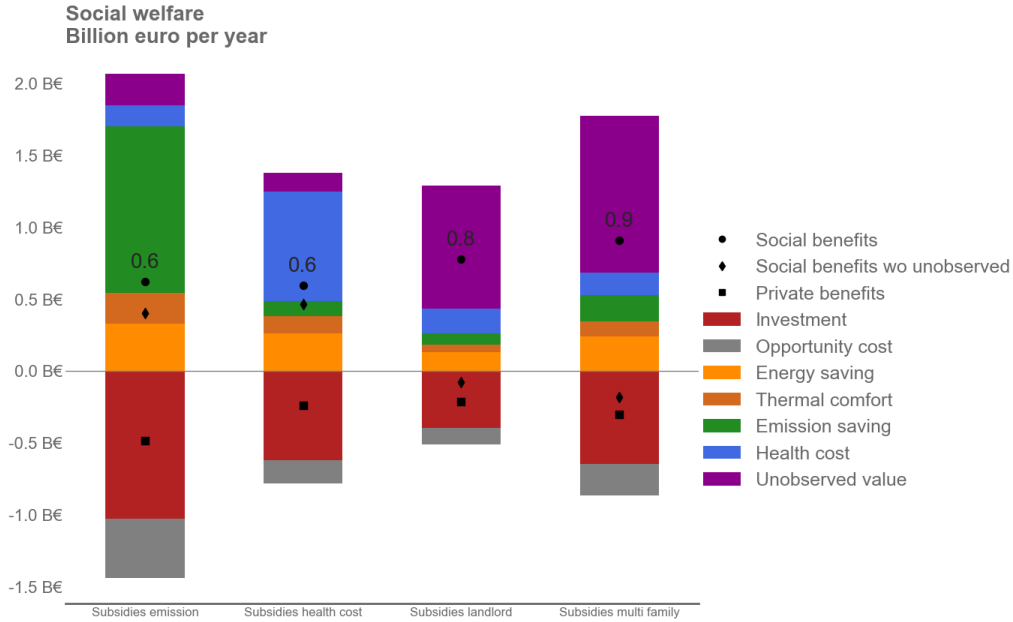


Figure 8: Marginal welfare impact of stylized policy solutions. The round marker represents total social benefits, including all private and social benefits. The diamond marker shows the total benefits excluding the unobserved benefits. The square marker represents private benefits, calculated as energy reduction and thermal comfort gains minus the investment cost.

4 Actual policies

We now turn to actual policy and ask whether the instruments in place are effective at closing the energy efficiency gap. We focus on France, which offers a particularly rich and well-diversified policy portfolio (for an overview, see Charlier et al., 2018; Giraudet et al., 2021a; Chlond et al., 2023).

4.1 Policy instruments

We consider five policy instruments already in place and one considered for future implementation. Broadly speaking, these instruments fall into three categories and hybrid forms thereof – carbon pricing, energy efficiency subsidies and regulations. Policy specifications are detailed in Table 3.

Policy	Instrument type	Justification	References
MPR subsidies	Incentive: energy efficiency subsidy (per-unit, targeted)	Externalities and public good; credit rationing; present bias	Nauleau (2014) and Risch (2020)
Zero-interest loan	Incentive: energy efficiency subsidy (ad valorem with varying rate)	Externalities and public good; credit rationing	Eryzhenskiy et al. (2023)
Carbon tax	Incentive: energy tax (per-unit)	Pigou	Bourgeois et al. (2021) and Douenne (2020)
White certificates	Hybrid energy efficiency subsidy/energy tax (targeted)	Externalities and public goods; credit rationing	Giraudet et al. (2008) and Glachant et al. (n.d.)
Rental ban on inefficient housing	Regulation	Externalities	Vivier et al. (2021)
Ban on new gas boilers	Regulation	Externalities	Escribe et al. (2024a)

Table 3: Policies considered

Carbon tax Carbon pricing is the textbook solution to the CO₂ externality. In the context of residential energy use, it encourages both energy efficiency investment and energy conservation behavior, whereas energy efficiency and regulations only activate the former channel.⁸ This advantage however comes with unintended effects when other market failures are considered. In particular, by making heating less affordable, it may increase exposure to cold temperatures, with significant adverse health effects.

One key question with carbon pricing is whether and how the proceeds are to be recycled and earmarked for certain purposes. The textbook approach recommends separating the price signal from revenue recycling, and therefore returning money in a lump-sum manner at best. Such a separation de facto prevails in France, where budgetary rules prevent the government from earmarking the revenue from the carbon tax. Meanwhile, the government does provide a lump-sum payment to low-income households, independent of carbon tax revenue, earmarked to cover either energy expenditure or energy efficiency investment. In any case, returning carbon tax proceeds can greatly mitigate the regressive effect the instrument has within the scope of space heating (Bourgeois et al., 2021).⁹ In addition, earmarking revenue to low-carbon technologies make carbon pricing more acceptable (Douenne et al., 2022).

We consider the carbon tax implemented in France in 2014. Since 2018, the retail prices of natural gas and fuel oil are subject to a €45/tCO₂ fee. We maintain that rate for the whole time horizon. We assume that tax proceeds are returned to home occupants in a uniform lump-sum manner. While this assumption does not affect quasi-linear utility, it is instrumental to examine tax incidence. We further assume that the carbon tax is superseded by an extension of the EU ETS to space heating in 2030, starting from €50/tCO₂ and gradually increasing to €85/tCO₂ in 2040 and €160/tCO₂ in 2050. The same revenue-recycling assumption holds. Importantly, we assume that households do not anticipate this ramp up, due to the prevalence of constant-price foresight (Anderson et al., 2013).

MPR program Subsidy programs have been the preferred approach to encouraging energy efficiency in France. As discussed in Section 3.4, compared to carbon pricing, they generate a rebound effect, making them less cost-effective at mitigating the CO₂ externality. They nevertheless contribute to addressing a number of other frictions. They provide a more salient investment signal than does the carbon tax, which may induce a stronger response among households prone to a present bias (Allcott et al., 2014; Chan et al., 2023). Moreover, by lowering upfront cost, they effectively reduce credit rationing. Lastly, they can also be used to mitigate free-riding problems in MFH.

The main concern with subsidies is infra-marginal participation – the participation of households who would have invested anyway (Boomhower et al., 2014). The problem typically occurs when subsidy programs have uniform schedules. It can be addressed by finely targeting subsidy programs where they are most needed – which can only partially be achieved based on observable characteristics. An effective approach is to target low-income households, whose investment decisions are distorted by multiple frictions. Another way to better target subsidies is to substitute per-unit schedules to ad valorem ones, the latter being prone to price distortion under imperfect competition (Nauleau et al., 2015).

Since 2005, the government has been running a direct subsidy program. Once called CITE and now called MPR, the program has gone through multiple design changes, which are summarized in Figure 30 and Table 20. Its earlier version was found to effectively stimulate investment on both the extensive and intensive margins

⁸The superiority of carbon pricing more generally lies in its ability to address all pollution channels – input choice, end-of-pipe treatment and output reduction (Goulder et al., 2008). The residential carbon tax activates the latter two.

⁹Outside this scope, incidence is not systematically regressive (Cronin et al., 2019).

(Nauleau, 2014; Risch, 2020). The latest version of the program is a per-unit subsidy with three legs. One leg targets low-income households, who are granted larger subsidy amounts. Another leg targets comprehensive retrofits and a third one targets MFH.

Zero-interest loan program (ZIL) Since 2009, households can take zero-interest rate loans from retail banks to finance home energy retrofits, up to a certain amount and duration. Banks get a compensation from the government on each loan. From the borrower perspective, the program can be seen as an ad valorem subsidy with a floating rate determined by the market interest rate. The program has been found to effectively stimulate investment – and particularly so for low-income homeowners – but only in its first two years of operation (Eryzhenskiy et al., 2023). The later failure is generally attributed to administrative complications making banks reluctant to participate. After some simplifications implemented in 2019, the instrument has been gaining traction again, to the point of reaching its expected level in 2014.

White certificate program (WCO) In 2006, an obligation was imposed on French energy suppliers to encourage energy efficiency investment. To do so, energy suppliers grant energy efficiency subsidies to end-users, in return to which they get certified energy savings, also known as white certificates, which provide compliance claims. In the liberalized energy markets in which they operate, energy suppliers are allowed to pass-through this compliance costs onto retail energy prices. They are also allowed to trade white certificates. Tightened up every three or five years, the aggregate target now requires 775 TWh lifetime discounted to be saved every year, 36% of which must be achieved among low-income households. Over the past three years, the residential sector has been contributing on average 65% of this obligation. Assuming a current white certificate price of €7/MWh lifetime discounted, this implies €3.5 billion annual spending on energy efficiency subsidies.

From a general perspective, the program can be considered a hybrid instrument combining an energy efficiency subsidy component and an energy tax component. As such, it provides a good compromise between cost-effectiveness and acceptability (Giraudet et al., 2008). The subsidy part corresponds to a per-unit regime differentiated by income level, with bonuses for insulation measures and low-carbon heating systems.

Rental ban on worst-performing housing Incentives are increasingly complemented with regulations. The textbook insight on regulations is that they are less cost-effective than incentives to reduce externalities. This is due to their lower flexibility, which materializes in our framework through utility losses associated with ancillary value.

Since 2023, the dwellings belonging to the worst performing fringe of EPC band G can no longer be rented out. The ban applies when a new rent is signed with a new tenant, which occurs on average every 7 years. It will be extended to the whole band G in 2025, then to band F in 2028 and band E in 2034. In our framework, the rent is modelled as an obligation for the owner to upgrade their dwelling to at least label D when a new rent is signed. Specifically, investment is forced on the extensive margin, with a choice set reduced to reaching band D or higher on the intensive margin.

Ban on new fossil fuel heating systems Since 2022, fuel oil boilers cannot be replaced by the same technology when they fail. We model this as an obligation to adopt an air-to-water heat pump. A similar ban is discussed at the European level with natural gas. We similarly model it as a switch toward heat pumps.

4.2 Results

We now run the model with standalone policies. We start with assessing the individual impact of each policy by comparing two scenarios – with and without the policy. We then consider alternative market and behavioural counterfactuals to delve further into their effect. All scenarios are run with the same exogenous inputs, introduced in Section 3. Note that we assume that all instruments work at their full capacity, meaning that households effectively claim the subsidy benefits they are entitled to. All numerical results are provided in Appendix D.

Individual impacts Figure 9 displays the benefit-cost balance for each policy. No policy appears to be profitable from a private perspective, thereby echoing myriad analyses calling into question the desirability of energy efficiency policies (e.g., Fowlie et al., 2018). Accounting for both non-energy private value and non-carbon social value however provides a very different picture, with a net positive balance for all policies but the natural gas ban.

Perhaps more than any other component, the ancillary value plays a critical role in the net benefit-cost balance. It turns out positive with subsidies, negative with regulations (especially so with the natural gas ban) and negligible with the carbon tax. The reason why lies in how the unobserved value is distributed across households. Since private benefits (i.e., bill savings and increased comfort) do not fully cover investment cost, it must be that the marginal investors have a positive ancillary value. In increasing participation at the margin, subsidies therefore attract new participants with a similarly close positive value. In contrast, regulations impose investment on households irrespective of their private profitability. Their ancillary value corresponds to the population average, which is strongly negative – from €8,585 for roof insulation to €87,104 for floor insulation, depending on the measure considered. This starkly illustrates the lack of flexibility of regulations, which inherently restrict choices.

Looking more specifically at each instrument, the carbon tax has a negligible effect on ancillary value. This is due to its low impact on investment, overshadowed by a strong impact on conservation behavior. The investment response is made even weaker by the accompanying frictions, in particular credit rationing and the present bias. Likewise, the carbon tax has a negligible effect on health. In turn, it raises public money, which secures a net positive balance.

Subsidy programs all yield net positive benefits which largely outweigh the associated opportunity costs of public funds. Their contribution to social welfare is €0.8 billion per year. The performance of WCO is very close to that of MPR, which is consistent with the fact that their subsidy schedules are very similar. The tax component of WCO is too small to significantly affect the net balance. The impact of the ZIL is smaller than that of its subsidy counterparts, due to a weaker effect on credit rationing.

While the two regulatory tools similarly increase ancillary costs, they have very contrasted impacts on CO₂ emissions and health. On the one hand, the rental ban reduces health costs and has a very modest impact on emissions reductions. This is the opposite with the gas ban – a massive impact on emissions reductions coupled with an adverse impact on health. Indeed, by overcoming investment barriers in rental housing, the ban takes low-income occupants out of fuel poverty. In contrast, under the natural gas ban, those households that use electrical heating stick with this low-carbon, high-operating cost option, which fails to reduce fuel poverty and the associated health costs.

Table 4 decomposes the costs and benefits and complements them with cost-effectiveness estimates. It suggests that the carbon tax and the gas ban are the most cost-effective tools to reduce CO₂ emissions, however with markedly different patterns – low cost, low effectiveness for the former, high cost, high effectiveness for the latter. It should be emphasized that such cost-effectiveness indicators undermine the

broader benefits generated by subsidies (chiefly health-related) at the denominator.

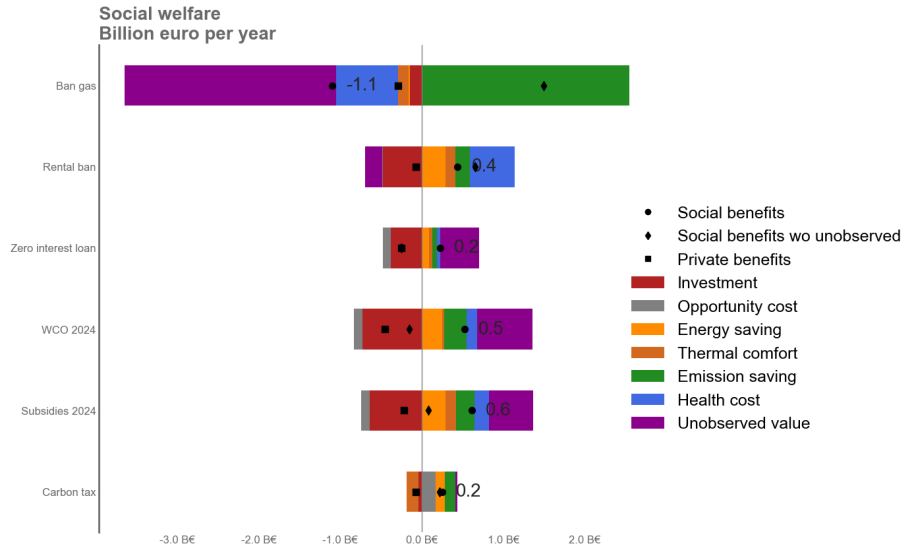


Figure 9: Cost-benefit analysis of individual policies implemented in France compared to the 'No Policy' scenario, with costs and benefits discounted at a social rate of 3.2%.

