THÈSE DE DOCTORAT
de l'École des Ponts ParisTech

Évaluation des politiques d'efficacité énergétique résidentielle à l'aune de multiples frictions de marché et comportementales

École doctorale N°528, Ville, Transports, Territoires (VTT)

Sciences Economiques

Thèse préparée au CIRED, UMR 8683

Thèse soutenue le 20 septembre 2024, par
Lucas VIVIER

Composition du jury:

Dorothée, CHARLIER Professeur, Université Savoie Mont-Blanc	*Rapporteur*
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THÈSE DE DOCTORAT
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Assessing residential energy efficiency policies subject to multiple market and behavioral frictions

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Remerciements

Ces trois années et demie furent un réel plaisir. Je mesure aujourd'hui la chance d'avoir pu réaliser ce doctorat dans ces conditions privilégiées. Ce chemin a été possible grâce à de nombreuses personnes qui m'ont guidé, encouragé, et soutenu.

Je remercie avant tout Gaëtan de m'avoir offert l'opportunité de réaliser cette thèse, puis de m'avoir accompagner dans une ambiance toujours sympathique. Je te remercie pour ton enthousiasme face à mes propositions et pour ton soutien constant dans tous les projets que j'ai menés. J'ai beaucoup appris à tes côtés, et je te souhaite sincèrement le meilleur pour l'avenir. Le rôle du directeur de thèse est évidemment crucial pour la réussite de cette expérience, et tu as largement contribué à rendre ces années à la fois fructueuses et agréables. Merci à Laurent pour nos discussions approfondies sur les équations des modèles et pour ses commentaires toujours pertinents. Vos contributions ont été essentielles.

Un grand merci également à Joachim Schleich et Dorothée Charlier pour leur lecture attentive et leurs remarques précieuses sur cette dissertation. Je vous remercie également, Peter Berrill, Ken Gillingham et Chiara Delmastro, d'avoir accepté de faire partie de ce jury malgré la distance ou le décalage horaire. Vos travaux sur l'efficacité énergétique et la rénovation des bâtiments ont largement nourri mes recherches, et je n'aurais pu espérer un jury plus pertinent pour évaluer ma dissertation.

Cette thèse n'aurait pas été possible sans le financement du projet ANR Prémoclasse, piloté par Catherine Grandlement. Je remercie chaleureusement les membres de ce projet, avec une mention spéciale à Marie-Hélène Laurent et Dominique Osso, dont les contributions ont été déterminantes pour le développement du modèle. Enfin, je souhaite également remercier la Fondation Palladio pour son soutien et pour les échanges stimulants nés des rencontres organisées dans ce cadre.

Cette thèse doit beaucoup aux collaborations académiques qui l'ont enrichie. Je ne peux que conseiller au futur doctorant, qui s'est perdu en lisant ses remerciements, de ne cesser de rechercher le travail d'équipe dans cette entreprise qui peut sembler solitaire. Un grand merci à Célia, avec qui j'ai coécrit deux articles, pour ta patience et ton optimisme.

Ce fut un réel plaisir de travailler à tes côtés. Merci à Philippe pour son soutien indéfectible et ses idées toujours inspirantes. Enfin, je suis très reconnaissant envers Alessio qui m'a donné l'opportunité de venir travailler au IIASA. Je garde un souvenir enchanté de mon séjour à Vienne grâce au Young Summer Scientist Program, et notamment des rencontres si enrichissantes.

Les discussions et relectures avec mes co-doctorants ont largement influencé ce travail. Un grand merci au T pour avoir relu la quasi-totalité de mes papiers, ainsi qu'au S et au R pour leur enthousiasme contagieux envers les sciences économiques, qui m'a beaucoup inspiré. Je vous souhaite de brillamment finir vos doctorats. J'en profite pour souhaiter une belle réussite au B dans sa nouvelle aventure. Ces remerciements s'adressent également à toute la team building, et notamment à Pille et Ilya qui ont toujours été disponibles pour m'aider et avec qui j'ai toujours eu plaisir à échanger.

Je tiens aussi à remercier chaleureusement Jessy et Carine pour leur efficacité remarquable. Plus globalement, je remercie les délégués des doctorants, les organisateurs des séminaires, Auriane pour son énergie débordante ou Florian pour s'être battu pour notre droit à la caféine. Le CIRED doit beaucoup à l'engagement de ceux qui, au détriment de leurs propres recherches, font vivre notre laboratoire.

Mais une thèse n'est pas seulement une aventure professionnelle. Pour moi, elle est aussi le fruit d'une culture familiale ancrée dans la recherche. Elle est également le résultat d'une chance particulière : celle de bénéficier d'un soutien affectif et matériel qui m'offre la sérénité nécessaire pour aborder toute nouvelle situation. Cette assurance m'a permis de me lancer avec confiance dans ce doctorat. Je remercie donc toute ma famille, et en particulier ma grand-mère, qui m'a accompagné depuis mon arrivée à Paris il y a dix ans.

Dix ans déjà, et l'occasion de remercier une bande d'amis avec qui j'ai grandi, appris, et beaucoup ri. Un grand merci aux Dr. Polo, Rimk, Mat, et Guigz pour m'avoir encouragé à débuter ce doctorat. J'étends ces remerciements à tous les amis qui, depuis l'enfance et jusqu'aux plus récentes rencontres, ont rendu mes expériences toujours plus riches, divertissantes et joyeuses.

Enfin, je tiens à exprimer ma gratitude infinie à mon amoureuse de toujours. Ton soutien sans faille est essentiel, si bien que tu es indissociable de chacune de mes réussites. Je suis immensément heureux de partager ma vie avec toi, et impatient de partager de nouvelles aventures.

Short Summary

Recognizing the multiple benefits of energy efficiency policies in the residential sector Western governments have implemented myriad policies in recent years. In practice, however, empirical assessments of these interventions find them economically inefficient. This gap between expectations and realizations calls for a better account of the key frictions impeding energy efficiency investment in policy assessments. In this thesis, I build a modeling framework that permits socio-economic assessment of a range of residential energy efficiency policies implemented in economies subject to market failures and behavioral anomalies. I show that achieving carbon neutrality requires ambitious policies to promote heat pumps in most European countries (France in particular), alongside the full decarbonization of the electricity system. I demonstrate that adopting heat pumps shifts gas use from heating to electricity generation, which from a whole-system perspective is a more efficient use of low-carbon biogas, only available in short supply. While regulatory measures underperform incentive-based instruments from a simple microeconomic perspective, they are crucial for meeting carbon neutrality, especially under uncertainty. Second, I find that the CO_2 externality is actually dominated by health, rental, and multi-family frictions in the ranking of justifications for energy efficiency policies. This finding underscores the importance of targeted subsidies for home insulation to address specific frictions while alleviating energy poverty. Finally, the assessment shows that the policies currently implemented in France only close about half of the energy efficiency gap in space heating, pointing to the need for better targeting.

Résumé court

Conscients des multiples bénéfices des politiques d'efficacité énergétique dans le secteur résidentiel, les gouvernements occidentaux ont déployé, ces dernières années, un large éventail de mesures combinant des instruments incitatifs et réglementaires. Dans la pratique, cependant, les évaluations empiriques de ces interventions les jugent économiquement inefficaces. Ce contraste entre ambitions et réalisations souligne la nécessité de mieux intégrer les frictions qui entravent les investissements dans l'évaluation des politiques publiques. Dans cette thèse, je propose un cadre de modélisation original pour évaluer, d'un point de vue socio-économique, les politiques d'efficacité énergétique résidentielle dans des contextes marqués par des défaillances de marché et des biais comportementaux. Je montre qu'atteindre la neutralité carbone nécessite des politiques ambitieuses favorisant l'adoption des pompes à chaleur dans la plupart des pays européens, en particulier en France, combinées à une décarbonation complète du système électrique. Je démontre que cette transition transfère l'utilisation du gaz, du chauffage à la production d'électricité, et maximise l'efficacité du gaz bas carbone. Bien que les mesures réglementaires soient généralement considérées comme peu flexibles par rapport aux instruments incitatifs, elles s'avèrent essentielles pour atteindre la neutralité carbone dans un contexte marqué par de fortes incertitudes. Deuxièmement, j'identifie que les externalités liées au carbone sont surpassées par d'autres frictions – notamment celles liées à la santé, à la location et aux logements collectifs – dans les justifications des politiques d'efficacité énergétique. Cela met en lumière l'importance d'aligner les barèmes des subventions sur les défaillances de marché. Enfin, mon travail montre que les politiques actuellement mises en oeuvre en France ne couvrent qu'environ la moitié du déficit d'efficacité énergétique, soulignant le besoin d'un ciblage plus précis.

General Summary

Recognizing the multiple benefits of energy efficiency policies in the residential sector – GHG emission reductions, fuel poverty alleviation, health improvement – Western governments have implemented myriad policies in recent years – mostly incentive-based (carbon taxes, subsidies, white certificate obligations, low-interest rate loans) and increasingly regulatory (mandatory renovation, ban on certain heating fuels). In practice, however, these policies have had deceptive effects. Participation rates have been lower than anticipated and, when realized, investment is found to have little impact on energy savings. This gap between expectations and realizations calls for a better account of the key frictions impeding energy efficiency investment in policy assessments.

In this thesis, I build a modeling framework that permits socio-economic assessment of a range of residential energy efficiency policies implemented in economies subject to market failures and behavioral anomalies. In doing so, I bridge a gap between building stock models, which contain rich technological detail but lack key market and behavioral mechanisms, and microeconomic models, which typically consider frictions one at a time, in a stylized way.

Specifically, I propose four improvements on the existing literature: a refinement of the depiction of residential energy efficiency technologies, accounting for complementarities between insulation levels and heating system performance; an explicit account of key barriers to energy savings, including rebound effects, non-energy costs, present bias, myopic expectation of energy prices, credit constraints, landlord-tenant dilemma and coordination problems in multi-family housing; an extended welfare assessment framework factoring in thermal comfort, fuel bill alleviation, health benefits, non-energy attributes and the opportunity cost of public funds; and a stronger integration between energy demand and supply in the residential sector, instrumental in capturing all margins of decarbonization. These improvements are applied to two different models – Res-IRF, an energy-economy model of energy demand in the French residential sector, and Message-ix Buildings, a building stock model that I have applied to the EU residential sector.

Taken together, these improvements allow me to generate the following insights. First, achieving carbon neutrality requires ambitious policies to promote heat pumps in most European countries (France in particular), alongside the full decarbonization of the electricity system. I demonstrate that adopting heat pumps shifts gas use from heating to electricity generation, which from a whole-system perspective is a more efficient use of low-carbon biogas, only available in short supply. While regulatory measures underperform incentive-based instruments from a simple microeconomic perspective, they are crucial for meeting carbon neutrality, especially under uncertainty. Second, I find that the CO_2 externality is actually dominated by health, rental, and multi-family frictions in the ranking of justifications for energy efficiency policies. This finding underscores the importance of targeted subsidies for home insulation to address specific frictions while alleviating energy poverty. Finally, our assessment shows that the policies currently implemented in France only close about half of the energy efficiency gap in space heating, pointing to the need for better targeting.