	Unit	C. tax	Subsidies	WCO	ZIL	Rental ban	Ban gas
Energy use	TWh	-61.57	-117.63	-107.17	-34.77	-100.46	-211.86
CO ₂	MtCO ₂	-14.26	-16.96	-25.19	-4.12	-9.69	-121.54
Investment	B€/year	-0.04	-0.64	-0.73	-0.38	-0.48	-0.15
Energy saving	B€/year	0.12	0.29	0.25	0.09	0.29	-0.01
Thermal comfort	B€/year	-0.15	0.12	0.03	0.04	0.12	-0.13
Unobserved value	B€/year	0.03	0.54	0.68	0.47	-0.21	-2.60
Opportunity cost	B€/year	0.17	-0.11	-0.10	-0.09	0.00	0.00
Emission saving	B€/year	0.13	0.23	0.27	0.06	0.18	2.55
Health cost	B€/year	0.00	0.18	0.13	0.04	0.55	-0.76
NET BALANCE	B€/year	0.25	0.61	0.53	0.22	0.44	-1.10
Negawatthour cost	€/kWh	0.02	0.17	0.22	0.35	0.15	0.02
Abatement cost	€/tCO ₂	97.22	1200.54	926.90	2962.04	1584.50	38.54

Table 4: Cost-benefit and cost-effectiveness assessment of standalone policies.

Merit order under alternative perspectives Up to now, we have assessed policies within an environment prone to market failures and behavioral anomalies. We find largely positive benefits – at odds with most of the literature. Importantly, we consider that households are aware of the energy performance gap and correctly anticipate that energy savings will be lower than predicted. This point is contentious, however, some authors pointing out that the deceptive effect of the energy performance gap can cause too much investment, hence significant deadweight loss (Fowlie et al., 2018; Allcott et al., 2024).

To examine the extent to which the normative perspective taken may affect policy performance, we consider three alternative counterfactuals alongside our baseline frictional environment (‘Friction’):

- **Friction, biased:** In addition to frictions, households make decisions based on predicted energy savings;
- **No friction:** All frictions have been removed and households accurately anticipate real energy savings;¹⁰
- **No friction, biased:** All frictions have been removed but households make decisions based on predicted energy savings.

Table 5 compares the welfare impact of policies across perspectives. In the most conservative ‘No friction, biased’ case, where no friction other than the CO₂ externality is to be addressed and people make incorrect decisions, policies have a strongly negative impact, save for the carbon tax (and to a lesser extent the ZIL), which by design is first-best in such an environment. The insight here is consistent with that established by Fowlie et al. (2018) and Allcott et al. (2024) in a similar environment. Yet assuming that households correctly anticipate real energy savings is enough for the net balance to turn positive – except for the gas ban, which is systematically negative. Generally speaking, the effect on welfare is of the same order of magnitude as that obtained when frictions are considered, with varying magnitudes across policies.

	Friction	Friction biased	No friction	No friction biased
Carbon tax	0.257	0.248	0.234	0.216
WCO	0.42	0.279	0.031	-0.195
Subsidies	0.607	0.332	0.337	-0.217
Zero interest loan	0.311	0.151	0.299	0.016
Rental ban	0.346	-0.36	0.219	-0.266
Ban gas	-1.251	-1.319	-2.509	-2.666

Table 5: Cost-benefit impact of French policies (Billion €per year) under alternative perspectives. ‘Biased’ refers to households making their decision based on overstated engineering predictions.

¹⁰Specifically, the ϕ s equal zero, λ is equal to 3.2%, health costs c_{health} and the social cost of carbon ζ are fully internalized and there is no borrowing constraint ($b = 0$).

Policy interactions We now examine interactions between policies in the same way as we assessed interactions among frictions. We consider both one-to-one interactions (Figure 10a) and all-order interactions from the 64 possible policy combinations (Figure 10b). In general, net benefits are slightly lower when interactions are considered than in the standalone case. Interactions can therefore be interpreted as under-additive, as pointed out in other works (Charlier et al., 2018). They are however too mild to change the sign of the net balance.

If anything, interactions are not systematically under-additive when it comes to the gas ban. On the one hand, the carbon tax exacerbates health costs in electricity-heated dwellings, hence amplifies the negative effect of the ban. The opposite is true with the other tools, which tend to alleviate health costs.

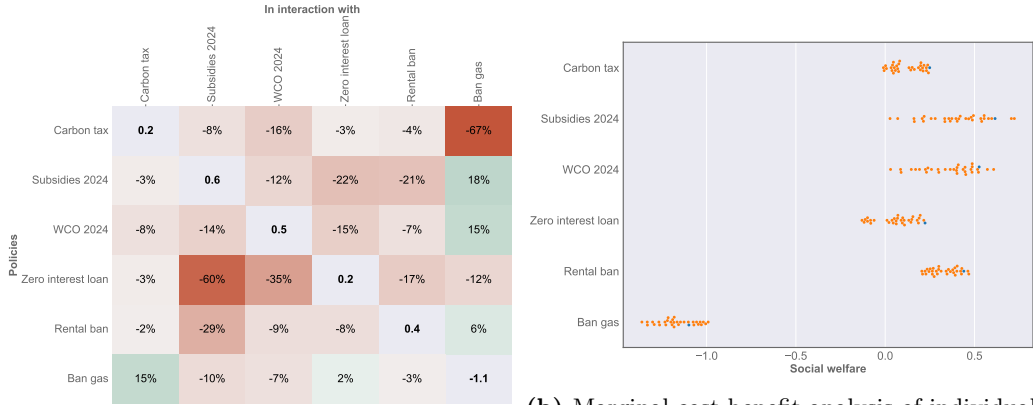


Figure 10: Net benefit-cost balance under various interactions.

5 Assessing the implementation gap

We now examine the actual policy package and some variants of it to assess the implementation gap on all relevant policy dimensions – total welfare, environmental effectiveness and distributional impacts.

5.1 Policy packages

All packages include the ban on fuel oil boilers implemented in 2022. Each package is further specified as follows:

- **Baseline Package:** Includes the policies currently in place, namely MPR subsidies, ZIL, WCO, the carbon tax and the rental ban;
- **Baseline Package + Gas Ban:** Additionally includes the ban on new gas boilers considered at the European level for implementation in 2030;
- **SCC benchmark:** The only instrument in place is a carbon tax set to the French SCC (€150/tCO₂ in 2024, €250/tCO₂ in 2030 and €775/tCO₂ in 2050). The proceeds are returned to households in a lump-sum manner (see Appendix B). This package allows us the appraise how the supposedly first-best solution to the CO₂ externality fares when several other frictions are considered. We continue to assume that households do not foresee the tax ramp up and make their decisions based on the contemporaneous rate.

Due to lacking data, we extrapolate to social housing the policy impacts obtained in private housing. The three packages are compared to two of the counterfactuals introduced above – ‘No policy’ and ‘No friction.’

5.2 Environmental effectiveness

Figures 11a and 11b display pathways of energy consumption for space heating and the associated CO₂ emissions. Absent policies, energy use falls by 20% and CO₂ emissions by 58% in 2050 compared to their 2018 levels. This is due to the autonomous energy efficiency improvements embedded in building stock turnover and some exogenous efforts on energy supply decarbonization. In a world devoid of frictions, higher energy efficiency investment would further reduce energy use by 19 percentage points (p.p.) and CO₂ emissions by 22 p.p. With 31 MtCO₂ in 2030, this scenario misses the 26 MtCO₂ mark corresponding to the ‘Fit for 55’ European target. With 10 MtCO₂ in 2050, it is not consistent with the carbon neutrality target either, estimated to involve 3 MtCO₂ from space heating by 2050 (ADEME, 2022).¹¹

The baseline policy package only partially closes the gap between the ‘No policy’ and ‘No friction’ scenarios – by about 80% for energy use and two thirds for CO₂ emissions. The SCC benchmark fares even less well, especially when it comes to energy use. This goes to illustrate how poorly the first-best solution to one problem – here the CO₂ externality – may perform when multiple other frictions are present and left unaddressed. Adding a ban on new gas boilers to the baseline package, which by design induces a massive switch towards heat pumps from 2030 on, generates significant additional energy savings (+9 p.p. in 2050 compared to the baseline package) and emissions reductions (+23 p.p.). This is the only option that comes close to carbon neutrality.

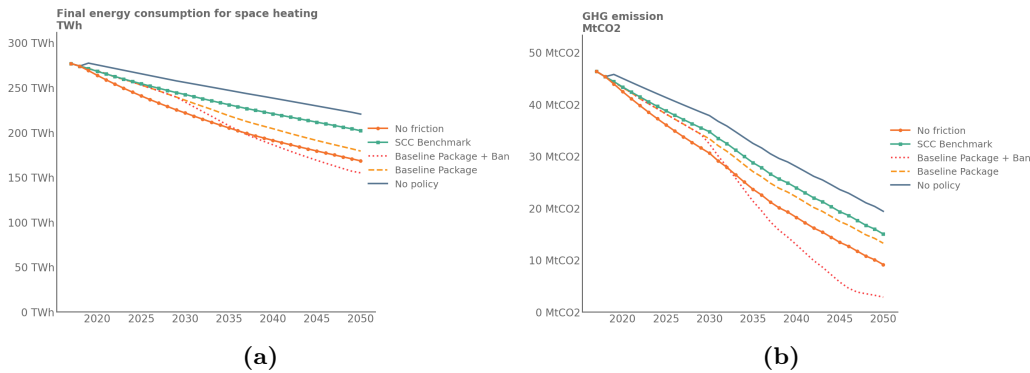


Figure 11: Evolution of (a) final energy consumption for space heating and (b) the associated CO₂ emissions.

Figure 12 illustrates changes in the energy performance of the dwelling stock, which overall increases from 28 millions in 2018 to 40 million in 2050. The baseline package succeeds in nearly eliminating the worst-performing dwellings – i.e., labels E, F and G of the EPC – by 2050, however without making the best-performing ones widespread – the fraction of labels A and B only goes as high as 50%. Noticeably, the SCC benchmark generates a less energy-efficient dwelling stock, which further illustrates the lack of significant impact of carbon pricing on energy efficiency investment.

Figure 13 illustrates changes in the prevalence of various heating systems. By design, all scenarios exhibit a substitution of heat pumps for the banned fuel-oil systems.

¹¹This result is at odds with the notion that the social cost of carbon reflects the shadow price of carbon neutrality in France (Quinet, 2019a). In fact, the models used for computing it did not feature as detailed a representation of the residential sector as ours, hence likely underestimated the cost of carbon neutrality for space heating.

The ban on gas boilers also amplifies heat pump adoption by forcing households to switch to low-carbon heating system. Likewise, under the SCC benchmark, direct electric systems remain prevalent among credit-rationed households and in poorly-insulated dwellings, thus generating high operating costs. Despite a general shift towards heat pumps, the overall increase in electricity consumption is limited to 20 TWh at most, only representing 4% of electricity consumption in 2024 (see Figure 37 in Appendix).

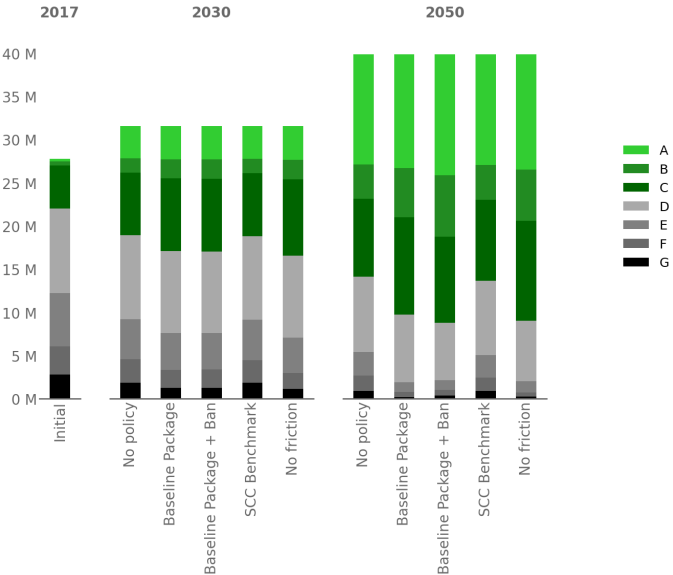


Figure 12: Evolution of the energy performance of the housing stock, by EPC rating (G: least efficient; A: most efficient).

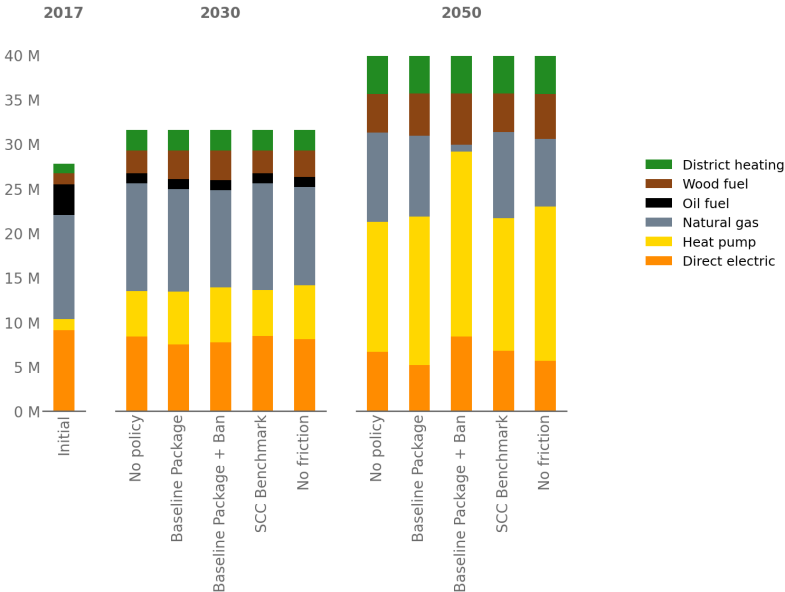


Figure 13: Evolution of heating systems prevalence.

5.3 Social welfare

Figure 14 displays benefit-cost balances for the different scenarios, assessed against the ‘No policy’ counterfactual. Further details are provided in Appendix E. As noted earlier, no scenario appears profitable from a narrow private perspective. With €1.4 billion net benefits per year, the baseline package appears as the most profitable from a social perspective. It however falls €3 billion short of closing the gap with the ‘No friction’ counterfactual. Adding the ban nearly annihilates the net benefits from the baseline package, essentially due to negative ancillary value discussed above.