My work begins with the observation that state-of-the-art bottom-up models for the residential sector typically provide a comprehensive description of the building stock, but only a succinct account of household behavior. When considered, barriers to energy efficiency investment, still mainly rely on implicit discount rates, which fails to capture their diversity. In Chapter 1, I improve on this situation by building an original microsimulation framework that combines a high level of technological detail regarding building envelopes and heating systems with a multitude of frictions in energy efficiency investments. This combination in turn allows me to evaluate energy policies with a high level of detail. After validating the model against past policy trends, the policy package currently implemented in France closes about half of the energy efficiency gap related to space heating, about two thirds related to energy savings and one third related to welfare. However, I show that the welfare gap is commensurate with current spending on subsidies, which call for a better alignment of subsidies with distortions to make them more efficient. In Chapter 2, I apply this extended modeling framework to the whole EU to assess the impact of the new Green Deal on the residential sector. In particular, I show that implementation of the EU Emissions Trading System 2, combined with energy supply deep decarbonization, falls short of climate targets and requires ambitious subsidies for heat pumps in most countries. Implementing a large 'Renovation wave' is not a cost-effective strategy at the EU level and would require large increases in public spending. Combining carbon tax and heat-pump subsidies with well-targeted subsidies for home insulation could alleviate potential strain on the electricity system and reduce energy poverty, while supporting residential sector decarbonization.

Albeit necessary, improvements in the modeling of energy demand will only generate limited insights about decarbonization as long as the interplay with energy supply is not properly taken into account. Indeed, state-of-the-art assessments of climate policy tend to focus on endogenous energy demand while keeping energy supply exogenous (or vice versa). When supply and demand are jointly considered, assessments still rely on simplified policy modeling and thus only offer limited insight into the design of climate policies. In chapter 3, I contribute to linking Res-IRF to EOLES, a bottom-up energy system model tailored for France. Running the joint framework confirms the Res-IRF-generated insight that achieving carbon neutrality most cost-effectively requires a balanced approach between improving energy performance, transitioning to low-carbon heating systems, and decarbonizing heating fuels. The framework reveals that total system costs can be underestimated by up to 15% in engineering studies by failure to realistically model energy-efficiency policies. Finally, in Chapter 4, I apply the same framework to assess the implementation of a ban on gas boiler. I find that heat pump adoption shifts gas use from heating demand to electricity generation, which is a more efficient use of low-carbon biogas from a whole-system perspective. Heat pump adoption therefore provides a hedge against short supply of low-carbon gas. I additionally find that widespread heat pump adoption is more effectively achieved through a ban on new gas boilers than through incentives under uncertainty. I therefore shed a more positive light on the ban.

In an effort to follow best practice, all modeling tools developed in this thesis have been released open-source and designed with a modular architecture that makes them easy to update and adapt to other economies. These developments have been used by French authorities in their own assessment of the household sector's contribution to the country's updated low-carbon strategy (Stratégie Nationale Bas-Carbone).

Résumé général

Conscients des multiples bénéfices des politiques d'efficacité énergétique dans le secteur résidentiel - réduction des émissions de gaz à effet de serre (GES), atténuation de la précarité énergétique, amélioration de la santé publique - les gouvernements occidentaux ont déployé, ces dernières années, un large éventail de mesures combinant aux instruments incitatifs (taxes carbone, subventions, certificats d'économies d'énergie, prêts à taux réduit) des réglementations (obligations de rénovation, interdictions de certains systèmes de chauffage). Cependant, ces politiques ont produit des résultats décevants. Les taux de participation sont inférieurs aux attentes et, lorsqu'ils se matérialisent, les investissements génèrent des économies d'énergie limitées. Ce contraste entre ambitions et réalisations souligne la nécessité de mieux intégrer les frictions qui entravent les investissements dans l'évaluation des politiques publiques.

Dans cette thèse, je propose un cadre de modélisation original pour évaluer, d'un point de vue socio-économique, les politiques d'efficacité énergétique résidentielle dans des contextes marqués par des défaillances de marché et des biais comportementaux. Ce travail comble un vide entre les modèles d'ingénieur de stock de bâtiments, riches en détails technologiques mais qui négligent les mécanismes de marché et les comportements, et les modèles microéconomiques, qui tendent à analyser les frictions de manière simplifiée et isolée.

Plus précisément, mon travail apporte quatre contributions majeures à la littérature existante. Premièrement, il affine la représentation des technologies d'efficacité énergétique résidentielle en intégrant les complémentarités entre les niveaux d'isolation et la performance des systèmes de chauffage. Deuxièmement, il introduit une prise en compte explicite des principales barrières aux économies d'énergie, telles que les effets de rebond, les coûts non énergétiques, le biais pour le présent, les comportements myopes sur les prix de l'énergie, les contraintes de crédit, le dilemme propriétaire-locataire et les problèmes de coordination dans les logements collectifs. Troisièmement, il élargit le cadre d'évaluation au bien-être économique en intégrant des dimensions telles que le confort thermique,

la réduction des factures énergétiques, les bénéfices pour la santé, les attributs non énergétiques et le coût d'opportunité des fonds publics. Enfin, il renforce l'intégration entre l'offre et la demande d'énergie dans le secteur résidentiel, permettant une meilleure prise en compte des leviers de décarbonation. Ces avancées sont mises en œuvre dans deux modèles: Res-IRF, un modèle de microsimulation de la demande énergétique résidentielle en France, et Message-ix Buildings, un modèle de stock de bâtiments appliqué au secteur résidentiel de l'Union européenne.

Ensemble, ces améliorations me permettent de générer les perspectives suivantes. Atteindre la neutralité carbone nécessite des politiques ambitieuses favorisant l'adoption des pompes à chaleur dans la plupart des pays européens, en particulier en France, combinées à une décarbonation complète du système électrique. Je démontre que cette transition transfère l'utilisation du gaz, du chauffage à la production d'électricité, et maximise l'efficacité du gaz bas carbone. Bien que les mesures réglementaires semblent moins performantes que les instruments incitatifs dans une approche micro-économique standard, elles s'avèrent essentielles pour atteindre la neutralité carbone dans un contexte de forte incertitude. Deuxièmement, j'identifie que les externalités liées au carbone sont surpassées par d'autres frictions – notamment celles liées à la santé, à la location et aux logements collectifs – dans les justifications des politiques d'efficacité énergétique. Cela met en lumière l'importance d'aligner les barèmes des subventions sur les défaillances de marché. Enfin, mon travail montre que les politiques actuellement mises en œuvre en France ne couvrent qu'environ la moitié du déficit d'efficacité énergétique, soulignant le besoin d'un ciblage plus précis.

Les chapitres de cette thèse approfondissent ces analyses. Dans le Chapitre 1, je développe un cadre de microsimulation combinant un haut niveau de détail technique sur les bâtiments et systèmes de chauffage avec une modélisation fine des frictions d'investissement. Validé sur les tendances passées, ce modèle révèle que les politiques actuelles en France couvrent environ deux tiers des économies d'énergie nécessaires mais seulement un tiers des bénéfices en termes de bien-être. Je montre également que le déficit de bien-être est comparable aux dépenses publiques actuelles, plaidant pour un alignement plus efficace des subventions. Le Chapitre 2 étend cette approche à l'échelle de l'Union européenne afin d'évaluer l'impact du Green Deal européen. Je montre que le système d'échange de quotas d'émission EU-ETS 2 et la décarbonation du mix énergétique ne suffisent pas à atteindre les objectifs climatiques, et nécessitent la mise en place de subventions ambitieuses pour les pompes à chaleur. Aussi, la mise en œuvre d'une Renovation Wave non ciblée apparaît comme une stratégie peu rentable au niveau de l'UE et nécessiterait de fortes augmentations des dépenses publiques. En revanche, une taxe carbone et des subventions pour les pompes à chaleur combinées à des subventions ciblées pour l'isolation des logements pourrait atténuer la pression potentielle sur le système électrique et réduire la précarité énergétique, tout en permettant la décarbonation du secteur résidentiel.

Le Chapitre 3 repose sur le couplage entre Res-IRF et un modèle énergétique bottom-up appliqué à la France, pour analyser conjointement l'offre et la demande d'énergie. L'analyse révèle que l'atteinte de la neutralité carbone nécessite une approche équilibrée entre l'amélioration de la performance énergétique, la transition vers des systèmes de chauffage bas-carbone et la décarbonation du système énergétique. En outre, cette évaluation révèle que les coûts du système peuvent être sous-estimés de 15% dans les études ne modélisant pas adéquatement les politiques d'efficacité énergétique. Enfin, le Chapitre 4 examine les implications d'une interdiction des chaudières à gaz en France. Nous constatons que l'interdiction engendre des transformations majeures dans le système énergétique, conduisant à des gains d'efficacité significatifs. De plus, elle augmente la probabilité d'atteindre la neutralité carbone tout en réduisant les coûts totaux du système dans plus de 75% des scénarios. Enfin, nous montrons que la mise en œuvre de cette interdiction, lorsqu'elle est associée au cadre actuel de subventions, permet de réduire les inégalités parmi les ménages propriétaires-occupants, mais génèrent des effets défavorables pour les locataires du secteur privé.

Enfin, conformément aux meilleures pratiques, tous les outils développés dans cette thèse sont disponibles en open source. Leur conception modulaire facilite leur adaptation à d'autres contextes économiques. Ces outils ont déjà été utilisés par les autorités françaises dans l'évaluation actualisée de leur Stratégie nationale bas-carbone.

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General introduction

Energy efficiency measures provide significant benefits, including energy savings, reduced greenhouse gas emissions, alleviation of fuel poverty, and improved health outcomes. Over time, the reasons for promoting energy efficiency have shifted in response to societal concerns. Initially focused on resource depletion in the classical age, the emphasis moved to energy security in the modern age, and now centers on the urgent need to address climate change in the contemporary era (Giraudet and Missemer, 2023). Specifically, residential space heating sector, which accounts for about 80% of energy use in EU homes and contributes over a third of the EU's energy-related greenhouse gas emissions has been the focus of various energy efficiency policies in recent years (Eurostat, 2023; Economidou et al., 2020).

However, these policies have often yielded disappointing results (Gillingham et al., 2018; Giandomenico et al., 2022). Participation rates have been lower than expected, and when investments are made, they frequently result in minimal energy savings(Christensen et al., 2021). This discrepancy between expectations and outcomes highlights the need for a more accurate assessment of the costs and benefits of energy efficiency technologies, as well as an understanding of the key barriers hindering investment. In this dissertation, I quantitatively assess the long-term impact of energy efficiency policies in the residential space heating sector, by developing a modeling framework that incorporates both detailed technology and rich behavioral insights.

This dissertation focuses on energy demand for space heating in the residential sector. It focuses on France, with one extension to the EU-27. France is a notable case study due to its comprehensive energy-efficiency policies, with nearly 8 billion Euros spent in 2021 on four major energy efficiency subsidy programs (Ledez and Hainaut, 2021). This dissertation specifically examines mitigation measures targeting the existing building stock. Although replacing old, inefficient homes with new, efficient ones naturally reduces direct GHG emissions, this strategy has proven little effective due to the significant emissions generated during construction (Berrill et al., 2022). Moreover, the slow rate of turnover in Europe means that 75% of the existing building stock is expected to remain in use by 2050.

This introduction is divided into two parts. First, I provide a literature review to summarize current knowledge and identify the main research gap this dissertation addresses. This review starts with an up-to-date assessment of the costs and benefits of energy-efficiency technologies, then examines the main obstacles and behavioral anomalies that hinder energy-efficiency investments. I also review the practical outcomes of energy efficiency policies. Finally, I discuss how models evaluate these policies and how they can help design more effective strategies. In the second part of the introduction, I outline the goals, methodologies, and contributions of my dissertation.

1 Literature review

1.1 Do the benefits of energy renovation outweigh costs?

Description of energy renovation technologies

The reduction of existing emissions from space heating is achieved through three main channels: home insulation, switching to low-carbon heating systems and decarbonization of heating fuels.

Home insulation involves insulating the four components of the building envelope: attics and roofs, walls, glazed walls and low floors. The second option is to replace the heating system with a more efficient model, switching from fossil fuels to potentially low-carbon fuels (electricity, wood and district heating).

Heating systems are characterized by their final energy efficiency and the heating medium used. Combustion systems (gas, oil, wood) are based on boiler-type systems with an overall efficiency of usually 0.8 - the combustion of 1 kWh of fuel produces 0.8 kWh of heat for the occupant of the dwelling. Electric systems are based on two very different technologies: Direct electric, which generate heat through the Joule effect, and heat pumps, which transfer heat from a hot source to a cold source by using the condensation-evaporation cycle. Radiators have a conventional efficiency of 1, while the average efficiency of heat pumps is 2.5. This means that the efficiency of heat pumps is almost three times higher than that of fuel systems.

Renovating a home for energy efficiency therefore involves acting on at least one out of six work packages: roof, wall, floor and window insulation, heating system upgrades and the installation of controlled mechanical ventilation. A renovation is generally considered to be of a high performance if it combines several measures - at least wall, roof and floor insulation, plus an upgrade of the heating system if the dwelling uses mainly coal, oil or gas.

Energy renovation cost

Each of the six renovation measures is available with different options (different insulation thickness and material) and are all deployed at different scales (number of windows, area to be covered, etc.). As a result, there is no such thing as a typical renovation project, but rather dozens of possible approaches, which leads to a wide variation in costs. An important aspect is that the cost of insulation does no depend on the existent insulation level, as insulation material must be usually completely replaced. For this reason, the cost-benefit ratio of home insulation is best in the worst-performing dwelling. Since the first oil shock in the 1970s, the escalation in building codes tightness has led to considerable heterogeneity in the overall energy efficiency of residential buildings, which thereby leads to large differences in the cost-effectiveness of energy renovations.

Finally, energy renovation, like any technology, is theoretically subject to cost reductions due to technical progress. The most important study to my knowledge reports learning rates - cost reductions associated with a doubling of cumulative production - of 32% for heat pumps, 10% for other heating systems, 18% for insulation and 15% for air conditioning (Weiss et al., 2010). However, given the non-standardized and labor-intensive nature of energy renovation, it seems unlikely that the cost reductions specific to each technology will add up. The extent of technical progress in the energy renovation of existing buildings has yet to be proven, and the expected innovations are at least as much organizational as technical in nature (Kiss, 2016) .

Energy renovation benefits

The benefits of energy renovation take many forms—financial, climatic, health-related, and even geopolitical—but they heavily depend on the performance of energy efficiency measures.

Energy performance gap The performance of an energy renovation project depends on complex interactions between the conductivity of the building envelope (which must be corrected for losses and infiltrations), the efficiency of the heating system and climatic factors (outside temperature), architectural factors (exposure, which determines solar gain) and behavioral factors (heating temperature and number of heated rooms). The use of thermal simulation software is required to take these interactions into account.

In practice, the energy savings measured on site are significantly lower than those predicted by these thermal simulation models. This gap, commonly referred to as the energy performance gap, has received much attention over the last decade due to the increase in public spending on energy retrofits worldwide and the 'credibility revolution' in applied economics Giraudet and Missemer (2023). Fowlie et al. (2018), often referred to as the gold standard assessment, find a 70 percent gap in a renovation program conducted in Michigan. In Table 0.2, I provide an overview of the assessment of the energy performance gap in the peer-reviewed literature, all of which were realized in the USA. The size of the gap depends on many factors such as the quality of the renovation work or the thermal simulation model used, but various studies find a gap of the same order of magnitude for France (Charlier, 2021).

Table 0.1 – Subset of realization rates from the peer-reviewed literature

Paper	**Location**	**Realization Rate**
Dubin et al. (1986)	Florida	≈0.9
Fowlie et al. (2018)	Michigan	0.30
Giraudet et al. (2018a)	Florida	0.68
Christensen et al. (2021)	Illinois	0.51
Allcott and Greenstone (2024)	Wisconsin	0.68

The energy performance gap is known to arise from a variety of problems, including rebound effects (Gillingham et al., 2016), the pre-bound effect (Sunikka-Blank and Galvin, 2012; Galvin and Sunikka-Blank, 2016) and issues with the quality with which retrofits are completed (Giraudet et al., 2018b). The reference study on the energy performance gap (Christensen et al., 2021), identifies a discrepancy of 51%, of which they attribute 42% to quality problems, 40% to modeling errors and 6% to the rebound effect (14% remaining unexplained).

Private benefits The most obvious private benefit of energy renovation is the reduction in energy bills, which equals the annual flow of real energy savings multiplied by energy prices. Additionally, investments in energy efficiency lead to changes in heating behavior, known as the rebound effect. As energy services become cheaper, households tend to increase their heating intensity. In France, recent estimates find a short-term price elasticity of -0.2 (Douenne, 2020), which aligns with findings in other economies and is commonly cited in the literature (Allcott and Greenstone, 2024), providing an estimate of the rebound effect's magnitude. Although the rebound effect reduces bill savings, it offers greater benefits for households by increasing thermal comfort. Recent evidence suggests that improvements in thermal comfort can be as significant a factor as financial considerations (Wekhof and Houde, 2023). This enhanced comfort is not only due to the rebound effect but also from the presence of warmer surfaces resulting from home insulation. This aspect warrants further research to quantify its full benefits for households.

Social benefits Real energy savings generate reductions in greenhouse gas emissions, to varying degrees depending on the carbon content of the energies involved, which by convention varies from 30 gCO2/kWh for wood energy to 234 gCO2/kWh for domestic heating oil in France (Légifrance, 2021).

Furthermore, space heating is far more than a comfort service - it's a matter of public health. A poorly heated home exposes its occupants to the risk of cardiovascular and respiratory diseases. These effects occur when the poor energy performance of a home is combined with the low income of its occupants, leaving them unable to afford the high cost of heating. Charlier and Legendre (2021) show that energy poverty significantly worsens the health status of people with a poor condition, while it has little effect on the health status of people in good health. These long ignored health effects have recently been estimated by a working group coordinated by France Strategy (Dervaux and Rochaix, 2022). Further evidence from experimental or quasi-experimental studies is required as health costs can be very high and therefore influence the impact of energy efficiency measures on welfare.

Finally, it should be recalled that concerns about controlling energy demand emerged as a reaction to the oil shocks of the 1970s (Giraudet and Missemer, 2023), long before the climate problem became the main justification in the 2000s. Even then, it was international conflicts that motivated the quest for energy independence. The war in Ukraine has revived this issue in a spectacular way. However, this aspect is rarely considered in the cost-benefit analysis of energy efficiency programs, and additional indicators such as the impact on the terms of trade should be emphasized.

Energy renovation value for the energy system

Energy bill savings for consumers result from a reduction in the cost of the energy system. However, there is a discrepancy between these savings and the reduction of system costs because energy pricing is usually based on regulated and average-cost pricing that does not directly reflect the real-time costs that can vary widely across different hours.

Space heating demand is particularly concentrated during winter when energy costs, especially electricity, are at their highest in temperate countries. Variations in electricity demand affect the need for peaking power plants or batteries. A large-scale switch from natural gas boilers to heat pumps could incur additional costs if the electricity system cannot easily absorb the increased demand. In contrast, insulating homes with electric heating can provide benefits beyond bill savings by reducing the strain on the electricity system. For instance, Zeyen et al. (2021) demonstrate that the optimal level of home insulation is more strongly influenced by seasonal heat peaks than by overall energy consumption, underscoring the significant value of reducing peak demand. Similarly, Boomhower and Davis (2020) show that accounting for the timing of energy use increases the value of energy efficiency for air conditioning by about 40 percent in California, due to the reduction in capacity payments received by electricity generators.

Non-energy or hidden value

Energy renovations involve a number of additional costs and benefits that are generally more difficult to identify.

Renovation work is often associated with non-energy-related ancillary costs, such as setup costs, demolition work, and subsequent makeover tasks like plastering, painting, and finishing. These essential tasks are not always included in the total cost, especially when energy upgrades are part of a larger project like a complete renovation or extension, making it difficult to isolate the energy-related expenses. For instance, a field study in France found that deep renovations incur 40% additional expenditure on non-energy and non-thermal items (Enertech et al., 2022). Moreover, intangible costs such as transaction costs—estimated at 20% of the total project cost—include efforts to gather information and find reliable contractors, with an energy audit alone costing around €1,000 in France (Kiss, 2016; Ebrahimigharehbaghi et al., 2020). Renovation work also causes inconvenience and discomfort; installing heating systems can take several days, electrical and plumbing work one to two weeks, and facade and roof work even longer, making homes uninhabitable or less livable during this period. The hedonic value of these disruptions can be estimated based on temporary relocation rent costs. These significant non-energy costs explain why households delay energy-saving investments until necessary renovations arise, when they will already incur non-energy expenses and search for reliable contractors (Wekhof and Houde, 2023). This contributes to the low price elasticity of demand for energy renovation. Following this rationale, Aldenhoff and Kurzrock (2024) estimate that increasing energy renovation rates to 2% per year or more is largely unrealistic when considering building renovation cycles.

On the other hand, some measures bring non-monetary benefits due to their non-energy characteristics, which are often overlooked. For example, windows provide aesthetic and acoustic benefits. Recent surveys indicate that environmental concerns are also a crucial determinant for energy renovations (Wekhof and Houde, 2023).

The net value of these non-energy attributes varies from household to household and over time and depends on certain events, such as moving to a new home, which can absorb inconvenience, or an unexpected inheritance, which reduces capital costs.

Cost-benefits assessment

There is consensus about the positive socio-economic balance of massively installing heat pumps, which provide energy savings due to higher efficiency and emission reductions by relying on electricity, a more easily decarbonized energy source. However, whether the benefits of home insulation improvements outweigh the costs remains ambiguous. This ambiguity arises from the heterogeneity of the building stock, variations in energy efficiency technologies, and the scope of considerations (Hummel et al., 2021).

On the one hand, Hummel et al. (2023) find that a large proportion of home insulation is economically viable for achieving a 95% reduction in CO_2 emissions across the EU-27's building stocks by 2050, with optimal energy demand savings ranging from 29–47%. In a broader scope, also including the benefits of home insulation to reduce the strain on the electricity system, Zeyen et al. (2021) calculate that home insulation achieves 44 to 51% energy savings, leading to cost savings of up to 14% compared to scenarios without home insulation. Similarly, Mandel et al. (2023) find that scenarios that double the energy renovation rate are almost as cost-effective as less ambitious scenario. They calculate that these scenarios lead to a slight cost increase of less than 10 euros per EU citizen per year, but argue that it would be likely offset by higher fossil fuel prices or by including additional, unmonetized co-benefits of energy efficiency.

On the other hand, a recent study carried out in Germany calculates that, in monetary terms, home insulation is never economically viable and that the average payback after 25 years is around 22.5% (Galvin, 2024). These results remain when the social value of avoided emissions is taken into account. In contrast to other studies, Galvin (2024) includes the financing costs and takes better account of the prebound effects, but it does not consider the benefits for the electricity system. It also focuses only on Germany, which is consistent with the results at national level find by Zeyen et al. (2021).