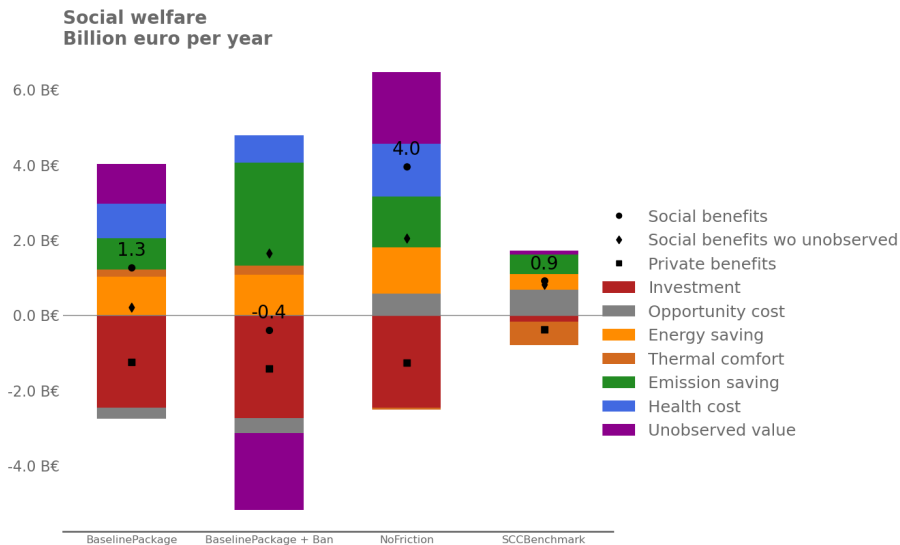


Figure 14: Welfare effects compared to the ‘No Policy’ scenario. Benefits are accumulated over 20 years. Costs and benefits are discounted at 3.2% per year.

5.4 Distributional impacts

Figure 15 displays variations in total household cost across several dimensions – income categories on the x-axis, capturing vertical inequalities, and housing type and occupancy status in the different quadrants, capturing horizontal inequalities. Total household cost is the net result of energy expenditure, investment repayment net of subsidies and benefit transfers. It is displayed in absolute terms in panel 15a and as a fraction of income in panel 15b.

The ‘No friction’ benchmark involves higher total cost, primarily falling on low-income households living in larger home (owner-occupied). This illustrates inequalities inherent in energy consumption, which weighs disproportionately heavy on low-income households’ expenditure. The only exception in is multi-family, privately rented housing, the low surface area of which keeps energy expenditure relatively low. Most policies tend to mitigate vertical inequalities – without fully eliminating them – thanks to income-based subsidy schedules. Subsidies do not effectively address horizontal inequalities, however. In particular, landlords, who tend to be well-off, are entitled less subsidies. As a result, they little invest in energy efficiency, thus leaving their tenants bear high energy costs. This calls for adjusting subsidy schedules to provide more benefits to landlords (as does the stylized subsidy introduced earlier).

5.5 First-best versus actual policy

We finally map the different packages within the Jaffe-Newell-Stavins diagram to visualize the implementation gap and compare actual and stylized policy solutions. Figure

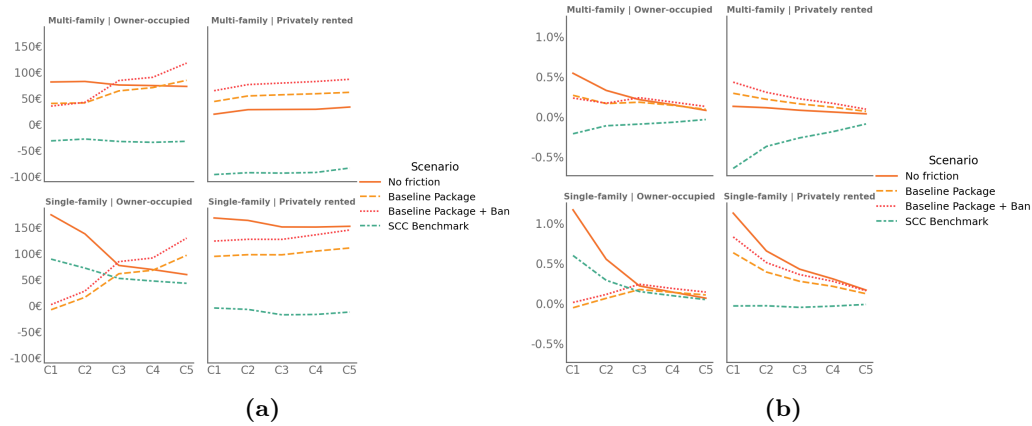


Figure 15: Evolution of total spending in 2050 compared to the ‘No policy’ counterfactual, (a) in absolute terms and (b) as a fraction of income.

16 and Table 6 indicate that the current package closes only about two thirds of the energy savings gap but only a third of the welfare gap. Better designing subsidies could help reduce the welfare gap, while only slightly reducing energy savings.

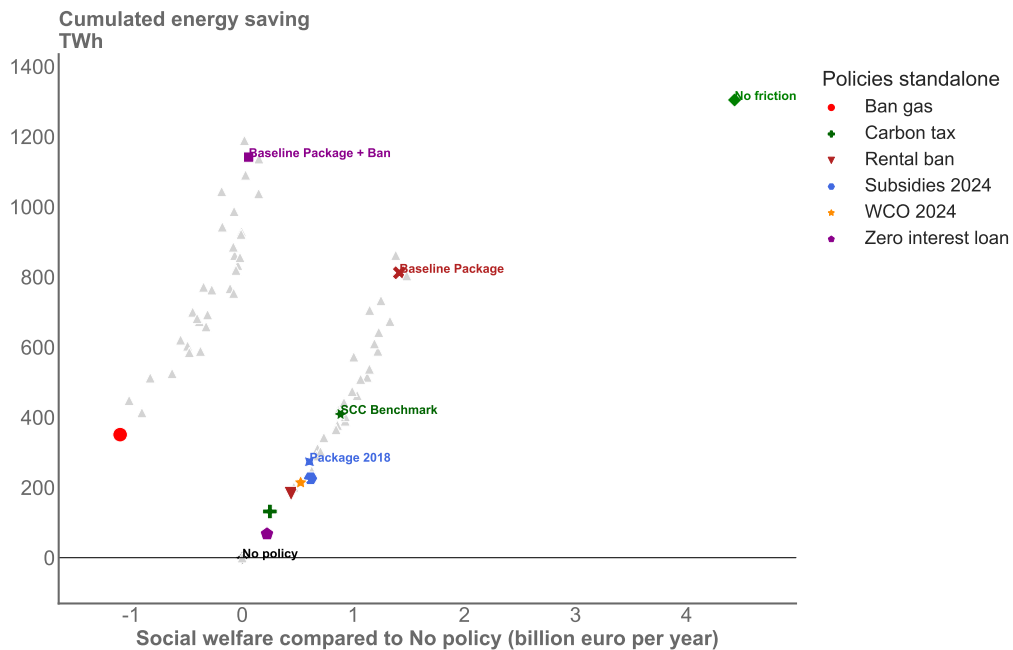


Figure 16: Implementation gap

To further investigate subsidy designs, we follow Allcott et al. (2024)’s approach and plot subsidy amounts against the frictions they are meant to address. Figure 18 shows that our baseline policy packages implies only a loose connection between the two. In contrast, subsidies and frictions show a much better alignment with stylized policy solutions (Figure 18b). The residual misalignment can be attributed to uncorrected behavioral biases.

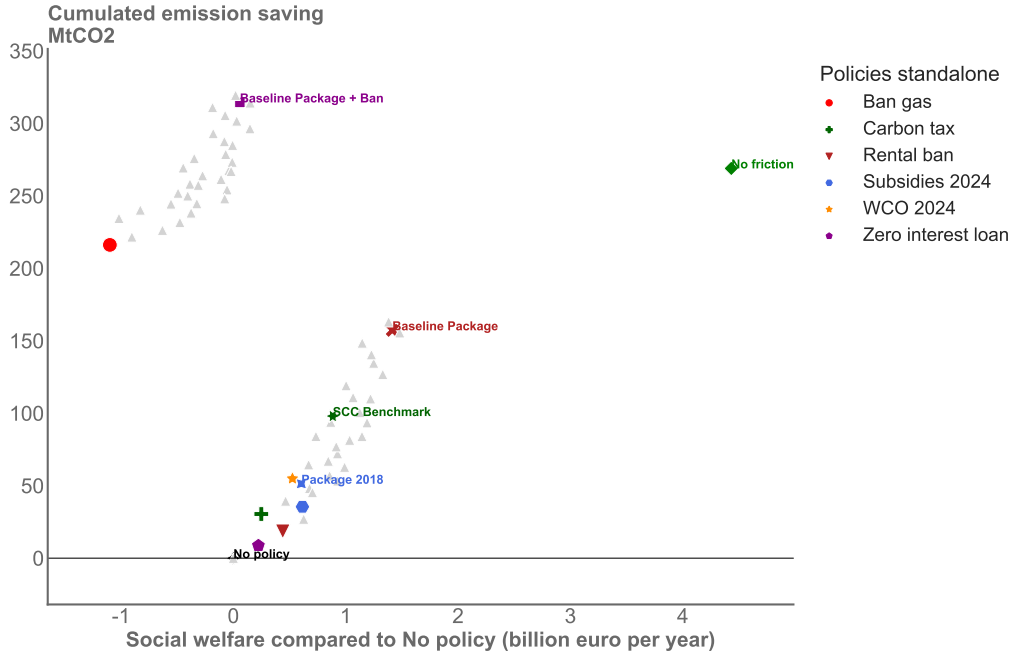


Figure 17: Implementation gap

	No friction	Stylized policies	Actual policies
Cumulated Consumption (TWh)	7297.60	7696.16	7675.35
Cumulated Emission (MtCO ₂)	898.01	920.92	994.95
Consumption (TWh) 2050	168.19	182.80	179.16
Emission (MtCO ₂) 2050	9.12	9.14	13.23
Δ cumulated energy (TWh)	7297.60	7696.16	7675.35
Δ cumulated emission (MtCO ₂)	898.01	920.92	994.95
Δ investment cumulated (B€)	-141.34	-140.54	-139.01
Δ subsidies cumulated (B€)	0.00	-202.22	-112.09
Δ investment (B€/year)	-2.43	-2.32	-2.42
Δ energy saving (B€/year)	1.12	0.74	0.89
Δ thermal comfort (B€/year)	0.10	0.38	0.34
Δ unobserved value (B€/year)	1.88	1.38	1.03
Δ opportunity cost (B€/year)	0.39	-0.80	-0.47
Δ emission saving (B€/year)	1.22	1.27	0.70
Δ health cost (B€/year)	1.42	0.82	0.92
Δ NPV annual (B€/year)	3.69	1.48	1.00
Δ NPV annual observed (B€/year)	1.82	0.09	-0.03
Investment/energy (euro/kWh)	0.15	0.23	0.22
Investment/emission (euro/tCO ₂)	761.90	788.77	1380.89

Table 6: Detailed assessment of the implementation gap.

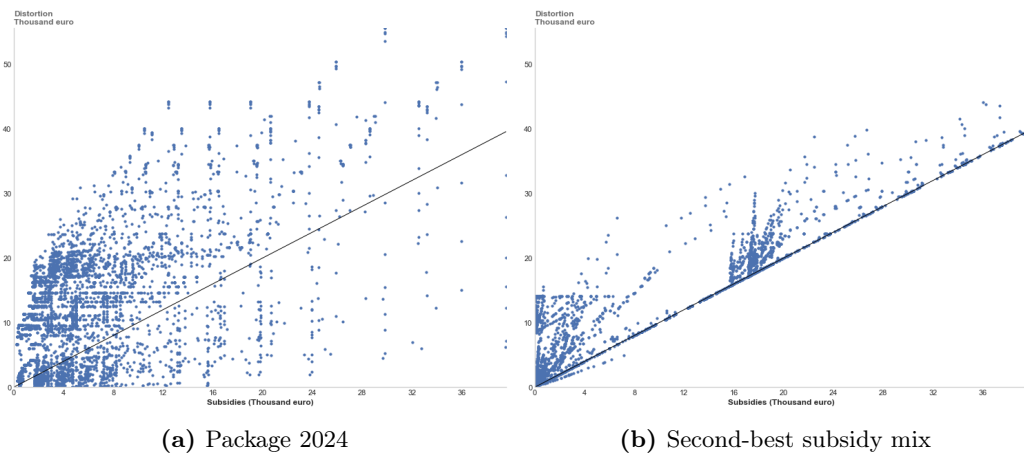


Figure 18: Subsidy Received versus Uninternalized Externality and Distortion by Household. Dots show the combination of households and energy efficiency options including all home insulation options and heat pumps. Distortions are calculated for each investment based on two externalities, landlord-tenant dilemma, multi-family friction, status quo bias and present bias.

6 Discussion

Our conclusion that incentive-based energy efficiency policies generate net social benefits is at odds with most of the literature – e.g., Fowlie et al. (2018) and Allcott et al. (2024). It derives from a specific framework prone to market and behavioral frictions, in which decision-makers correctly anticipate that real energy savings will under-perform engineering predictions – which we think are more realistic assumptions than assumed in previous works. Our positive assessment is also more basically due to parametric assumptions, including a higher social cost of carbon – growing from €150/tCO₂ in 2024 to €775/tCO₂ in 2050, against a €38/tCO₂ flat rate in Fowlie et al. (2018) and €172/tCO₂ in Allcott et al. (2024) – and a longer time horizon – 20 years, similar to Allcott et al. (2024) and higher than the 16 years assumed in Fowlie et al. (2018).

Another key insight from our analysis is the lack of appeal of direct regulations, i.e., bans, from a social welfare perspective. This is due to the ancillary costs they indistinctly impose on households – an original feature of our model. Inherently intangible, this negative value may materialize as political costs. That said, we see at least two reasons for not discarding bans on this sole basis. First, among all the options we consider, the ban on new gas boilers is the only one enabling carbon neutrality. Furthermore, direct regulations are robust to uncertainties – the famous price vs. quantity debate. In this spirit, using the same demand-side model as used here and coupling it with an energy supply-side model, Escribe et al. (2024a) find that such a ban can provide a hedge against short low-carbon gas supply.

On a more technical note, our quasi-linear utility assumption, borrowed from other works (Allcott et al., 2024; Chan et al., 2023), conveniently expresses utility in monetary terms and thus facilitates cost-benefit analysis. Under this assumption, however, the privately optimal energy use does not depend on income – at odds with empirical evidence in France (Allibe, 2012; Belaïd, 2017; Charlier et al., 2021). More general utility functions should therefore be considered, which nevertheless raises computational challenges.