Research gap

Recent advances in the granularity of building stock assessment at a regional level have significantly improved the accuracy of energy efficiency analyzes (Berrill et al., 2022;

Camarasa et al., 2022; Hummel et al., 2023). Energy efficiency technologies now include detailed assessments of home insulation at the level of building components and different heating system technologies. Here I highlight four research gaps that could improve the cost-benefit analysis to better define energy efficiency uptake targets.

First, technical studies estimate a significant potential for energy renovation but still rely on thermal simulation models to estimate energy savings without fully addressing the energy performance gap. These models assume ideal conditions for energy renovations, which empirical evidence often disputes (Christensen et al., 2021), leading to an overestimation of their role in mitigation strategies.

Second, these studies typically do not take into account the financing costs and, more importantly, the non-energy (or unobserved) costs of homeowners. In particular, non-energy costs have been shown to be a decisive factor in the decision to renovate or postpone renovation work. Not taking such factors into account results in pathways that are not anchored in reality by projecting renovation rates that do not match the renovation cycles of buildings.

Third, new assessments should focus on the interaction between heat pumps and home insulation. The efficiency of heat pumps tends to increase with improved home insulation, and there may be technical incompatibilities when heat pumps are installed in poorly insulated homes. Proper home insulation is crucial to enable the installation of cost-effective heat pumps that keep homes warm enough. However, there is no consensus on the level of home insulation required to install heat pumps. A recent study spanning almost two years analyzed the performance of 750 heat pumps in the UK and demonstrated successful installations even in older pre-1945 properties (System, 2024). The study showed that minimal insulation (costing less than €1,000) may be adequate for installing heat pumps in the worst-performing dwellings. Therefore, additional empirical evidence is needed to draw definitive conclusions on this matter.

Fourth, the scope of these analyses has also broadened to include a wider range of co-benefits from energy renovations beyond GHG emission reductions (Ürge Vorsatz et al., 2016). State-of-the-art technical assessments, such as those by (Zeyen et al., 2021; Mandel et al., 2023), now consider both air pollution impacts and broader energy system impacts. However, few studies include the potential health benefits for residents of poorly performing homes. Inefficient homes expose occupants to risks such as acute coronary syndrome, pneumonia, and severe respiratory infections (Gillingham et al., 2021; Symonds et al., 2021). A study in France estimates that homes with theoretical heating consumption above 378 kWhEF/m^2/year incur a social cost of €135,000 per case, averaging €7,500 per exposed home (Dervaux and Rochaix, 2022). The probability of these diseases is higher for low-income households. Including these health benefits would make home insulation more beneficial for households at risk. Again, additional empirical evidence is needed to draw definitive estimates on this matter.

1.2 Do market frictions or behavioral anomalies prevent the diffusion of energy renovation ?

For at least three decades, technical studies have advocated the widespread use of energy efficiency technologies, estimating that benefits outweigh the costs in the long term (McKinsey, 2009). This belief in profitable yet untapped mitigation action has led energy efficiency scholars to investigate the so-called energy efficiency gap—the difference between the economically optimal level of energy efficiency and the actual level. Historically, this gap has been measured by estimating unusually high discount rates to explain observed investments (Train, 1985). Since the seminal paper by Jaffe and Stavins (1994), extensive research has sought to identify the causes of this gap. Possible explanations include classical market failures, behavioral failures rooted in behavioral economics, and analysts' misperceptions of the cost-effectiveness of energy efficiency investments (Figure 0.3).

Market and behavioral failures lead to a divergence between socially optimal and privately optimal decisions, justifying the implementation of public policies. However, if the apparent energy efficiency gap is solely due to hidden costs or incorrect calculations by analysts, then there is no actual gap, and no public policy intervention is warranted. The objective of this literature has therefore been to investigate the heterogeneity of homeowners' investment decisions to identify situations that genuinely require public policy intervention from others that may sometimes discourage individuals from adopting energy-efficient technologies but does not constitute a market failure.

There are many comprehensive literature review on the subject (Allcott and Greenstone, 2012; Gillingham and Palmer, 2014; Gerarden et al., 2017). In this section I briefly review the main evidence found in the literature on market failures or behavioral anomalies in the residential space heating sector. Where possible, I draw on evidence from the French or European context, which is the focus of this dissertation.

Market failures

Energy market failures Misalignment of the price and marginal social cost of energy lead to a divergence between optimal and actual investments in energy efficiency. Lower cost make households invest too little, while higher cost make households invest too much.

On the one hand, the most common argument is that energy prices do not take into account the negative externalities of energy use. In particular, the use of fossil fuels releases significant environmental pollutants, including GHG emissions, which are not fully priced into energy costs. While in Europe electricity and large district heating systems are subject to carbon taxes through the EU Emissions Trading Scheme (EU ETS), emissions from the direct use of fossil fuels in the domestic sector are largely ignored or not set at the social cost of carbon. In France, for example, the residential carbon tax €45/tCO_2, well below the estimated social cost of carbon of at least €150/tCO_2 in 2024 (Quinet, 2019; EPA, 2022). This translated into the failure to include environmental benefits into energy efficiency investment decision.

On the other hand, as already described, energy renovation decision are subject to positive or negative externalities on the electricity system. The retail price of energy is a utility-regulated price that does not reflect marginal costs, and often lead to electricity and gas prices above marginal costs of production. In addition, the average costs faced by households cause energy prices to deviate from marginal costs, as there are no time-varying energy prices. This could lead to prices being too low at some times and too high at other times. The overall impact of these regulatory mechanisms is unclear and not fully understood. Overall, this leads to ambiguous externalities on the energy system, which depends on the tariff in place.

Information asymmetries in credit markets : credit rationing In a recent survey on energy renovation in France, financial constraints are cited as the main obstacle to investment (MTE, 2020). Although loans can help overcome this barrier, they are particularly expensive compared to those backing other green assets, e.g. vehicles (Giraudet et al., 2021b), and only partially effective due to information asymmetries. Banks, unable to fully assess the risk associated with investment, often use household income as a proxy and enforce maximum debt ratios. Although income and risk are related, they are not identical, which means that modest but financially stable households may be denied loans (Stiglitz and Weiss, 1981). Credit rationing may be especially acute for borrowers considering investments with high energy savings payoffs, and a correspondingly low risk of default, but who also happen to have poor credit (Palmer et al., 2012).

Information asymmetries in real estate markets : landlord-tenant dilemma If real estate markets worked perfectly, each euro of discounted cumulative energy savings would translate into €1 of capital gain on sale or €1 of annual rent increase (Myers, 2019). However, this mechanism is countervailed by the partially unobservable nature of energy performance, where it is often to assess the level of insulation accurately. In this context, the buyer (purchaser or tenant) is not prepared to pay more for uncertain benefits.

The introduction of the energy performance certificate (EPC) in Europe in 2007 was intended to address this problem. It also provided valuable material for numerous empirical assessments of the green value. An analysis of some 30 studies (21 on sales and 9 on rentals) concludes that the EPC label is reflected in house prices, at a ratio close to 1:1, albeit with a more or less strong gradient depending on the match between supply and demand on the local market; for rents, on the other hand, the gradient is very weak (Giraudet, 2020). This results in under-investment in energy efficiency in private rental housing (Gillingham et al., 2012; Melvin, 2018; Myers, 2020; Lang et al., 2021b; Petrov and Ryan, 2021). This phenomenon is known as the problem of split incentives and is often referred to as the landlord-tenant dilemma.

Coordination problems in multi-family housing The energy renovation rate in multi-family houses tends to be lower than that of single-family houses (MTE, 2020). This phenomenon can be attributed to two coordination problems.

First, energy retrofits of dwellings within condominium often require decisions by homewowner's association, which are usually subject to a public good problem - the co-owners do not necessarily enjoy benefits commensurate with their contribution. This problem can be addressed by adjusting the investment contribution according to the Lindhal formula, as in the case of elevator financing, for example, where the required contribution increases with the floor of the apartment. However, this rule does not apply to energy renovation measures, such as roof insulation, which is still financed on the basis of the ownership share, which can lead to residents of intermediate floors being disadvantaged.

On the other hand, the decision-making power of condominium owners does not extend to all heat-emitting areas of their apartment, regardless of the resolutions of the condominium owners. As a result, heat may move across neighboring dwellings, leading to external effects - both negative and positive - which in any case reduce the benefits of the investment.

Behavioral anomalies

In addition to market failure, the behavior of economic agents can deviate from the perfect-rationality benchmark assumed in standard microeconomic models. Such behavioral anomalies are referred to as behavioral failures if they lead to a systematic difference between the utility at the time of the decision — the so-called decision utility — and the utility at the time when the consequences of the decision occur — the so-called experienced utility (Gillingham and Palmer, 2014).

It is important to distinguish between preferences such as standard time preferences or risk preferences and behavioral biases such as present bias or status quo bias. Although preferences may discourage individuals from adopting energy-efficient technologies, they lead to rational decisions. Consequently, policies aimed at counteracting these preferences would not make these individuals better off. In contrast, individuals with status quo biases or present biases may make technological decisions that run counter to their own long-term goals. In this sense, status quo bias and present bias are defined as behavioral failure as they cause a difference between decision utility and experienced utility (Gillingham and Palmer, 2014).

However, the merits of measures aimed at correcting these effects are controversial at a conceptual level, mainly because of their paternalistic aspect (Gillingham and Palmer, 2014). Deviations from rationality, however, affect the action of traditional instruments for correcting market failures and must therefore be taken into account for policy planning.

Identifying behavioral biases in empirical research is a significant challenge, particularly when trying to differentiate them from inherent preferences. Ideally, this process requires panel data that provides detailed household information along with estimates of key drivers like energy prices and renovation costs. However, such comprehensive data is difficult to obtain and not always lend themselves to experiments.

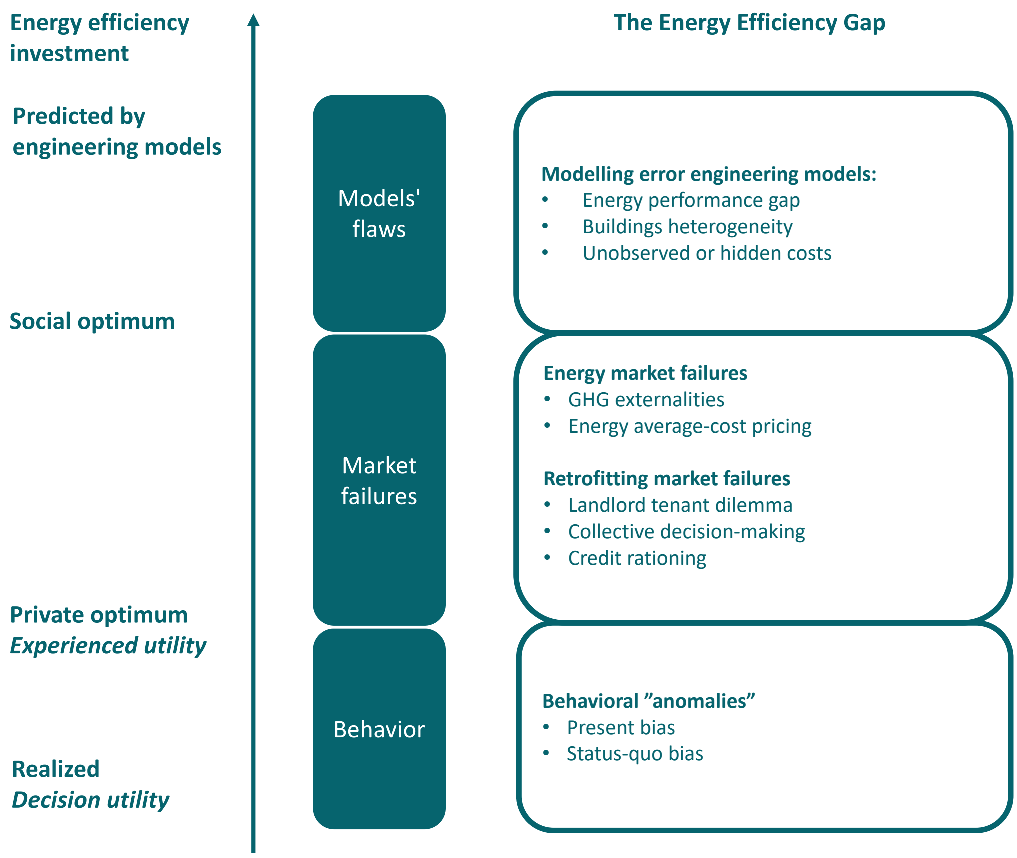
In this situation, discrete choice experiments have emerged as valuable tools for uncovering behavioral anomalies (Michelsen and Madlener, 2012; Newell and Siikamäki, 2015; Achtnicht and Madlener, 2014; Schleich et al., 2021). These surveys present respondents with multiple investment options and ask them to choose one, allowing for the consideration of a broad range of factors. Despite their usefulness, a major limitation of stated-preference approaches is that the choices respondents indicate do not always reflect their actual behavior.

Much of this literature focuses on how consumers discount future fuel savings from energy efficient investments and whether they underestimate future fuel savings compared to what would be expected based on how consumers discount in other contexts. Specifically there is evidence in the literature showing that consumers are short-sighted when investing in home insulation and demand higher returns than those offered by the financial markets (Stolyarova, 2016; Schleich et al., 2019). This strong preference for the present is often inferred from the high discount rates that rationalize investment decisions in discrete choice experiments. This bias tends to be correlated with income, with low-income households having a higher present bias than high-income households (Stolyarova, 2016).

Other behavioral anomalies, such as inattention to energy price, are also discussed in the literature and could also lead to underestimation of future energy savings (Lang et al., 2024). In addition, loss averse homeowners also tend to undervalue potential future benefits, which result in lower probability to invest in energy renovation (Schleich et al., 2019).

Lastly, Stolyarova (2016) and Lang et al. (2021a) show that households tend to stick to their current technology when considering a heating replacement, despite the higher profitability of some alternatives, a phenomenon known as status quo bias.

Figure 0.1 – Components of the Energy Efficiency Gap considered in this dissertation.



Research gap

An important explanation for the energy efficiency gap is the carbon externality. As long as the social costs of energy consumption are not reflected in prices, investment in energy efficiency will remain insufficient. This principle has been the main justification for many energy efficiency measures worldwide. In addition to this problem, there are other factors such as modeling errors (Metcalf and Hassett, 1999), the landlord-tenant dilemma (Gillingham et al., 2012), behavioral anomalies (Allcott et al., 2014), the rebound effect (Chan and Gillingham, 2015), moral hazard in the provision of quality (Giraudet et al., 2018b), and information asymmetries in the capitalization of energy efficiency (Myers, 2020) have been identified, but only a few have been empirically investigated. These frictions are usually studied individually and rarely in combination with the carbon externality. To our knowledge, only one study has investigated several frictions simultaneously — modeling errors, information asymmetries and the rebound effect (Christensen et al., 2021). Consequently, the energy efficiency gap was investigated in second or third best scenarios, while the “nth best” world of the Jaffe and Stavins (1994) framework remained largely unexplored.

1.3 What are the impact of energy efficiency policies in the residential sector ?

Tackling multiple market failures requires using variety of instruments. However, only a comprehensive assessment of the effectiveness, cost-effectiveness, welfare impacts and distributional effects of policies or programs can justify their implementation. Indeed, programs to promote energy savings may be poorly designed, poorly implemented, or inadequately targeted to the relevant market or behavioral failure, leading to non-cost-effective outcomes. I provide some background on the theoretical first-best policy mix and then review empirical evidence on energy efficiency instruments. In doing so, I focus on the evaluation of energy renovation programs rather than the energy renovation themselves.

First best policy mix

The textbook economic solution to the GHG externality is to set a carbon price equal to the marginal damage of GHG emissions. In the context of residential energy use, its the only instruments that simultaneously influences both energy consumption and investment decisions, whereas energy efficiency and regulations only activate the former channel (Goulder and Parry, 2008). However, the presence of other market failures and behavioral anomalies requires a mix of policies. Allcott et al. (2014) argue that in the presence of market and behavioral failures, an optimal policy would involve an energy tax below the marginal damage combined with subsidies targeting behavioral failures. This conclusion follows from their finding that the consumers who undervalue energy costs the most are also the least sensitive to energy taxes, so that the optimal policy would target the more disadvantaged customers while limiting distortions for the less biased customers.

However, practical or political constraints often limit the implementation of first-best policies. First, carbon prices are rarely set at their socially optimal level and do not always cover all relevant sectors—if they are implemented at all. For example, in France, the government froze the residential carbon tax rate in response to the Yellow Vest protest movement (Douenne and Fabre, 2022). Second, when distortions in the population are heterogeneous, the optimal policy mix should be tailored to each individual. However, these distortions are not always correlated with characteristics observable by the government, preventing perfect targeting. Allcott et al. (2014) show that in such cases, subsidies should be based on the average marginal internality rate rather than the average internality rate, though this still does not achieve optimal targeting. Overall, these challenges make first-best policies politically unfeasible, necessitating the implementation of second-best policy designs by authorities.

Second best policy instruments

The most common policy measures in the housing sector include incentives (taxes and subsidies), regulatory instruments (standards and bans) and information measures (energy performance certificates, information campaigns, etc.). In this thesis, I focus only on the first two categories of instruments, which aim to address the market failures described above.

Carbon pricing One key question with carbon pricing is whether and how the proceeds should be recycled and earmarked for specific purposes. The standard economic approach recommends separating the price signal from revenue recycling, ideally returning the money in a lump-sum manner. In France, this separation is effectively in place due to budgetary rules that prevent the government from earmarking carbon tax revenue. Nevertheless, the government provides a lump-sum payment to low-income households, earmarked for either energy expenditures or energy efficiency investments, independently of carbon tax revenue. Returning carbon tax proceeds in this way can significantly mitigate the regressive effect of the tax within the scope of space heating (Bourgeois et al., 2021).

Subsidies Subsidy programs have been the favored method for promoting energy efficiency in France. They provide a more noticeable investment incentive than carbon taxes, potentially eliciting a stronger response from households undervaluing energy savings (Allcott et al., 2014; Chan and Globus-Harris, 2023). The main concern with subsidy programs is non-additional beneficiaries—households that would have invested regardless (Boomhower and Davis, 2014). These non-additional beneficiaries lead to adverse distributional effects, where taxpayers end up funding the investments of a few households that do not need financial assistance. This problem typically arises when subsidies have uniform design. It can be mitigated by precisely targeting subsidies programs to where they are most needed, although this can only partially be achieved based on observable characteristics. One effective approach is to focus on low-income households, whose investment decisions are distorted by multiple frictions. Another method to better target grants is to use per-unit design instead of ad valorem ones, as the latter are prone to price distortion under imperfect competition (Nauleau et al., 2015). Additionally, poorly designed subsidies may encourage unprofitable investments from a social planner's perspective. This situation arises when governments have biased beliefs about the benefits of energy renovation, which can occur when there is a significant energy performance gap.

In France, the proportion of these non-additional beneficiaries under the income tax credit was estimated at 85% hence 15% additional investors (Nauleau, 2014). However, solely looking at the extensive margin of investments overlooks the significant impact on the intensive margin. Risch (2020) found that non-additional participants in the Income Tax Credit increased their spending by 22%. In the French zero interest loan (EPTZ), the patterns were reversed — high impact at the extensive margin (+22%) and low impact at the intensive margin (+3%) (Eryzhenskiy et al., 2023). These evaluations typically rely on quasi-experimental methods, which can raise concerns about internal validity due to the potential non-comparability of treatment and control groups in baseline. Giandomenico et al. (2022) investigated the effectiveness and cost-effectiveness of energy renovation policies and find that the higher the internal validity of the study, the lower the reported savings, suggesting that a quasi-experimental design may exaggerate the benefits of energy efficiency programs compared to Randomized Controlled Trial (RCT).

To my knowledge, only two RCTs have examined the effects of energy renovation (weatherization) programs, both in the USA. First, Fowlie et al. (2018) evaluate the Weatherization Assistance Program in Michigan, targeted at low-income households, and find that these investments generally reduced energy consumption by 10-19%, primarily from natural gas. However, the investments were mostly unprofitable due to actual savings being far lower than expected, with investment costs being about twice the realized energy savings. Even when including an optimistic estimate of willingness to pay to increase thermal comfort and reduction of greenhouse externalities, the investment fails to provide any private or social benefits. These results are based on assumptions about the social carbon price of 38 dollars per tonne of CO2 and a standard lifetime of 16 years for home insulation — both of which are at the lower end of current literature values. Allcott and Greenstone (2024) use RCTs to evaluate an energy efficiency program, relying on a structural model and field experiments to estimate model parameters. Their approach allows them to evaluate counterfactual policy scenarios. They demonstrate that the Wisconsin subsidy program is welfare-reducing due to poor predictions of household energy savings, resulting in socially unprofitable investments, despite using higher estimates for the social cost of carbon (190 dollars per ton of CO2), a social discount rate of 3%, and a 20-year lifetime. However, they demonstrate that better designed subsidy programs could lead to positive welfare effects, especially subsidies that align with externality reductions.

Regulatory instruments Regulatory instruments such as technology mandates (e.g., mandatory renovation) and bans (e.g., on inefficient rental housing or on fossil-fuel boilers) are generally less cost-effective than price-based policies. These measures often do not take into account the heterogeneity of households and impose uniform requirements that may not be consistent with individual cost-effectiveness (Hepburn, 2006; Goulder and Parry, 2008). Even when regulations target apparently cost-effective investments (mandatory renovations target the worst performing dwellings and heat pumps are the most efficient heating system), their uniform application overlooks households' hidden costs, making such measures less cost-effective.

However, standards can have economic benefits when behavioral biases prevent consumers from responding rationally to price signals. For example, Tsvetanov and Segerson (2013) use a theoretical model that incorporates temptation and show that product standards can lead to better welfare outcomes than price-based measures because they reduce the ability of consumers to give in to the temptation to buy low-cost products that are less energy efficient.

Research gap

Overall, while the econometric literature tends to show that energy efficiency subsidy programs reduce welfare, these results are highly sensitive to the assumptions and factors included in the evaluation (Fowlie et al., 2018; Allcott and Greenstone, 2024). First, most studies focus on estimates of cost-effectiveness or abatement cost, which only approximate the impact on welfare and often overlook non-energy benefits of energy renovation that have been shown to explain a significant portion of the motivation (Wekhof and Houde, 2023). Second, when studies do account for welfare impacts, they typically do not consider other barriers to energy efficiency investment. In a highly imperfect market and behavioral environment, GHG externalities are only one of the reasons that justify implementing the policy. Third, the social cost of carbon and the investment time horizon are key exogenous variables that can significantly influence conclusions. Additionally, policies are usually assessed individually, while governments often rely on multiple instruments. Evaluating a comprehensive strategy requires a better understanding of how policies interact.