Lastly, our partial-equilibrium, demand-side analysis inherently fails to capture important market effects. First, it takes energy price and carbon intensities as exogenous, rather than resulting from supply-demand equilibrium in energy markets. In a companion paper, this gap is filled by coupling the present model with EOLES, an optimisation model of the French energy system (Escribe et al., 2024b). The authors find that achieving carbon neutrality in a cost-optimal way involves 45% emissions reductions from fuel decarbonization and 55% from home energy retrofit (i.e., insulation and fuel switch). The latter is close to what our baseline package implements, suggesting our partial-equilibrium approach does not miss crucial effects. Second, the many frictions we consider primarily affect the demand side of renovation while hardly affecting the supply side, for lack of empirical evidence. Inefficiencies could however be envisioned under imperfect competition, such as a disproportionate price surge in response to a subsidy- or mandatory-induced demand surge (Fischer, 2005). The magnitude of the effect will depend on the importance of barriers to entry. Recent work suggests they may not be so significant, a €1 million increase in subsidy spending causing a 1.4 job creation in the renovation industry (Cohen et al., 2024). The same question arises regarding credit markets. Third, instead of being two separate entities as modelled here, owner-occupied housing and privately rented housing are linked through real estate markets. In response to a rental ban on worst-performing housing, landlords may prefer selling their property to engaging renovation works, thereby causing a supply shock in sales market, with ambiguous effects – more affordable housing, but more fuel poverty. Better representing renovation supply, credit supply and real estate markets are fruitful areas for further research.

7 Conclusion

Home energy retrofits contribute essential household services – decent housing, thermal comfort, asset value. They are subject to various forms of public support in Western economies, motivated by climate and energy security concerns. Most empirical assessments of these interventions find them economically inefficient (Fowlie et al., 2018; Allcott et al., 2024). We show that this conclusion can be reversed when other relevant barriers to energy efficiency investment are taken into account – health externalities, landlord-tenant dilemma, free-riding in multi-family housing, credit rationing, present bias and status quo bias. In such a highly imperfect environment, the carbon dioxide externality only ranks fourth in the justifications for policy intervention and subsidies are strongly warranted to address the first-order frictions.

These conclusions are drawn from an original microsimulation framework enhanced with two key features. First, renovation technology (insulation, heating system) is represented with the high level of detail typically found in building stock models. Second, renovation decisions are based on discrete choices, distorted by reduced-form frictions taken from the empirical literature when available and otherwise calibrated using the best available data. While related models tend to focus on ‘second-best worlds’ in which the CO₂ externality interacts with one other friction at best – e.g., behavioral anomalies (Allcott et al., 2014) or information asymmetries (Giraudet et al., 2018) – we set out to capture the cumulative inefficiencies occurring in an ‘n-th best world’ plagued with multiple frictions, conceptualized by Jaffe et al. (1994b) but never quite explored in all its ramifications. We thus trade off some form of external consistency – a highly imperfect market, so complex that it can only be assessed numerically – for internal consistency – typically achieved in theoretical and applied microeconomic studies examining frictions one-at-a-time. The accuracy with which our model reproduces past trends builds confidence in its ability to generative unique policy insights – both normative and positive.

On the normative side, we reassess the textbook merit order of Pigovian instruments, according to which the carbon tax is first-best, energy efficiency subsidies second-best and energy efficiency regulations third-best. We show that energy efficiency subsidies may be superior to the carbon tax when the accompanying frictions are considered. We confirm that regulations underperform subsidies and show that this is due to ancillary value – a feature rarely taken into account. Looking more carefully at subsidies, we emphasize that Pigovian schedules should be adjusted to accompanying frictions. The insight is not new – see Allcott et al. (2014) and Giraudet et al. (2018). However, when multiple frictions are to be addressed, as considered here, it implies differentiating subsidy schedules along multiple dimensions – household income, occupancy status, insulation level, etc.. Such fine-tuning may be impractical for policy-makers, who can only imperfectly observe household characteristics.

On the positive side, we find that the policy package currently implemented in France closes about half of the energy efficiency gap associated with space heating – about two thirds along the energy savings dimension and one-third on the welfare dimension. The total welfare gap is however smaller than current spending on subsidies. Subsidy schedules should therefore be adjusted to make intervention more cost-efficient. In particular, more generous subsidies should be given to landlords, multi-family owner and low-income households.

The most immediate avenue for improving our modelling framework is to continue to feed it with the most up-to-date empirical estimates. In addition, more processes could be included to investigate further inefficiencies. In this spirit, our energy demand framework has recently been coupled with an energy supply framework to investigate the optimal distribution of abatement effort across different channels (Escribe et al., 2024b) and its robustness to uncertainty regarding low-carbon energy supply (Escribe et al., 2024a). Current research involves adding energy use for air conditioning to assess the optimal coordination of mitigation and adaptation efforts under climate

change. The next step will be to better represent renovation supply, credit supply and real estate markets, which are all likely to significantly affect policy performance.

Code availability

The code of Res-IRF 4.0 is open-source and can be freely accessed at DOI: <https://zenodo.org/doi/10.5281/zenodo.10000000> or on GitHub: <https://github.com/CIREN/Res-IRF4>.

CRedit authorship contribution statement

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

Acknowledgements

This research was supported by Agence Nationale de la Recherche (ANR) project PRE-MOCLASSE (contrat ANR-19-CE22-0013-01). Lucas Viver thanks Palladio Foundation for their funding and support. We thank Celia Escribe, Laurent Lamy, Dominique Osso and Marie-Hélène Laurent for their comments and suggestion during the development of Res-IRF 4.0. We thank Laurent Lamy, Thibault Briera, Celia Escribe and Dominique Osso for their valuable feedback on earlier drafts of this paper.

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Appendices

A Method

Price elasticity of energy consumption

$$e = \eta \left(\frac{A}{p\eta} \right)^{1/\zeta} = A^{1/\zeta} \eta^{1-1/\zeta} p^{-1/\zeta} \quad (18)$$

$$\frac{de}{dp} = -\frac{1}{\zeta} A^{1/\zeta} \eta^{1-1/\zeta} p^{-1/\zeta-1} \quad (19)$$

$$\epsilon = \frac{p}{e} \frac{de}{dp} = -\frac{1}{\zeta} \quad (20)$$

Indirect utility function of energy service

We derive the indirect utility function, $v(p, \eta)$ from the consumer problem described in 2.2 by substituting the optimal consumption of m^* and x^* back into the utility function. Given:

$$m^* = \left(\frac{A}{p\eta} \right)^{1/\zeta} \quad (21)$$

$$x^* = \omega - p\eta \cdot m^* \quad (22)$$

$$v(p, \eta) = u(x^*, m^*) = \omega - p\eta \cdot m^* + h(m^*) \quad (23)$$

$$= \left(\omega - A^{1/\zeta} \eta^{1-1/\zeta} p^{1/\zeta} \right) + A \frac{\left(\frac{A}{p\eta} \right)^{\frac{1-\zeta}{\zeta}}}{1-\zeta} \quad (24)$$

$$= \omega + A \frac{\left(\frac{A}{p\eta} \right)^{\frac{1-\zeta}{\zeta}}}{1-\zeta} - A^{1/\zeta} \eta^{1-1/\zeta} p^{1/\zeta} \quad (25)$$

Gross utility gain from energy-efficiency investment

We define $V_{i,k} = v(p, \eta_k) - v(p, \eta_i)$ as the gross utility gain (in units of euros) from energy efficiency investment k , which reflects both the energy cost savings and the utility from increased utilization for the energy efficient good relative to the energy inefficient good.

$$V_{i,k} = v(p, \eta_k) - v(p, \eta_i) \quad (26)$$

$$V_{i,k} = \underbrace{p \cdot (e_i^* - e_k^*)}_{\text{bill saving}} + \underbrace{h(m_k^*) - h(m_i^*)}_{\text{thermal comfort}} \quad (27)$$

Unobserved value

We assume that $\epsilon_{i,k} + \delta_k$ are distributed to a standard Gumbel law, where δ_k is a constant and θ is a scaling factor. Mathematically, unobserved value, in monetary units, can be computed as follows:

$$\text{Unobserved value}_{i,k} = E[\delta_{i,k} + \overline{\epsilon_{i,k}} | V_{i,k} > V_{i,j}, \forall j \neq k] \quad (28)$$

$$= E[\delta_{i,k} + \overline{\epsilon_{i,k}} | V_{i,k} = \max_j V_{i,j}] \quad (29)$$

$$= \delta_{i,k} + E[\overline{\epsilon_{i,k}} | V_{i,k} = \max_j V_{i,j}] \quad (30)$$

$$= \delta_{i,k} + \ln \left(\sum_j e^{v_{i,j} + \delta_{i,j}} \right) - (v_{i,k} + \delta_{i,k}) \quad (31)$$

$$= \ln \left(\sum_j e^{v_{i,j} + \delta_{i,j}} \right) - v_{i,k} \quad (32)$$

where $v_{i,j}$ is the observed utility of $V_{i,k}$ (also called the representative utility).

We demonstrate the calculation of $E[\epsilon_j | X_j = \max_k X_k]$, where ϵ_j follows a Gumbel distribution,¹² and $X_j = v_j + \epsilon_j$ is a collection of variables, where:

- v_j is a deterministic utility unique to each variable.
- ϵ_j is a random number coming from the Gumbel distribution .

We are interested in finding the maximum value out of all the X_j 's, which we denote as \hat{X} .

\hat{X}_j refers to the value of X_j conditional on being the maximum. The invariance property states that \hat{X} and all the \hat{X}_j 's follow the same statistical rules, denoted as F^* . This means that if we know the behavior of the maximum, we know the behavior of each X_j assuming it is the maximum. In other words, the statement assumes that the conditional expectation of X_j given it is the maximum is equal to the unconditional expectation of the maximum, $E[\hat{X}]$.

Because they all follow the same rules, \hat{X} and \hat{X}_j 's have the same expected value. This implies that the expected value of $v_j + \epsilon_j$, given j is the index of the maximum value (j^*), is the same as the expected value of \hat{X} .

Following Train (2009), if each ϵ_j is iid extreme value, there is an analytical closed form for $\mathbb{E}[\hat{X}]$ as the standard log-sum expression:

$$\mathbb{E}[v_j + \epsilon_j | j = j^*] = \mathbb{E}[\hat{X}] = \ln \left(\sum_j e^{V_j} \right) + C \quad (33)$$

where C is an unknown constant that represents the fact that the absolute level of utility cannot be measured. From a policy perspective, since the unknown constant C enters hidden benefits in all scenarios, it drops out of the difference and therefore can be ignored when calculating changes in hidden benefits.

Therefore, the expected value of ϵ_j given that j is the maximum (j^*) if the difference between the expected maximum value $\mathbb{E}[\hat{X}]$ and v_j .

$$\mathbb{E}[\epsilon_j | j = j^*] = \ln \left(\sum_j e^{v_j} \right) - v_j \quad (34)$$

Calculating energy consumption

Theoretical space heating energy consumption We estimate the theoretical annual space heating requirements through the utilization of the seasonal method, adhering to the guidelines outlined in EN ISO 13790 (Loga, 2013). Our approach is aligned 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

¹²which is a type of distribution often used in extreme value theory to model the distribution of the maximum (or minimum) of a set of variables

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 [m²], U_i is the U-value of the envelope element i [W/(m².K)], and U_{tbr} is the surcharge on all U-values, taking into account the additional losses caused by thermal bridging [W/(m².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/(m².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 m², 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.

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).¹³ The current version of our model does not consider energy usage for cooling purposes, while the estimation

¹³Notably, 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

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.

Accounting for secondary heating system We calculate an allocation coefficient that allocates a portion of the aggregate 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.

We do not consider an implicit secondary wood heating system for dwellings heated with a heat pump.

Assessing distributional consequences

The distributional consequences of implementing the ban result from the calculation of the average costs incurred by the household i over time. This cost in time step t includes technology k purchase costs, $p_{i,t}^k$ net of subsidies, $s_{i,t}^k$, and energy expenditure $p_t^{\text{energy}} \cdot \text{Conso}_{i,t}$, inclusive of taxes meant to cover subsidy costs $T(t, s)$.

We annualized the cost in t by using a 10-year life horizon and a discount rate of 3.9% to mimic household loan terms.

$$\forall k \in \text{heater, insulation} \quad p_{i,t}^k = \hat{p}_{i,t}^k / \gamma_{i,t,k,D}$$

Therefore, the $C_{I,t}^{\text{investment}}$ paid by households that make investments in t is:

$$C_{I,t}^{\text{investment}} = \sum_{i \in I} (p_{i,t}^{\text{heater}} - s_{i,t}^{\text{heater}}) \cdot N_{i,t}^{\text{switch}} + (p_{i,t}^{\text{insulation}} - s_{i,t}^{\text{insulation}}) \cdot N_{i,t}^{\text{insulation}}$$

where $N_{i,t}^{\text{switch}}$ is the number of households that buy a new heating system and $N_{i,t}^{\text{insulation}}$ is the number of households that insulate their homes.

We define $C_{I,t}^{\text{investment}}$ as the sum of cost paid in t that includes past cost that still need to be reimbursed:

$$C_{I,t}^{\text{investment}} = \sum_{tt=t-D}^t C_{I,tt}^{\text{investment}}$$

The average costs within the group I , which contains $N_{I,t}$ households in t , are thus:

$$C_{I,t} = \frac{C_{I,t}^{\text{investment}} + T(t, s) + \sum_{i \in I} p_t^{\text{energy}} \cdot \text{Conso}_{i,t}}{N_{I,t}}$$

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.

The average costs over time is: $C_I = \frac{\sum_{t=2025}^{2050} C_{I,t} \cdot N_{I,t}}{\sum_{t=2025}^{2050} N_{I,t}}$

Figure in section ?? show the difference of average total cost for household group I when the ban is implemented compared to the counterfactual scenario.

$$\Delta C_I = C_I^{\text{ban}} - C_I^{\text{reference}}$$

Calibration procedures

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 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.

	Attribute	Value
Cost		-0.11
Benefits	C1	0.56
Benefits	C2	0.92
Benefits	C3	1.35
Benefits	C4	1.35
Benefits	C5	1.61
Status quo		0.95
Constant measure	Multi-family Direct electric	0.00
Constant measure	Multi-family Heat pump	0.10
Constant measure	Multi-family Natural gas boiler	2.96
Constant measure	Single-family Direct electric	0.00
Constant measure	Single-family Heat pump	-0.64
Constant measure	Single-family Natural gas boiler	1.71
Constant measure	Single-family Wood fuel boiler	1.41

Table 7: Parameter estimates used in investment decision utility function for heating system .

We construct the market share for home insulation measures by integrating two data sources. First, we calculate a home insulation renovation rate using data from the white certificate obligations program. This data offers two key advantages: the program mandates a minimum performance level for each insulation measure, ensuring standardization of the data; once these performance levels are met, all major insulation measures (walls, roofs, floors, and windows) receive subsidies. This ensures that the data represents a reliable proxy for the overall renovations occurring in France within the year.¹⁴ To complement these aggregated data, we use information from the national survey on home renovations (TREMI), which offers detailed insights into combined insulation measures. Since the survey focuses exclusively on single-family housing, we extrapolate the results to multi-family dwellings by assuming that similar combinations of measures are implemented in these types of buildings. Furthermore, we use data on the proportion of buildings with the worst energy performance (EPC ratings F and G) that have been effectively renovated (MTE, 2020a) to calibrate the scale of the utility function. The calibration results are detailed in Table 9.