Moreover, the low number of energy renovations compared to objectives has pushed governments to implement more aggressive measures, such as regulatory instruments. Notably, the consensus on the efficiency of heat pumps suggests the need to ban new fossil fuel boilers. Despite its potentially massive impact and controversial nature, this measure has been little studied. In particular, no energy-efficiency policy evolution consider the robustness of instruments in achieving carbon neutrality under uncertainty (Goulder and Parry, 2008).

1.4 How to model the impact of energy efficiency policies ?

The gap between the objectives and realizations of energy efficiency investments necessitates a more accurate accounting of investment decisions in ex-ante policy assessments for effective policy planning. Various partial equilibrium models of the residential sector, known as building stock models, have been developed in recent decades (Mundaca et al., 2010; Langevin et al., 2020) (Figure 0.4). The advancement of building libraries and GIS data has particularly facilitated the creation of detailed bottom-up models for the housing sector, accurately capturing the diverse characteristics of the housing stock. These models estimate the energy use of buildings and endogenously consider structural changes in the building stock due to demolition, construction, and renovation.

Most of these models have been used to explore long-term mitigation pathways by relying on exogenous scenarios (Sandberg et al., 2021; Mastrucci et al., 2021; Berrill et al., 2022) or by minimizing system costs (Zeyen et al., 2021; Mandel et al., 2023). While these approaches provide quantitative estimates of the sector's mitigation potential and the technological shifts needed, they do not offer insights into how to achieve these targets with realistic policies. Furthermore, most models depend on energy savings estimates from technical simulations rather than actual observations, leading to overoptimistic views of energy-saving potential and cost-efficiency (Christensen et al., 2021).

We note that a few studies, generally linked to Integrated Assessment Models (IAM), use multinomial logit models based on the total cost of technologies to endogenously simulate the diffusion of energy efficiency technologies (Knobloch et al., 2021; Levesque et al., 2021). One caveat of such system dynamics models is that they rely on a coarse representation of technical details, using a top-down approach to represent the building sector. As detailed in the previous section, the heterogeneity in investment profitability and frictions makes findings from such approaches less grounded in reality.

Dynamic multi-agent and micro-simulation models

Few studies, mostly at the national level, attempt to combine technological detail with investment decisions (Giraudet et al., 2012; Charlier et al., 2018; Giraudet et al., 2021a; Camarasa et al., 2022; Müller et al., 2024). These models often use discrete choice models (typically multinomial logit) to represent the various decisions of households and include empirically calibrated investment barriers. They are typically employed to assess whether the current policy mix can achieve climate targets and to evaluate the cost-effectiveness of different policy instruments.

However, this approach has several caveats. First, despite using a bottom-up framework, the technical details are sometimes still too coarse to accurately represent both home insulation and heating systems within the same model (Giraudet et al., 2021a; Charlier et al., 2018). Second, these models often include a limited number of market frictions, if any (Charlier et al., 2018; Müller et al., 2024), which can lead to overly optimistic findings. When they do account for frictions, they often rely on implicit discount rates (Schleich et al., 2016), which can misrepresent investment barriers and lead to inconsistent policy analyses. For example, this approach may underestimate the impact of energy taxes on investment decisions, especially when barriers stem from unobserved costs. Finally, these models often lack a solid theoretical basis, as they rely on ad hoc investment decision functions that do not align with a utility-consistent framework (Giraudet et al., 2021a). Consequently, these evaluations cannot assess the social welfare impact of policies, limiting their analysis to energy savings or emissions avoided. Furthermore, the unclear economic rationale for the estimated parameters, despite their importance, complicates the interpretation of the results (Branger et al., 2015).

Agent-based model

In the past decade, agent-based models (ABMs) have made significant progress due to better access to data and improved computing capacities (Rai and Henry, 2016). These models incorporate psychological and social factors into agents' decision-making processes, utilizing theories from psychological research. Recent studies have employed ABMs to analyze investment decisions for energy renovation (Sachs et al., 2019; Chersoni et al., 2022; Niamir et al., 2024). Unlike multi-agent energy economy models, ABMs explicitly simulate interactions between agents, their access to information, and the effects of social networks, social norms, and peer influence on energy renovation decisions.

Despite these strengths, the complexity of estimating interaction-driven parameters limits their broader use in comprehensive policy evaluations, although they may be more suitable for highlighting the impact of specific household behaviors. Additionally, while these models can predict possible dynamics of energy renovations, they are not well-suited for assessing the impact of policy measures on welfare.

Structural model

Finally, structural models of energy efficiency investment decisions are grounded in microeconomic consumer theory. Unlike other modeling techniques, their main advantage lies in providing welfare assessments of policies (Dubin and McFadden, 1984; Davis, 2008; Allcott et al., 2014; Chan and Globus-Harris, 2023; Allcott and Greenstone, 2024). From a normative standpoint, these models have been employed to determine the optimal policy mix in the presence of market and behavioral failures. For instance, Allcott et al. (2014) use a structural model to identify the most effective policies in scenarios with both internalities (behavioral anomalies) and GHG externalities. More recently, Allcott and Greenstone (2024) employed field experiments to identify structural econometric models to evaluate the welfare impacts of an energy efficiency program in Wisconsin, highlighting the importance of incorporating non-observed attributes and actual energy savings into the welfare function.

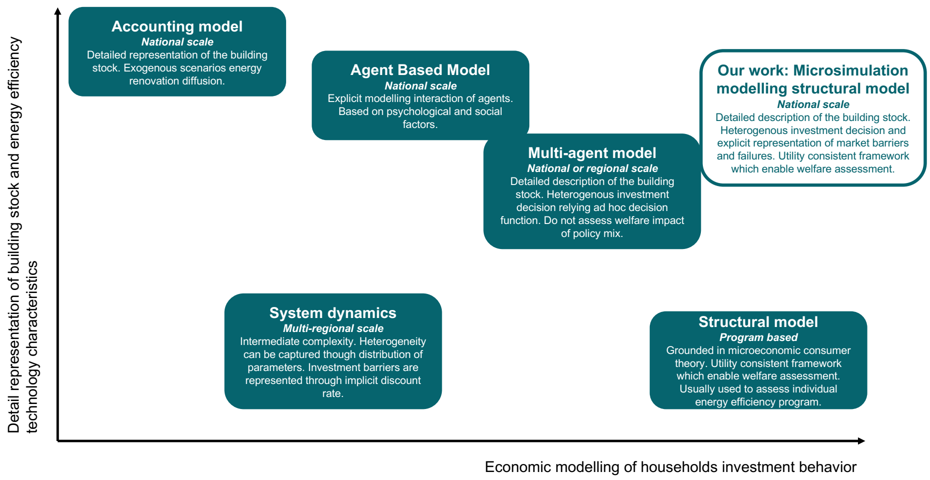
These approaches are considered the gold standard for the credibility of energy efficiency evaluations. However, they typically focus on a single policy program, whereas a more comprehensive policy mix might be in place. Additionally, they address a limited set of frictions, even though other unconsidered market failures might influence household investment decisions. Finally, these models are usually not designed to consider the structural changes of the building stock over time and are therefore not suited for assessing whether policies enable meeting climate targets.

Research gap

On the one hand, technico-economic assessments in the literature often fail to adequately represent key market and behavioral mechanisms, making them unsuitable for evaluating real-world policies (Zeyen et al., 2021; Hummel et al., 2023; Mandel et al., 2023). These assessments typically use narrow cost-benefit analysis that overestimates energy savings and physical costs, neglecting non-energy benefits that are crucial for investment decisions. On the other hand, microeconomic structural models use a consistent utility framework, enabling the assessment of the welfare impact of policies. However, they usually address frictions or assess policies individually, despite the presence of multiple market failures or complex policy mixes (Allcott et al., 2014; Allcott and Greenstone, 2024). Additionally, these models are generally designed to evaluate the short-term impacts of policies and cannot capture the long-term structural evolution of the housing stock.

This gap in literature calls for a better account of the key frictions impeding energy efficiency investment in policy assessments to improve policy planning.

Figure 0.2 – Overview of modeling literature on energy efficiency diffusion in the building sector.



2 This dissertation

This dissertation collects four modelling research studies on the evaluation of energy-efficiency policies. The objective is to build a modeling framework that permits socio-economic assessment of a range of residential energy efficiency policies implemented in economies subject to market failures and behavioral anomalies.

Overall, I propose four improvements on the existing literature: a refinement of the depiction of residential energy efficiency technologies, accounting for complementarities between insulation levels and heating system performance; an explicit account of key barriers to energy savings, including rebound effects, present bias, myopic expectation of energy prices, credit constraints, landlord-tenant dilemma and coordination problems in multi-family housing; an extended welfare assessment framework factoring in thermal comfort, fuel bill alleviation, health benefits, non-energy benefits and the opportunity cost of public funds ; and a stronger integration between energy demand and supply in the residential sector, instrumental in capturing all margins of decarbonization. These improvements are applied to two different models – Res-IRF, an energy-economy model of energy demand in the French residential sector, and Message-ix Buildings, a global building stock model that I have applied to the EU residential sector. Below, I summarize the contribution of each chapter:

Contributions by chapter

The first chapter, titled *Energy efficiency policy in an n-th best world: Assessing the implementation gap*, is joint work with Louis-Gaëtan Giraudet. In this chapter, I develop a detailed structural model of energy demand for space heating, including a multitude of frictions in energy efficiency investments. I use this framework to evaluate the impact of these frictions on welfare, energy use, and CO_2 emissions in France, before assessing the actual policies in place. I conclude by addressing the implementation gap, emphasizing the need to better target policies in situations where frictions are most significant.

The second chapter, titled *Meeting climate target with realistic demand-side policies in the residential sector in the EU-27*, is joint work with Alessio Mastrucci. In this chapter, I extend the investment decision model developed in Chapter 1 to the EU level. Specifically, I couple it with Message-ix Buildings, a model of building stock turnover. Using this framework, I conduct a comprehensive quantitative assessment of a wide range of demand-side policy mixes in the EU-27.

The third chapter, titled *How to allocate mitigation efforts between home insulation, fuel switch and fuel decarbonization? Insights from the French residential sector*, is joint work with Célia Escribe, Louis-Gaëtan Giraudet and Philippe Quirion. In this chapter, I contribute to coupling the structural model developed for France in Chapter 1 with an energy system model. This innovative framework captures the trade-offs between insulating homes, switching to low-carbon heating systems, and decarbonizing heating fuels in mitigation strategies. In particular, we use this framework to explore the role of home insulation subsidies in these strategies.

The fourth chapter, titled *Banning new gas boilers as a hedge against the limited availability of renewable gas supply*, is joint work with Célia Escribe. In this chapter, we use the same framework as in Chapter 3 to assess the impact of a ban on the installation of new fossil fuel boilers, a measure previously investigated in Chapter 1 without considering its impact on the energy system. Specifically, we evaluate the robustness of implementing this ban under a wide range of uncertainties.

Published and Accepted Article

Chapter 3: Escribe, C.*, **Vivier, L.***, Giraudet, and L.-G, Quirion, P. *How to allocate mitigation efforts between home insulation, fuel switch and fuel decarbonization? Insights from the French residential sector.* Environmental Research Letters, 2024.
Equal contribution co-first author with Célia Escribe
Chapter 4: Escribe, C.* and **Vivier, L.*** *Banning new gas boilers as a no-regret mitigation option.* Accepted in Nature Communications. *Equal contribution as co-first author with Célia Escribe*

Paper Under Review

Chapter 2: Vivier, L., van Ruijven, B. and Mastrucci, A. *Meeting climate target with realistic demand-side policies in the residential sector in the EU-27.* In revision in Nature Climate Change.
Previous version of this paper received the IIASA Levien Award.