¹⁴However, 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.

Attribute		Value
Cost		-0.09
Benefits	C1	0.46
Benefits	C2	0.81
Benefits	C3	1.32
Benefits	C4	1.32
Benefits	C5	1.68
Constant insulation	Single-family Owner-occupied	-0.69
Constant insulation	Single-family Privately rented	-2.18
Constant insulation	Single-family Social-housing	-1.91
Constant insulation	Multi-family Owner-occupied	-2.07
Constant insulation	Multi-family Privately rented	-3.35
Constant insulation	Multi-family Social-housing	-2.36
Constant measure	Wall, Floor, Roof	-1.80
Constant measure	Floor, Roof	-5.17
Constant measure	Wall, Floor	-5.56
Constant measure	Wall, Roof	-1.13
Constant measure	Wall	-1.55
Constant measure	Roof	0.00
Constant measure	Floor	-6.65
Constant measure	Wall, Floor, Roof, Windows	-0.99
Constant measure	Floor, Roof, Windows	-1.98
Constant measure	Wall, Floor, Windows	-2.40
Constant measure	Wall, Roof, Windows	-2.76
Constant measure	Wall, Windows	-4.07
Constant measure	Roof, Windows	-3.75
Constant measure	Floor, Windows	-1.96
Constant measure	Windows	-2.31

Table 8: Parameter estimates used in investment decision utility function for home insulation.

Housing type	Occupancy status	Landlord-tenant dilemma	Multi-family friction
Single-family	Owner-occupied	0	0
Single-family	Privately rented	16939	0
Single-family	Social-housing	13972	0
Multi-family	Owner-occupied	0	15765
Multi-family	Privately rented	14567	15765
Multi-family	Social-housing	3291	15765

Table 9: Calibration results of reduced-form distortion to invest in home insulation. Values are expressed in euros.

Insulation measure	Value
Wall, Floor, Roof	32,748
Floor, Roof	70,423
Wall, Floor	75,889
Wall, Roof	23,657
Wall	28,104
Roof	8,585
Floor	87,104
Wall, Floor, Roof, Windows	24,136
Floor, Roof, Windows	32,708
Wall, Floor, Windows	40,331
Wall, Roof, Windows	45,535
Wall, Windows	60,433
Roof, Windows	54,051
Floor, Windows	32,776
Windows	36,963

Table 10: Calibration results of reduced-form distortion of specific home insulation measures

Variable	Value
Stock (Million)	28.05
Surface (Million m ²)	2393.48
Consumption (TWh)	273.90
Consumption (kWh/m ²)	114.44
Consumption Electricity (TWh)	38.02
Consumption Heating (TWh)	9.97
Consumption Natural gas (TWh)	119.64
Consumption Oil fuel (TWh)	37.24
Consumption Wood fuel (TWh)	69.04
Emission (MtCO ₂)	45.31
Rate Multi-family - Social-housing (%)	0.015
Rate Single-family - Owner-occupied (%)	0.029
Rate Single-family - Privately rented (%)	0.011
Rate Single-family - Social-housing (%)	0.014
Consumption standard saving insulation (TWh/year)	2.30
Consumption saving insulation (TWh/year)	1.40
Realization rate (% standard)	0.61
Rebound insulation (% performance gap)	0.26
Investment insulation (B€)	5.68
Efficiency insulation (euro/kWh)	0.21
Subsidies insulation (B€)	1.21
Switch Electricity-Direct electric (Thousand households)	377.45
Switch Electricity-Heat pump water (Thousand households)	134.27
Switch Heating-District heating (Thousand households)	133.10
Switch Natural gas-Performance boiler (Thousand households)	569.76
Switch Wood fuel-Performance boiler (Thousand households)	169.62
Investment heater (B€)	9.33
Subsidies heater (B€)	1.09
Consumption saving (TWh/year)	2.77
Emission saving (MtCO ₂ /year)	0.99

Table 11: Simulation result for base year.

B Data

Overview

All data sources are comprehensively listed in Table 12, 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 19. 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 gCO₂/kWh by 2050. In our reference scenario, we use business-as-usual data and critically examine the impact of key variables through sensitivity analysis.

Inputs	Source
Energy system	
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 (ADEME, 2022)
Number of dwelling connected to district heating	Scenario BAU ADEME (2022)
Housing market	
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)
Macro	
Household income by decile in 2018	INSEE (2021)
Income growth	DGEC (2023)*
Initial housing stock	
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)*
Technical data	
U-value of renovated envelope components	ADEME (2024)
Cost insulation by envelope component	effienergie_maisons_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)
Behavioral parameters	
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)
Financing information	
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)
Indicators	
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)
Thermal module data	
	Loga (2013) and Arquin et al. (2020)

Table 12: List of data sources used in Res-IRF. * means data are not publicly available.

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.

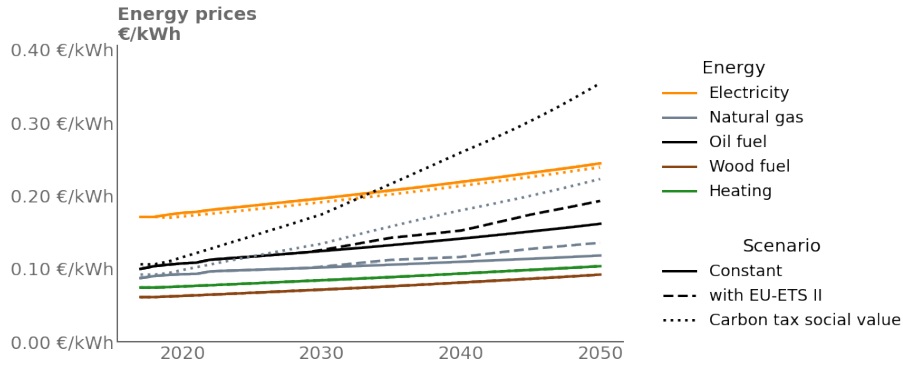


Figure 19: Energy prices with taxes used in the reference scenario in Res-IRF 4.0. Source: DGEC.

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 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.

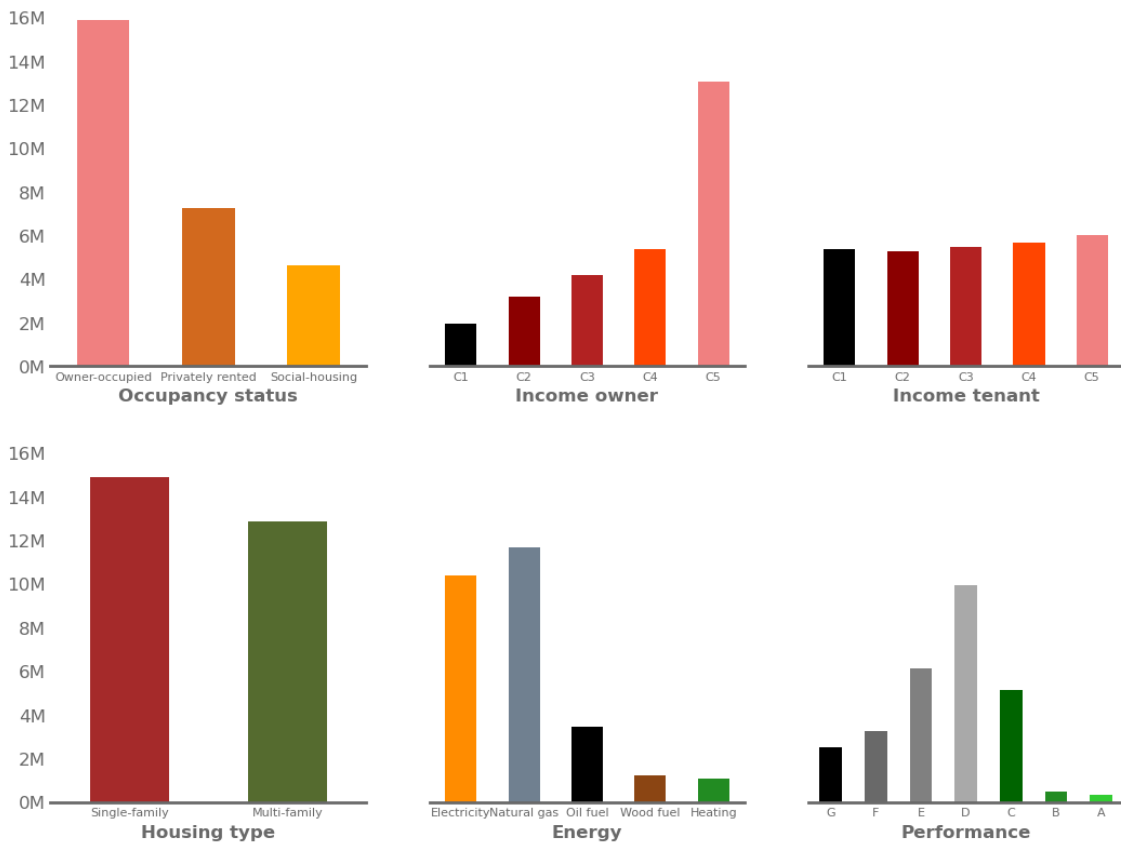


Figure 20: Description of the building stock in France in 2018. To simplify the presentation, the energy performance levels are described with EPC, but Res-IRF 4.0 uses the level of insulation for each component of the building envelope.

Technical data

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

Table 13: Cost analysis from Observatoire BBC field study ([effienergie_maisons_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 ancillary 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 [E](#).

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

Table 14: 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).

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 15: 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 (2020a).

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 16: Share of insulation measures in total renovation in 2019 in France. Own calculation from MTE (2020a).

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 17: 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 18: Probability of health-risk and social cost by income class of the tenant(Dervaux et al., 2022)

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 19: Carbon tax and carbon value. In the ‘Carbon tax’ policy scenario, the carbon tax is levied on the social value of carbon (Quinet, 2019)

Climate targets

Authorities have established targets to guide mitigation strategies effectively. Defining precise targets within a limited scope presents significant challenges, especially when employing partial equilibrium models. Often, these targets are not delineated by specific sectors, and when they are, they may not align with the framework’s scope. This discrepancy is evident in our analysis, where we evaluate emissions from fossil-fuel boilers included in the building carbon budget as well as indirect emissions (scope 2) from electricity use or district heating for space heating. Additionally, targets are not consistently calculated with the same reference year. For instance, the ‘Fit for 55’ policy packages aim to reduce emissions by 60% by 2030 relative to 1990 levels, whereas the new Energy Directives propose an additional energy reduction target of 11.7% by 2030 compared to a 2020 counterfactual developed by the EU Commission. There is also variability in energy efficiency targets, which are sometimes based on final energy and other times on primary energy. The latter often involves a conversion factor not strictly derived from physical calculations, as seen in France’s method to incorporate nuclear energy, which may change independently of any efficiency improvements. Achieving the goal of net climate neutrality by sector is further complicated by dependencies on carbon sinks and sector-specific emissions allocations.

To determine the scale of climate targets in the scope of this analysis, we rely on the revised Energy Performance of Buildings Directive (EPBD), which sets new interim targets for the buildings sector as part of the European Green Deal, aiming to reduce emissions by at least 60% by 2030 compared to 2015 levels and to achieve climate neutrality by 2050. Assuming that the tertiary sector and the residential sector contribute equally, and taking into account all emissions from the residential sector — which is an optimistic assumption as space heating has the greatest reduction potential due to the use of fossil fuels — we have set an interim target for reducing emissions in the French space heating sector by 60% by 2030. For carbon neutrality, the latest roadmap for France’s mitigation strategies sets a target of 5 MtCO_{2e} by 2050 for all buildings, which corresponds to around 3 MtCO_{2e} for the residential sector, assuming that both sectors contribute equally. In the latest EPBD agreement, the targets for reducing primary energy consumption were set at 16% by 2030 and 20-22% by 2035. These targets are not directly translated into our framework, but are used for comparison with an ideal scenario that includes carbon pricing at the social cost to determine the socially desirable targets.

C Mapping the energy efficiency gap

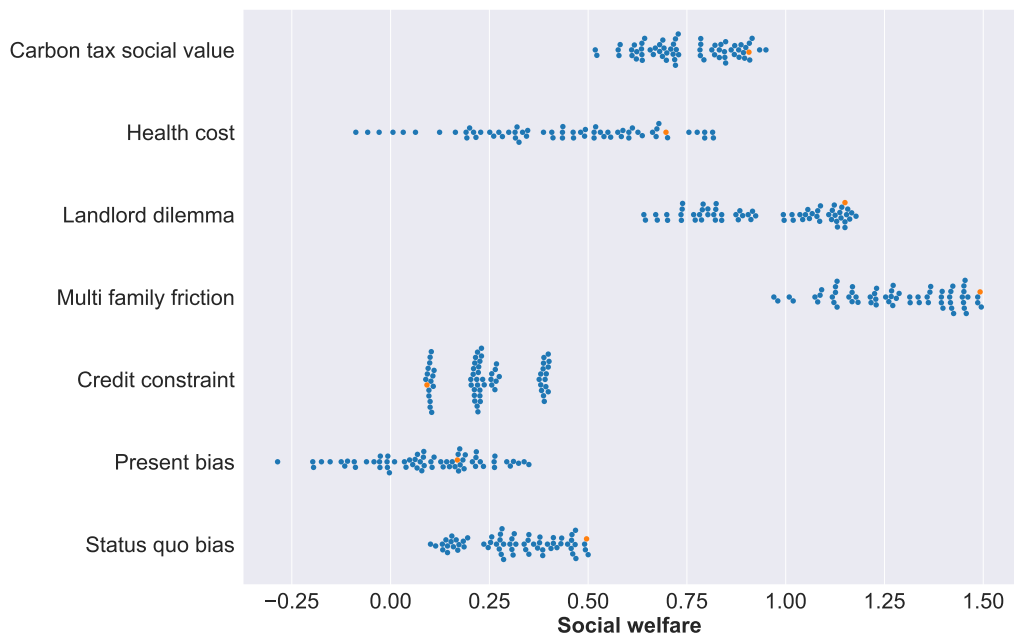


Figure 21: Marginal impact of market failures on cost-benefits analysis when interacting with all possible combinations of market failures.