Working Paper

Chapter 1: Vivier, L. and Giraudet, L.-G. *Energy efficiency policy in an n-th best world: Assessing the implementation gap.* Working paper, 2024.

Other contributions

Vivier, L. and Giraudet, L.-G., 2024. *Analyse socio-économique de la rénovation énergétique des logements.* Focus Conseil d'Analyse Économique.

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Introduction générale

Les mesures d'efficacité énergétique présentent des bénéfices notables, notamment des économies d'énergie, une diminution des émissions de gaz à effet de serre, une réduction de la précarité énergétique et une amélioration de la santé publique. Les motivations en faveur de l'efficacité énergétique ont évolué au fil du temps en réponse aux préoccupations sociétales. Initialement centrées sur l'épuisement des ressources à l'époque classique, elles ont progressivement mis l'accent sur la sécurité énergétique à l'ère moderne, pour se concentrer aujourd'hui sur l'urgence de lutter contre le changement climatique à l'époque contemporaine (Giraudet and Missemer, 2023). Plus spécifiquement, le secteur du chauffage résidentiel, qui représente environ 80% de la consommation énergétique des ménages de l'Union Européenne (UE) et contribue à plus d'un tiers des émissions de gaz à effet de serre liées à l'énergie dans l'UE, a été l'objet de nombreuses politiques d'efficacité énergétique ces dernières années (Eurostat, 2023; Economidou et al., 2020).

Toutefois, ces politiques ont souvent produit des résultats en deçà des attentes (Gillingham et al., 2018; Giandomenico et al., 2022). Les taux de participation se sont révélés inférieurs aux prévisions, et lorsque des investissements ont été réalisés, les économies d'énergie obtenues se sont fréquemment avérées modestes (Christensen et al., 2021). Ce décalage entre les attentes et les résultats met en évidence la nécessité d'une évaluation plus rigoureuse des coûts et des avantages des technologies d'efficacité énergétique, ainsi que d'une meilleure compréhension des obstacles majeurs freinant les investissements. Dans cette thèse, j'analyse quantitativement l'impact à long terme des politiques d'efficacité énergétique dans le secteur du chauffage résidentiel, en élaborant un cadre de modélisation combinant une représentation détaillée des technologies et une prise en compte approfondie des dynamiques comportementales.

Cette thèse porte sur la demande énergétique liée au chauffage dans le secteur résidentiel, en se concentrant principalement sur la France, avec une extension à l'échelle de l'UE. La France constitue un cas d'étude pertinent en raison de ses nombreuses politiques d'efficacité énergétique, illustrées par des dépenses avoisinant 8milliards d'euros en 2021 pour financer quatre grands programmes de subventions dans ce domaine (Ledez and Hainaut, 2021). Cette recherche s'intéresse spécifiquement aux mesures d'atténuation ciblant le parc immobilier existant. Bien que le remplacement des logements anciens et énergivores par des constructions neuves et performantes permette de réduire les émissions directes de gaz à effet de serre, cette stratégie s'avère peu optimale en raison des émissions substantielles engendrées lors des phases de construction (Berrill et al., 2022). Par ailleurs, le faible taux de renouvellement des bâtiments en Europe implique que 75% du parc immobilier actuel devrait rester en usage à l'horizon 2050.

Cette introduction est structurée en deux parties. Dans un premier temps, je propose une revue de la littérature visant à synthétiser les connaissances actuelles et à identifier la principale lacune de recherche que cette thèse cherche à combler. Cette revue débute par une analyse actualisée des coûts et des bénéfices associés aux technologies d'efficacité énergétique, avant d'examiner les principaux obstacles ainsi que les biais comportementaux freinant les investissements dans ce domaine. J'y analyse également les résultats concrets des politiques d'efficacité énergétique. Enfin, je discute de la manière dont les modèles permettent d'évaluer ces politiques et de contribuer à l'élaboration de stratégies plus efficaces. Dans un second temps, je présente les objectifs, les méthodologies employées et les principales contributions de cette thèse.

4 Revue de la littérature

4.1 Les avantages de la rénovation énergétique dépassent-ils les coûts ?

Description des technologies de rénovation énergétique

La réduction des émissions liées au chauffage des espaces repose sur trois leviers principaux : l'amélioration de l'isolation des habitations, la transition vers des systèmes de chauffage à faibles émissions de carbone et la décarbonation des combustibles de chauffage.

L'isolation des habitations concerne les quatre composantes de l'enveloppe du bâtiment : les combles et toitures, les murs, les fenêtres et les planchers bas. La deuxième approche consiste à remplacer les systèmes de chauffage existants par des systèmes plus performants, en substituant les combustibles fossiles par des alternatives potentiellement à faibles émissions de carbone, telles que l'électricité, le bois ou le chauffage urbain.

Les systèmes de chauffage se distinguent par leur efficacité énergétique finale et le vecteur énergétique utilisé. Les systèmes à combustion (gaz, fioul, bois) fonctionnent généralement avec des chaudières, présentant une efficacité moyenne de 0,8 : la combustion de 1kWh de combustible génère 0,8kWh de chaleur utilisable pour l'occupant. Les systèmes électriques se répartissent en deux catégories distinctes : les systèmes à effet Joule, qui produisent directement de la chaleur, et les pompes à chaleur, qui transfèrent la chaleur d'un milieu à un autre en exploitant le cycle condensation-évaporation. Les systèmes à effet Joule affichent une efficacité conventionnelle de 1, tandis que les pompes à chaleur atteignent une efficacité moyenne de 2,5, soit une performance presque trois fois supérieure à celle des systèmes à combustion.

La rénovation énergétique d'un logement pour améliorer son efficacité nécessite d'intervenir sur au moins l'un des six volets suivants : isolation du toit, des murs, des planchers, des fenêtres, amélioration du système de chauffage ou installation d'une ventilation mécanique contrôlée. Une rénovation est généralement qualifiée de haute performance lorsqu'elle combine plusieurs de ces mesures, notamment l'isolation des murs, du toit et des planchers, ainsi que la modernisation du système de chauffage si le logement utilise principalement des combustibles comme le charbon, le fioul ou le gaz.

Coût de la rénovation énergétique

Chacune des six mesures de rénovation peut être mise en œuvre à l'aide de diverses options (épaisseurs et matériaux d'isolation variés) et à différentes échelles (nombre de fenêtres à remplacer, surface à isoler, etc.). Par conséquent, il n'existe pas de modèle unique de projet de rénovation, mais plutôt une multitude d'approches possibles, entraînant une variabilité significative des coûts. Un aspect clé est que le coût de l'isolation est indépendant du niveau d'isolation existant, car le matériau isolant doit généralement être entièrement remplacé. Ainsi, le rapport coût-bénéfice de l'isolation est plus favorable dans les logements les moins performants. Depuis le premier choc pétrolier des années 1970, le renforcement des codes de construction a considérablement accru l'hétérogénéité de l'efficacité énergétique des bâtiments résidentiels, entraînant d'importantes variations dans la rentabilité des rénovations énergétiques.

Par ailleurs, comme toute technologie, la rénovation énergétique est théoriquement sujette à des réductions de coût liées au progrès technique. La littérature la plus complète sur ce sujet rapporte des taux d'apprentissage — réductions de coût associées au doublement de la production cumulée — de 32% pour les pompes à chaleur, 10% pour les autres systèmes de chauffage, 18% pour l'isolation et 15% pour la climatisation (Weiss et al., 2010). Cependant, en raison du caractère non standardisé et intensif en main-d'œuvre des rénovations énergétiques, il est peu probable que ces réductions de coût spécifiques aux technologies s'additionnent. L'ampleur du progrès technique dans la rénovation énergétique des bâtiments existants reste incertaine, et les innovations à venir devraient être autant organisationnelles que technologiques (Kiss, 2016).

Bénéfices de la rénovation énergétique

Les avantages de la rénovation énergétique se manifestent sous diverses formes — financières, climatiques, sanitaires et même géopolitiques — mais leur ampleur est étroitement liée à l'efficacité des mesures mises en œuvre.

The Energy Performance Gap La performance d'un projet de rénovation énergétique résulte d'interactions complexes entre plusieurs facteurs : la conductivité thermique de l'enveloppe du bâtiment (incluant les pertes thermiques et les infiltrations d'air), l'efficacité du système de chauffage, ainsi que des variables climatiques (telles que la température extérieure), architecturales (comme l'exposition, qui influe sur les gains solaires) et comportementales (par exemple, la température de consigne et le nombre de pièces chauffées). Ces interactions nécessitent l'utilisation de logiciels de simulation thermique pour être correctement modélisées.

En pratique, cependant, les économies d'énergie observées après travaux sont généralement bien inférieures à celles prévues par les modèles de simulation thermique. Ce phénomène, connu sous le nom d'écart de performance énergétique, a suscité une attention croissante au cours de la dernière décennie, en raison de l'augmentation des dépenses publiques consacrées aux rénovations énergétiques et de la montée en puissance de la « révolution de la crédibilité » en économie appliquée (Giraudet and Missemer, 2023). L'étude de Fowlie et al. (2018), souvent considérée comme une référence, rapporte un écart de 70% dans le cadre d'un programme de rénovation mené dans l'État du Michigan. Dans le tableau 0.2, je présente un aperçu des évaluations de l'écart de performance énergétique issues de la littérature académique, toutes réalisées aux États-Unis. Bien que la taille de cet écart varie en fonction de nombreux paramètres, tels que la qualité des travaux ou le modèle de simulation thermique utilisé, des études similaires trouvent des écarts de même ordre de grandeur pour la France (Charlier, 2021).

Table 0.2 – Extrait des taux de réalisation de la littérature revue par les pairs

Article	**Lieu**	**Taux de Réalisation**
Dubin et al. (1986)	Floride	≈0,9
Fowlie et al. (2018)	Michigan	0,30
Giraudet et al. (2018a)	Floride	0,68
Christensen et al. (2021)	Illinois	0,51
Allcott and Greenstone (2024)	Wisconsin	0,68

L'écart de performance énergétique résulte d'une diversité de facteurs, parmi lesquels les effets de rebond (Gillingham et al., 2016), l'effet de pré-rebond (Sunikka-Blank and Galvin, 2012; Galvin and Sunikka-Blank, 2016), ainsi que des problèmes de qualité dans l'exécution des rénovations (Giraudet et al., 2018b). L'étude de référence sur ce sujet (Christensen et al., 2021) quantifie un écart global de 51%, dont 42% sont attribués à des problèmes de qualité des travaux, 40% à des erreurs dans les modèles de simulation, et 6% à l'effet de rebond, laissant 14

Bénéfices privés Le principal bénéfice privé de la rénovation énergétique réside dans la réduction des factures d'énergie, calculée comme le produit des économies d'énergie réelles annuelles et des prix de l'énergie. Toutefois, les investissements dans l'efficacité énergétique entraînent également des ajustements dans les comportements de chauffage, connus sous le nom d'effet de rebond. À mesure que le coût des services énergétiques diminue, les ménages tendent à intensifier leur usage du chauffage. En France, des estimations récentes indiquent une élasticité-prix à court terme de -0,2 (Douenne, 2020), un résultat cohérent avec les observations faites dans d'autres économies et souvent cité dans la littérature (Allcott and Greenstone, 2024), fournissant ainsi une estimation de l'ampleur de cet effet.