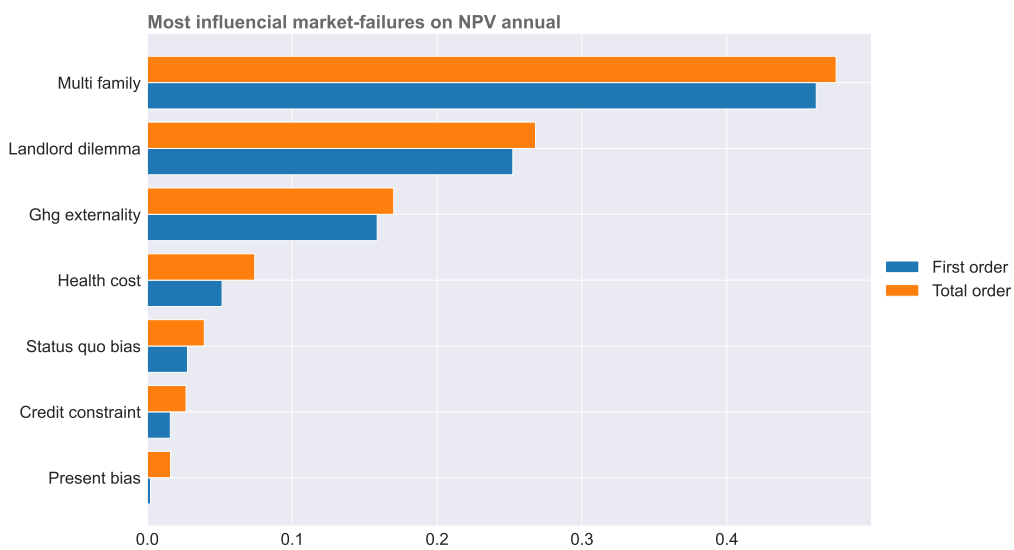


Figure 22: Assessment of most influential market failures on social welfare.

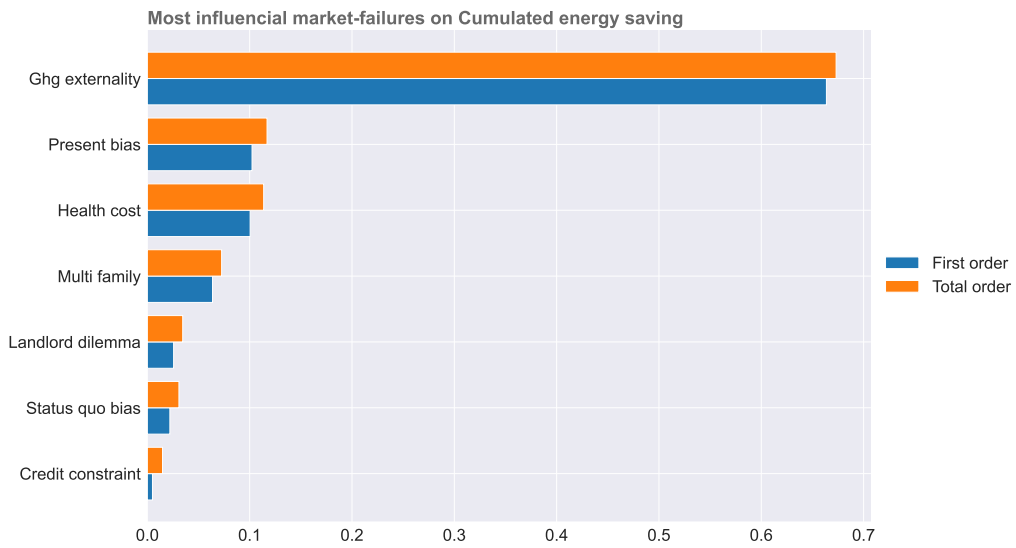


Figure 23: Assessment of most influential market failures on energy reduction.

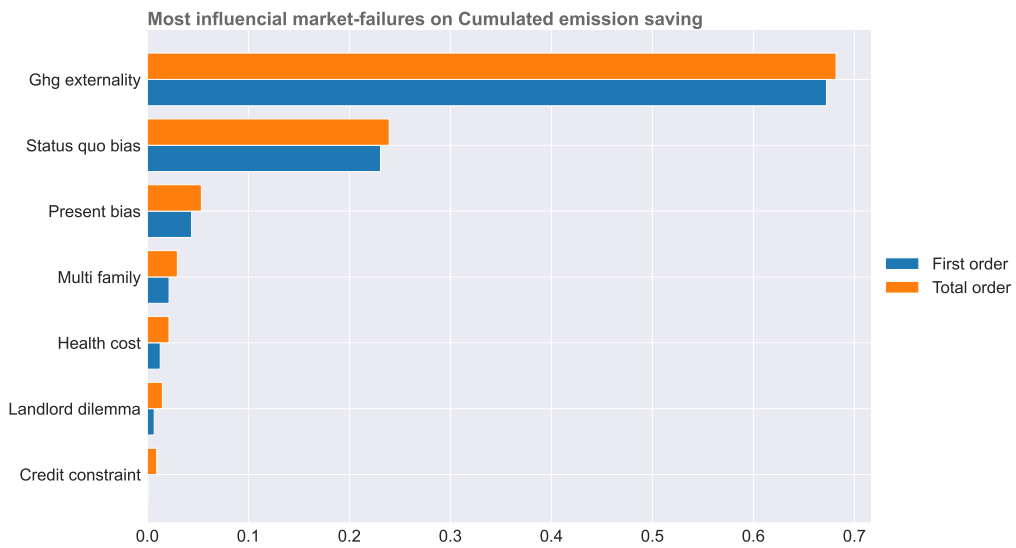


Figure 24: Assessment of most influential market failures on emission saving.

Stylized policy solutions

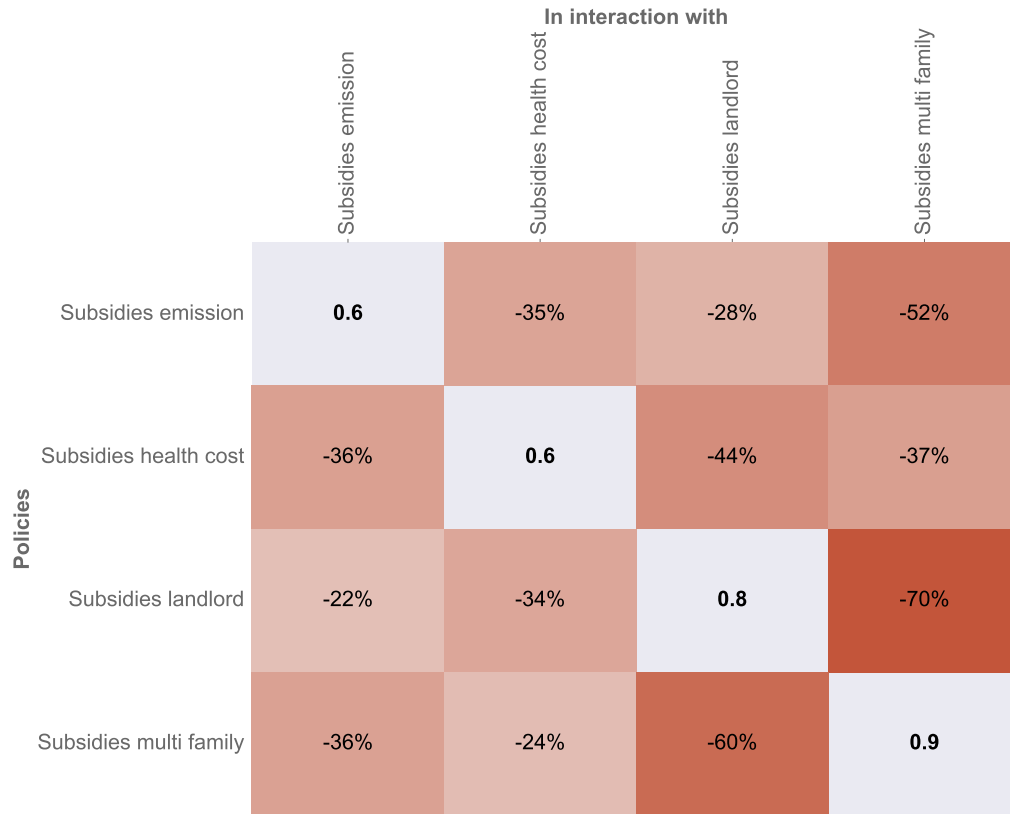


Figure 25: Interaction one at a time between subsidies.

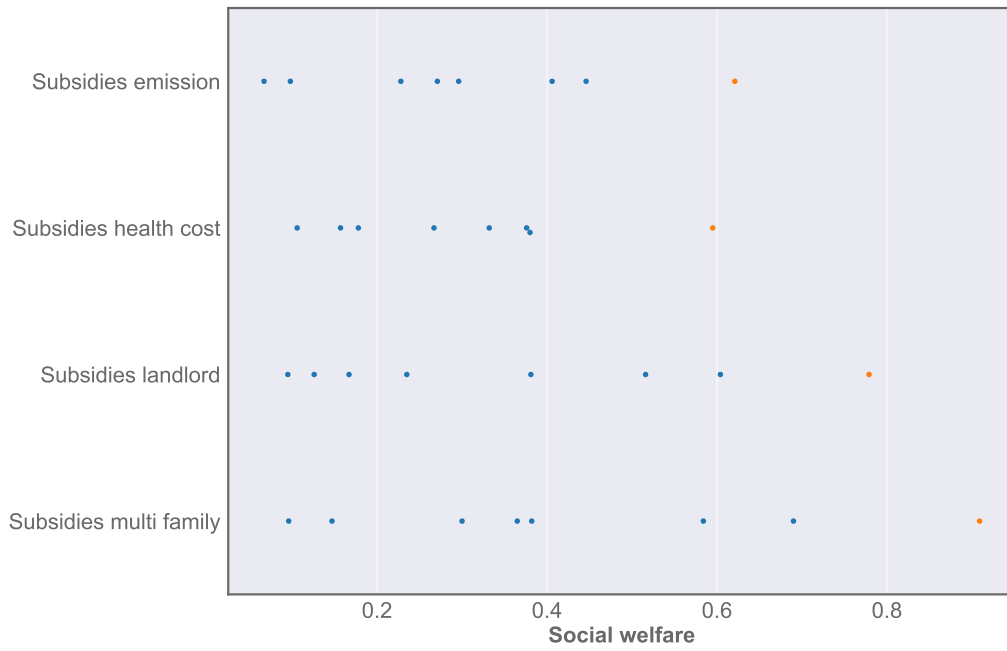


Figure 26: Marginal social welfare impact of market failures when interacting with all possible combination of market failures.

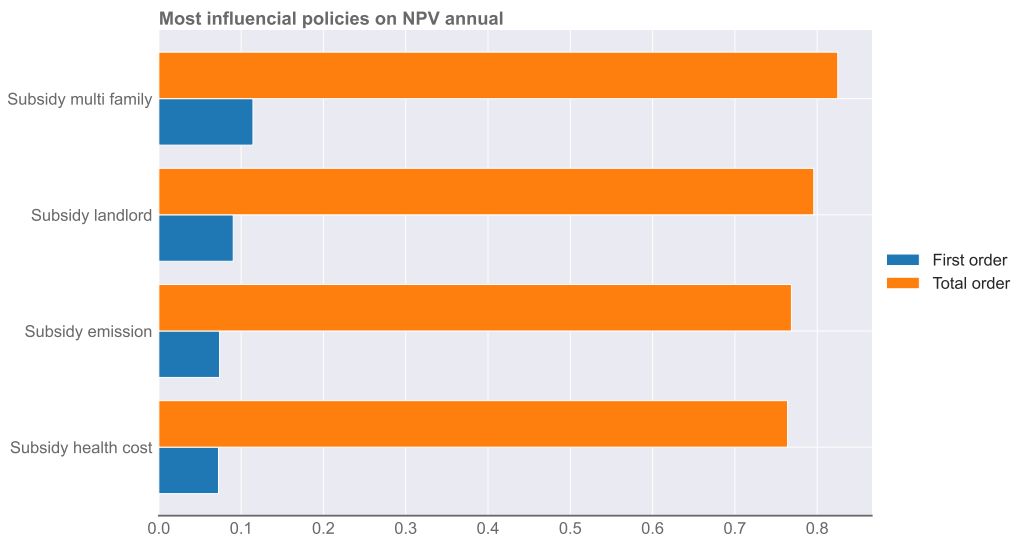


Figure 27: Assessment of most influential market failures on social welfare.

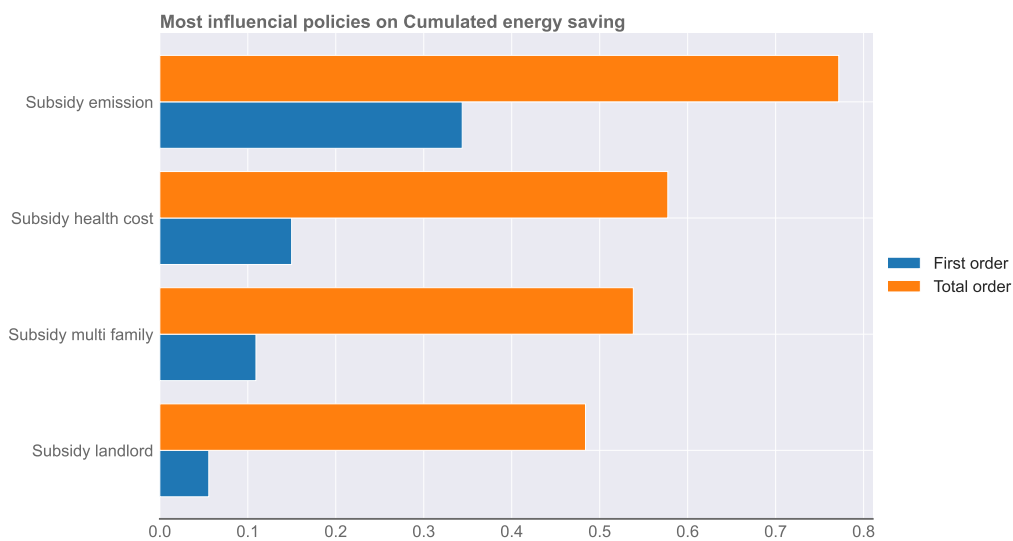


Figure 28: Assessment of most influential market failures on energy reduction.

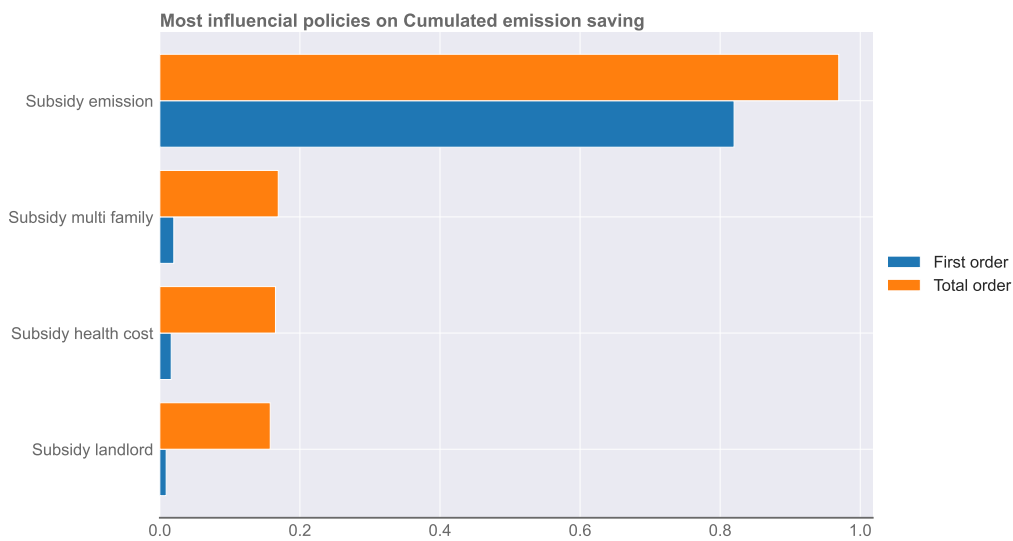


Figure 29: Assessment of most influential market failures on emission avoided.

D Actual policies

Description of actual policies

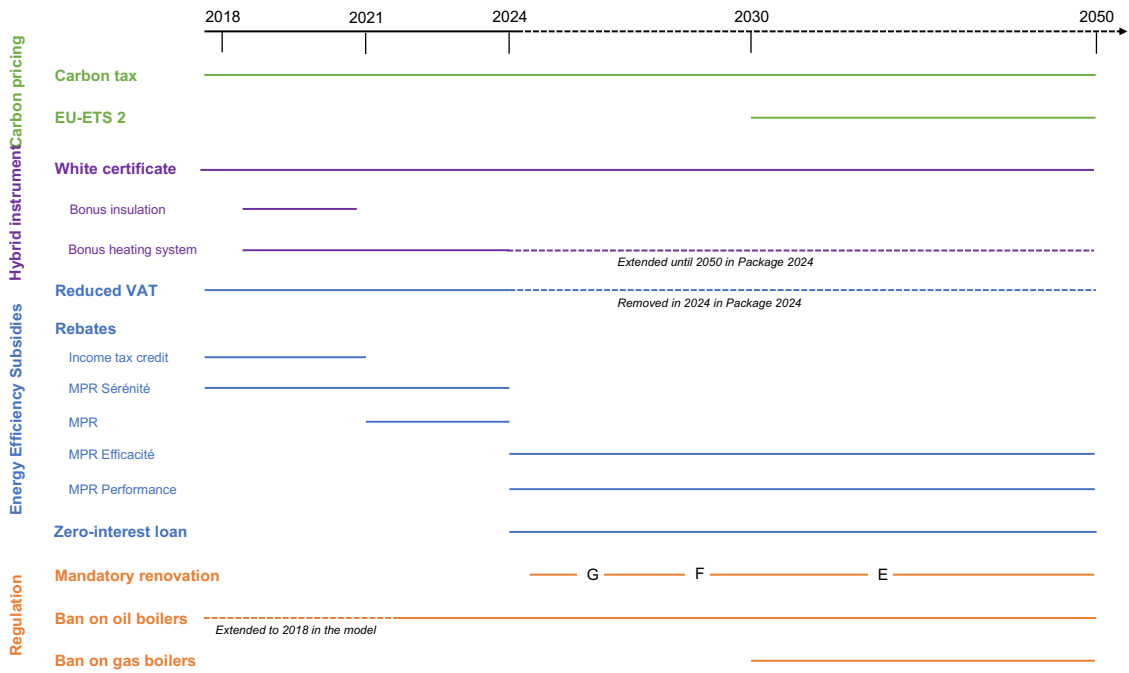


Figure 30: Description of implementation of energy efficiency policies in the residential sector in France.

Instruments	Type, ‘Scenario’	Details
Reduced VAT	Reduced tax, ‘Package 2018’	VAT 5.5% instead of 10%. Reduced VAT is removed in 2024.
Carbon tax	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 B for further details.
Carbon tax SCC	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.
CITE	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.
MPR Serenite	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.
MPR	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.
MPR Multi-family	Direct subsidies, ‘Package 2021’	25% ad valorem for renovation that save 35% of primary energy in multi-family buildings. Revised in 2024.
MPR Efficacite	Direct subsidies, ‘Package 2024’	Similar to MPR, but prohibited for F and G dwellings and dwelling that have not replaced their heating system.
MPR Performance	Direct subsidies, ‘Package 2024’	60% to 15% for deep renovation depending on households income.
MPR Multi-family	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.
CEE	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.
Subsidies cap	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’.
EPTZ	Soft loan, ‘Package 2024’	Zero-interest loan for a maximum loan of €15,000 starting in 2024.
Rental ban	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%.
Oil-fuel ban	Regulation, ‘Package 2018’	Ban to purchase new oil boiler after 2018.
Gas ban	Regulation, ‘Package 2024 + Ban’	Ban to purchase new gas boiler after 2030.

Table 20: Description of the main policies implemented in France. Policy packages are a mix of these instruments. ‘Package 2024’ is the ‘Baseline Package’.

Results

	C. tax	Subsidies	WCO	ZIL	Rental ban	Ban gas
Consumption (TWh)	-68.76	-288.77	-119.63	-86.21	-70.54	-212.36
Emission (MtCO ₂)	-16.01	-37.44	-23.08	-9.41	-7.42	-120.91
Investment (B€/year)	-0.06	-1.45	-0.66	-0.56	-0.33	-0.08
Energy saving (B€/year)	0.13	0.72	0.29	0.23	0.20	-0.02
Thermal comfort (B€/year)	-0.14	0.30	0.05	0.10	0.08	-0.15
Unobserved value (B€/year)	-0.02	-0.21	-0.08	0.22	-0.17	-4.20
Opportunity cost (B€/year)	0.17	-0.23	-0.06	-0.07	0.00	0.00
Emission saving (B€/year)	0.15	0.47	0.25	0.14	0.13	2.52
Health cost (B€/year)	0.01	0.73	0.23	0.24	0.31	-0.57
NPV annual (B€/year)	0.23	0.34	0.03	0.30	0.22	-2.51
- wo/ externalities (B€/year)	-0.09	-0.64	-0.40	-0.01	-0.22	-4.46
Investment/energy (euro/kWh)	0.03	0.16	0.18	0.21	0.15	0.01
Investment/emission (euro/tCO ₂)	123.23	1240.21	916.58	1897.69	1423.66	22.19

Table 21: Cost-benefit analysis of policies implemented in France. C. tax stands for Carbon tax complemented with EU-ETS 2 when the model does not include any friction.

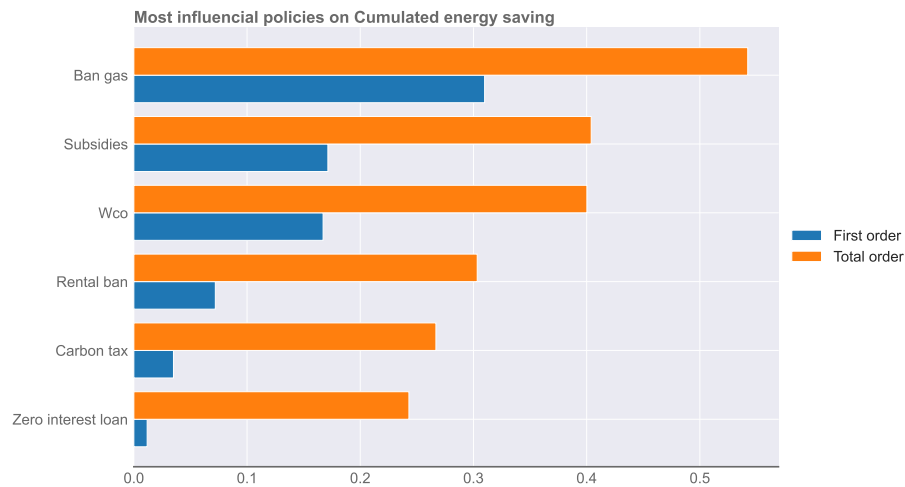


Figure 31: Most influential policies in reducing energy consumption.

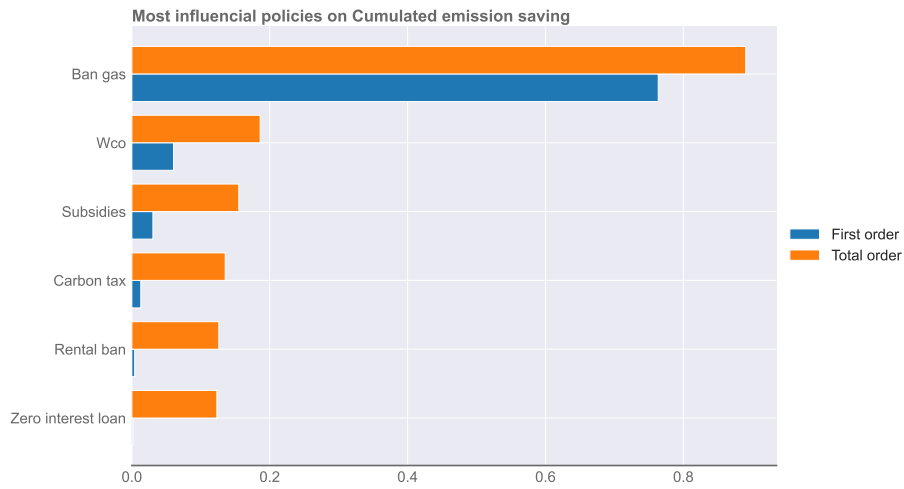


Figure 32: Most influential policies in avoiding GHG emission.

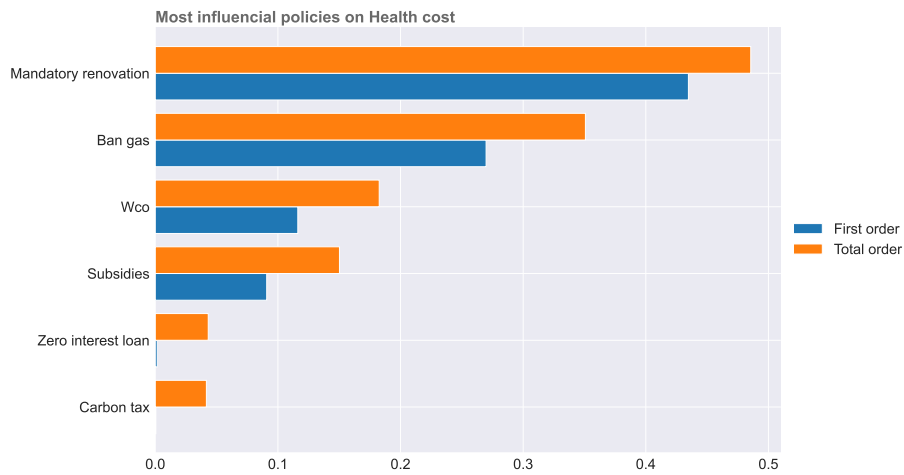


Figure 33: Most influential policies on health cost.

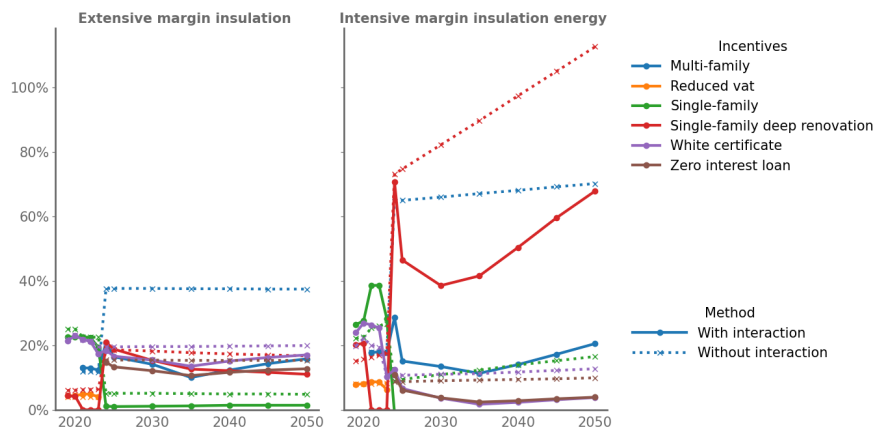


Figure 34: Simulated extensive margin of home insulation subsidies.

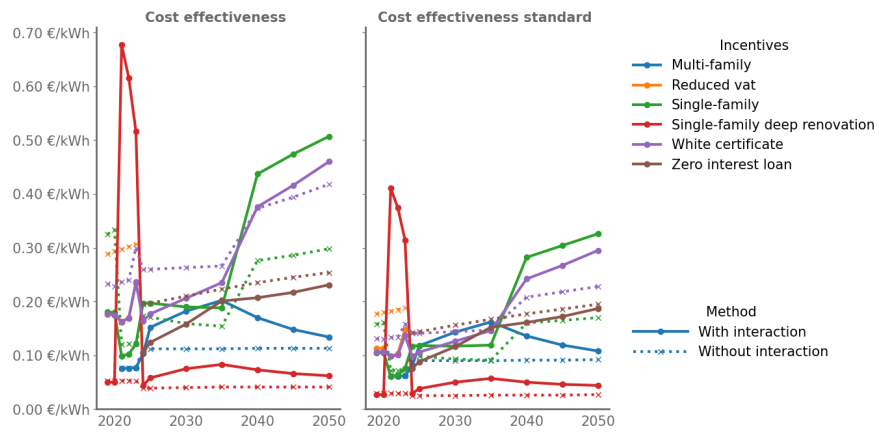


Figure 35: Cost-effectiveness of home insulation subsidies

E Assessing the implementation gap

	No policy	Baseline Package	Baseline Package + Ban	SCC Benchmark	No friction
Stock (M)	32	32	32	32	32
Surface (M m2)	2730	2731	2731	2730	2728
Energy (TWh)	256	236	234	242	222
Energy (kWh/m2)	94	86	86	89	81
Energy PE (TWh)	308	284	284	296	273
Energy Electricity (TWh)	40	37	39	41	39
Energy Natural gas (TWh)	119	102	97	107	91
Energy Oil fuel (TWh)	12	11	11	11	10
Energy Wood fuel (TWh)	68	70	72	67	66
Energy Heating (TWh)	16	16	16	16	15
Energy poverty (M)	3	3	3	4	3
Emission (MtCO2)	38	33	32	35	31
Stock G (M)	2	1	1	2	1
Stock F (M)	3	2	2	3	2
Stock E (M)	5	4	4	5	4
Stock D (M)	10	9	9	10	10
Stock C (M)	7	8	8	7	9
Stock B (M)	2	2	2	2	2
Stock A (M)	4	4	4	4	4
Stock Heat pump (M)	5	6	6	5	6
Stock Direct electric (M)	8	7	8	8	8
Stock Gas boiler (M)	12	11	11	12	11
Stock Oil boiler (M)	1	1	1	1	1
Stock Wood boiler (M)	3	3	3	3	3
Stock District heating (M)	2	2	2	2	2
Carbon value (B€)	9	8	8	9	8
Health cost (B€)	6	4	4	6	2
Energy expenditures (B€)	26	26	25	30	28
Cum. Emission (MtCO2)	1146	995	824	1037	898
Cum. Renovation (Thousand hh)	12366	17844	17648	12904	22855
Cum. Investment insulation (B€)	116	229	230	127	229
Cum. Subsidies insulation (B€)	1	67	68	1	1
Cum. Investment heater (B€)	286	313	332	287	316
Cum. Subsidies heater (B€)	1	47	64	1	1
Avg. Renovation (Thousand hh)	951	1373	1358	993	1758
Avg. Investment insulation (B€)	8.9	17.6	17.7	9.8	17.6
Avg. Subsidies insulation (B€)	0.1	5.2	5.2	0.1	0.1
Avg. Investment heater (B€)	22.0	24.1	25.6	22.1	24.3
Avg. Subsidies heater (B €)	0.1	3.6	5.0	0.1	0.1
Energy saving (%)	8%	15%	15%	12%	20%
Emission saving (%)	18%	28%	30%	25%	34%
Energy poverty reduction (%)	24%	29%	29%	-11%	13%

Table 22: Simulation results in 2030.

	No policy	Baseline Package	Baseline Package + Ban	SCC Benchmark	No friction
Stock (M)	40	40	40	40	40
Surface (M m2)	3522	3514	3516	3523	3508
Energy (TWh)	220	179	155	202	168
Energy (kWh/m2)	63	51	44	57	48
Energy PE (TWh)	277	231	233	261	226
Energy Electricity (TWh)	44	40	60	46	44
Energy Natural gas (TWh)	87	62	2	68	43
Energy Wood fuel (TWh)	66	56	72	65	61
Energy Heating (TWh)	24	21	21	23	20
Energy poverty (M)	2	1	1	3	2
Emission (MtCO2)	19	13	3	15	9
Stock G (M)	1	0	0	1	0
Stock F (M)	2	1	1	2	0
Stock E (M)	3	1	1	3	1
Stock D (M)	9	8	7	9	7
Stock C (M)	9	11	10	9	12
Stock B (M)	4	6	7	4	6
Stock A (M)	13	13	14	13	13
Stock Heat pump (M)	15	17	21	15	17
Stock Direct electric (M)	7	5	8	7	6
Stock Gas boiler (M)	10	9	1	10	8
Stock Wood boiler (M)	4	5	6	4	5
Stock District heating (M)	4	4	4	4	4
Carbon value (B€)	15	10	2	12	7
Health cost (B€)	4	1	2	4	0
Energy expenditures (B€)	28	26	24	34	28
Cum. Emission (MtCO2)	1146	995	824	1037	898
Cum. Renovation (Thousand hh)	12366	17844	17648	12904	22855
Cum. Investment insulation (B€)	116	229	230	127	229
Cum. Subsidies insulation (B€)	1	67	68	1	1
Cum. Investment heater (B€)	286	313	332	287	316
Cum. Subsidies heater (B€)	1	47	64	1	1
Avg. Renovation (Thousand hh)	375	541	535	391	693
Avg. Investment insulation (B€)	3.5	7.0	7.0	3.8	6.9
Avg. Subsidies insulation (B€)	0.0	2.0	2.1	0.0	0.0
Avg. Investment heater (B€)	8.7	9.5	10.1	8.7	9.6
Avg. Subsidies heater (B€)	0.0	1.4	2.0	0.0	0.0
Energy saving (%)	20%	35%	44%	27%	39%
Emission saving (%)	58%	71%	94%	68%	80%
Energy poverty reduction (%)	42%	63%	67%	7%	50%

Table 23: Simulation results in 2050.

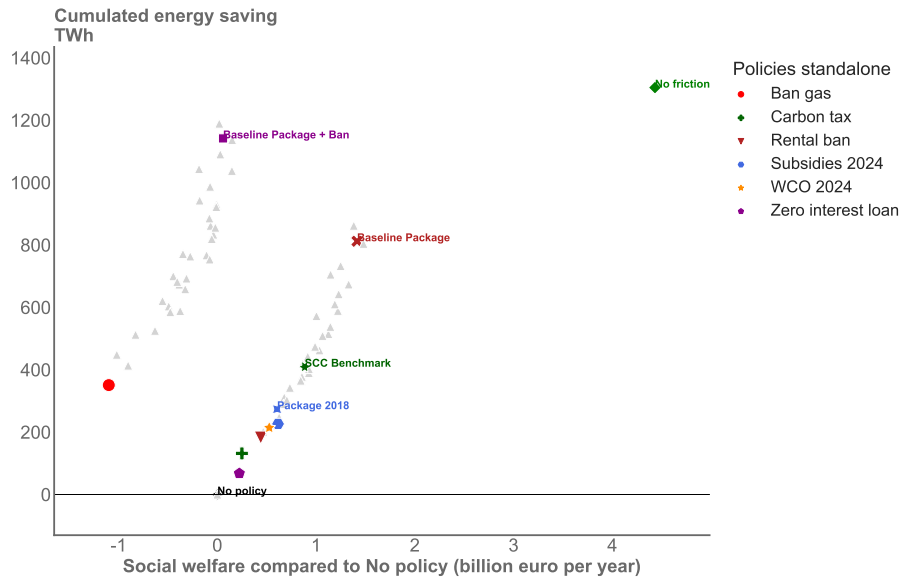


Figure 36: Mapping the French energy efficiency gap

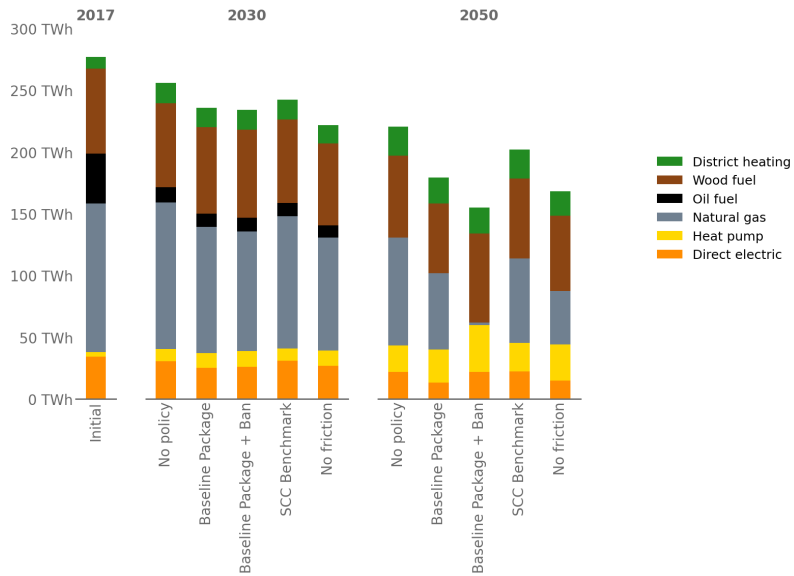


Figure 37: Evolution of residential space heating consumption in France.

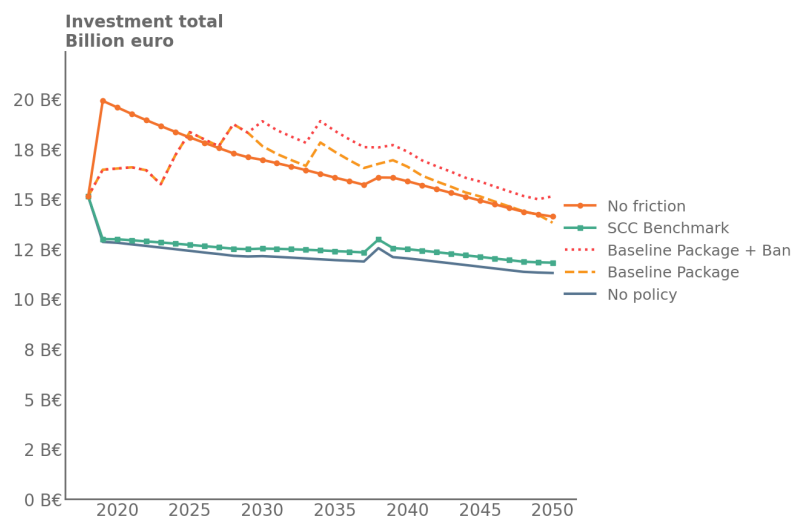


Figure 38: Evolution of total investment in home renovation and heating system in France.

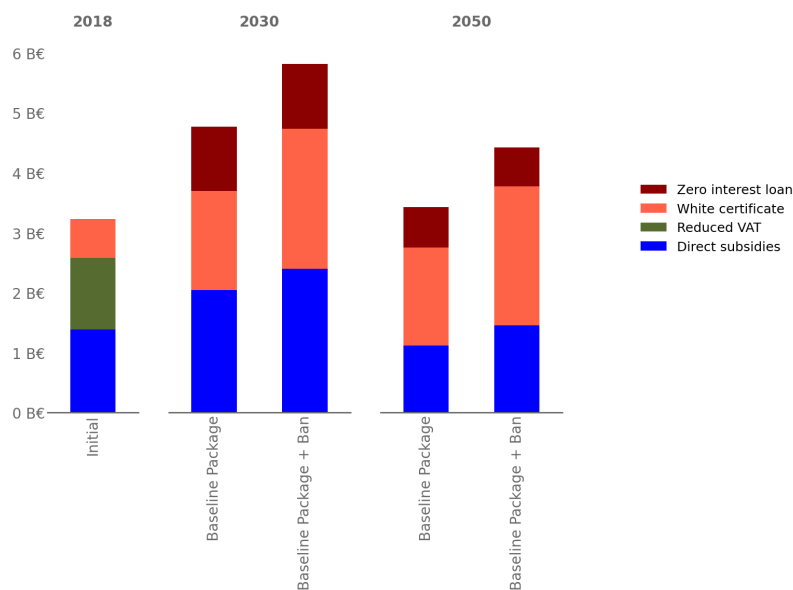


Figure 39: Policy cost. To simplify the figure we aggregate all subsidies under the name ‘Direct subsidies’. The calculation of the public cost of the zero-interest loan is based on an interest rate of 1.5% paid by the authorities to the bank (Eryzhenskiy et al., 2023).

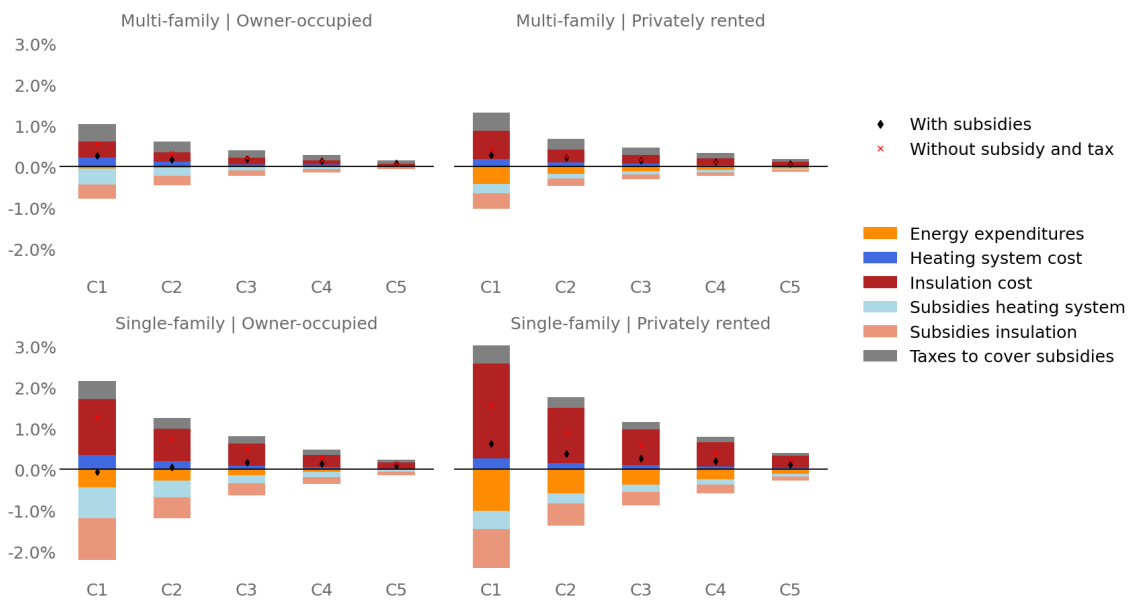


Figure 40: Ratio of households energy expenditures (including energy efficiency investment) on income in the '2024 Package' compared to 'No policy'.

Sensitivity analysis

Table 24 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 CO₂ 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 ₂)	Poverty (Million)
2024 Package	206	12	1.2
Income rate (ref = 1.2%)			
low: 0%	195	11	2.2
high: 2%	222	14	0.2
Energy prices annual growth rate			
low: -20%	210	13	1.1
medium: +20%	201	12	1.3
high: +50%	194	11	1.7
Emission content (ref = 0 by 2050)			
constant emission content electricity	206	16	1.2
Renewable gas (ref = 14 TWh by 2050)			
low: 0 TWh	206	16	1.2
high: 25 TWh by 2050 (S3)	206	10	1.2
District heating (ref = 5 M (S2))			
low: 3.5 M dwellings (S1)	203	13	1.2
high: 8 M dwellings (S3)	210	11	1.1
Stock turnover (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
Heat-pumps in construction			
low: S1	213	13	1.2
high: S4	199	12	1.2
Share of buildings that cannot make renovation			
medium: 5%	211	13	1.3
high: 10%	216	15	1.5
Reduction cost heat-pumps (ref = -20% by 2035)			
low: no cost reduction	206	12	1.2
high: -50% by 2035	199	11	1.1
Reduction cost insulation (ref = 0%)			
high: -30%	195	12	0.8
Financing cost			
low: interest: 2.5%/year, saving: 1%/year	202	12	1.0
high: interest: 10%/year, saving: 5%/year	213	13	1.4
Price-elasticity heat-pumps			
low: -0.8	208	13	1.3
high: -1.2	202	11	1.1

Table 24: Sensitivity analysis of the most important inputs in 2050. Consumption in TWh, GHG emission in MtCO₂, 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.

F Building stock models

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 25: Previous development of Res-IRF.

Subtopic	Res-IRF
Overview	
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.
Model components	
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 26: Description of the model following Nägeli et al. (2022)

Subtopic	Res-IRF
Input and output	
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.
Quality assurance	
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.
Additional information	
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: https://cired.github.io/Res-IRF/ + (Giraudet et al., 2021)	

Table 27: Description of the model following Nægeli et al. (2022).

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