Bien que l'effet de rebond réduise les économies sur les factures énergétiques, il génère un avantage significatif en améliorant le confort thermique des ménages. Des études récentes suggèrent que ce confort accru peut être tout aussi déterminant que les considérations financières (Wekhof and Houde, 2023). Cette amélioration du confort est attribuable non seulement à l'effet de rebond, mais également à la présence de surfaces plus chaudes grâce à une meilleure isolation des habitations. Ce phénomène mérite des recherches supplémentaires pour évaluer l'ensemble de ses bénéfices pour les ménages.

Bénéfices sociaux Les économies d'énergie réelles résultant des rénovations énergétiques permettent de réduire les émissions de gaz à effet de serre, selon des niveaux qui varient en fonction du contenu carbone des énergies utilisées. En France, ces valeurs vont par convention de 30gCO_2/kWh pour l'énergie bois à 234gCO_2/kWh pour le fioul domestique (Légifrance, 2021).

Par ailleurs, le chauffage dépasse la simple fonction de confort : il s'agit d'un enjeu de santé publique. Un logement mal chauffé expose ses occupants à des risques accrus de maladies cardiovasculaires et respiratoires. Ces effets sont particulièrement marqués lorsque la faible performance énergétique d'un logement s'ajoute aux revenus modestes de ses habitants, les empêchant de couvrir les coûts élevés du chauffage. Charlier and Legendre (2021) montrent que la précarité énergétique détériore significativement l'état de santé des individus déjà vulnérables, bien qu'elle ait un impact limité sur les personnes en bonne santé. Ces conséquences sanitaires, longtemps négligées, ont récemment été évaluées par un groupe de travail coordonné par France Stratégie (Dervaux and Rochaix, 2022). Toutefois, des preuves supplémentaires issues d'études expérimentales ou quasi-expérimentales sont nécessaires, car les coûts de santé associés peuvent être considérables et influencer de manière significative l'évaluation des bénéfices des mesures d'efficacité énergétique.

Enfin, il convient de rappeler que les préoccupations liées au contrôle de la demande énergétique remontent aux chocs pétroliers des années 1970 (Giraudet and Missemer, 2023), bien avant que les enjeux climatiques ne deviennent la justification principale des années 2000. À l'époque, ce sont les tensions internationales qui ont motivé la recherche d'une plus grande indépendance énergétique. La guerre en Ukraine a récemment ravivé cette problématique de façon spectaculaire. Cependant, cet aspect reste rarement intégré dans les analyses coûts-bénéfices des programmes d'efficacité énergétique. Il serait pertinent de développer des indicateurs supplémentaires, tels que l'impact sur les termes de l'échange, pour mieux capturer ces dimensions géopolitiques.

Valeur de la rénovation énergétique pour le système énergétique

Les économies sur les factures d'énergie des consommateurs découlent d'une réduction des coûts pour le système énergétique, mais un écart subsiste entre ces économies et la diminution réelle des coûts du système. Cet écart s'explique par le fait que la tarification de l'énergie repose généralement sur des prix régulés et des coûts moyens, qui ne reflètent pas les variations des coûts en temps réel, pouvant fluctuer considérablement d'une heure à l'autre.

La demande de chauffage des espaces est particulièrement concentrée durant l'hiver, une période où les coûts de l'énergie, notamment ceux de l'électricité, atteignent leur maximum dans les pays au climat tempéré. Ces fluctuations de la demande énergétique influencent le besoin de centrales de pointe ou de solutions de stockage telles que les batteries. Un passage à grande échelle des chaudières à gaz naturel vers des pompes à chaleur pourrait engendrer des coûts supplémentaires si le système électrique n'est pas en mesure d'absorber aisément la demande accrue. À l'inverse, l'isolation des maisons équipées de chauffage électrique peut générer des bénéfices au-delà des économies sur les factures d'énergie en allégeant la pression exercée sur le système électrique.

Par exemple, Zeyen et al. (2021) montrent que le niveau optimal d'isolation des maisons est davantage déterminé par les pics de demande saisonniers que par la consommation énergétique globale, ce qui met en lumière la valeur significative de la réduction de la demande de pointe. De même, Boomhower and Davis (2020) soulignent que prendre en compte le moment de l'utilisation de l'énergie accroît la valeur des mesures d'efficacité énergétique pour la climatisation d'environ 40% en Californie, en raison de la réduction des paiements de capacité versés aux producteurs d'électricité.

Valeur non énergétique ou cachée

Les rénovations énergétiques engendrent divers coûts et bénéfices supplémentaires, souvent difficiles à identifier et à quantifier précisément.

Les travaux de rénovation impliquent fréquemment des coûts annexes non directement liés à l'énergie, tels que les frais d'installation, les travaux de démolition, ou encore les tâches de finition comme le plâtrage, la peinture et d'autres remises en état. Ces coûts, essentiels à la réalisation des travaux, sont souvent exclus des estimations globales, en particulier lorsque les améliorations énergétiques s'inscrivent dans des projets plus vastes, comme une rénovation complète ou une extension. Cela complique l'identification des dépenses spécifiquement liées à l'énergie. Une étude menée en France montre que les rénovations profondes entraînent des dépenses additionnelles de 40% pour des éléments non énergétiques (Enertech et al., 2022).

Par ailleurs, des coûts intangibles tels que les coûts de transaction — estimés à environ 20% du coût total du projet — incluent des éléments comme le temps et les efforts nécessaires pour recueillir des informations, trouver des entrepreneurs fiables ou réaliser un audit énergétique, lequel coûte à lui seul environ 1 000 € en France (Kiss, 2016; Ebrahimigharehbaghi et al., 2020). Les travaux de rénovation occasionnent également des désagréments significatifs : l'installation de systèmes de chauffage peut durer plusieurs jours, tandis que des travaux électriques et de plomberie prennent généralement une à deux semaines, et des travaux de façade ou de toiture encore plus longtemps. Ces perturbations rendent les logements temporairement moins habitables, voire inhabitables. La valeur monétaire de ces désagréments peut être approximée à l'aide des coûts de relogement temporaire.

Ces coûts non énergétiques élevés expliquent pourquoi les ménages reportent souvent leurs investissements en efficacité énergétique jusqu'à ce qu'ils entreprennent des rénovations nécessaires pour d'autres raisons. À ce moment-là, les dépenses non énergétiques sont déjà engagées, et les ménages sont plus enclins à rechercher des entrepreneurs fiables (Wekhof and Houde, 2023). Cela contribue à la faible élasticité-prix de la demande de rénovation énergétique. En suivant cette logique, Aldenhoff and

Kurzrock (2024) estiment qu'un taux annuel de rénovation énergétique de 2% ou plus est peu réaliste, compte tenu des cycles de rénovation existants des bâtiments.

En parallèle, certaines mesures de rénovation offrent des avantages non financiers liés à leurs caractéristiques non énergétiques, souvent négligés dans les analyses classiques. Par exemple, les fenêtres apportent des bénéfices esthétiques et acoustiques significatifs. De plus, des enquêtes récentes montrent que les préoccupations environnementales jouent également un rôle majeur dans la décision des ménages d'entreprendre des rénovations énergétiques (Wekhof and Houde, 2023).

La valeur nette de ces attributs non énergétiques varie considérablement d'un ménage à l'autre et peut évoluer en fonction des événements de la vie, tels qu'un déménagement ou un héritage inattendu. Un déménagement peut atténuer les inconvénients des travaux en permettant d'éviter temporairement les perturbations, tandis qu'un héritage peut réduire les contraintes financières, rendant les rénovations plus accessibles.

Évaluation des coûts et des bénéfices Il existe un consensus général sur le bilan socio-économique favorable de l'installation massive de pompes à chaleur. Ces systèmes offrent des économies d'énergie significatives grâce à leur efficacité supérieure et permettent de réduire les émissions en utilisant l'électricité, une source d'énergie plus facilement décarbonée. En revanche, la question de la rentabilité des améliorations de l'isolation des bâtiments reste sujette à débat. Cette ambiguïté découle de l'hétérogénéité des parcs immobiliers, des variations technologiques dans les solutions d'efficacité énergétique et des différences dans l'étendue des critères pris en compte (Hummel et al., 2021).

D'un côté, certaines études soutiennent la viabilité économique de l'isolation des maisons dans le cadre de scénarios ambitieux de décarbonation. Par exemple, Hummel et al. (2023) concluent qu'une grande partie des investissements en isolation est économiquement viable pour atteindre une réduction de 95% des émissions de CO_2 dans les parcs immobiliers de l'UE-27 d'ici 2050. Ils estiment des économies d'énergie optimales allant de 29% à 47%. Dans une perspective plus large, incluant les bénéfices de l'isolation sur la réduction de la pression exercée sur le système électrique, Zeyen et al. (2021) calculent que l'isolation permet d'atteindre des économies énergétiques comprises entre 44% et 51%, entraînant une réduction des coûts jusqu'à 14% par rapport aux scénarios sans isolation. De manière similaire, Mandel et al. (2023) montrent que des scénarios doublant le taux de rénovation énergétique sont presque aussi rentables que des scénarios plus modestes. Ils estiment que ces scénarios entraîneraient une légère augmentation des coûts de moins de 10 € par citoyen de l'UE par an, un montant probablement compensé par une hausse des prix des combustibles fossiles ou par la prise en compte de co-bénéfices supplémentaires non monétisés.

D'un autre côté, d'autres études expriment des réserves quant à la viabilité économique de l'isolation des maisons. Une analyse récente menée en Allemagne conclut que, en termes strictement financiers, l'isolation n'est jamais économiquement rentable, avec un taux de retour sur investissement moyen de seulement 22,5% après 25 ans (Galvin, 2024). Ces résultats restent inchangés même en intégrant la valeur sociale des émissions évitées. Contrairement à d'autres études, Galvin (2024) incluent explicitement les coûts de financement et tiennent mieux compte des effets de pré-liaison, bien qu'ils n'intègrent pas les bénéfices potentiels pour le système électrique. De plus, cette étude se concentre exclusivement sur l'Allemagne, ce qui est cohérent avec les résultats nationaux rapportés par Zeyen et al. (2021).

Ces divergences soulignent la complexité de l'évaluation de la rentabilité des mesures d'isolation, dépendant largement du cadre méthodologique, du contexte géographique et des critères pris en compte.

Lacunes de la recherche Les avancées récentes dans la granularité des évaluations du parc immobilier à un niveau régional ont considérablement amélioré la précision des analyses d'efficacité énergétique (Berrill et al., 2022; Camarasa et al., 2022; Hummel et al., 2023). Ces progrès permettent d'évaluer les mesures d'efficacité énergétique en détail, en considérant à la fois l'isolation des différentes composantes du bâtiment et les technologies variées des systèmes de chauffage. Cependant, plusieurs lacunes subsistent dans la recherche, entravant l'optimisation des analyses coûts-bénéfices et la définition des cibles d'adoption des mesures d'efficacité énergétique. Voici quatre de ces lacunes clés.

Les études techniques estiment souvent un potentiel élevé pour les rénovations énergétiques, mais s'appuient principalement sur des modèles de simulation thermique pour calculer les économies d'énergie. Ces modèles supposent des conditions idéales pour les rénovations, ce que les preuves empiriques contredisent fréquemment (Christensen et al., 2021). Cela conduit à une surestimation de leur contribution dans les stratégies d'atténuation des émissions et à une sous-estimation de l'écart de performance énergétique, compromettant ainsi la fiabilité des résultats.

Ces études négligent souvent d'inclure les coûts de financement et, plus crucialement, les coûts non énergétiques (ou non observés) encourus par les propriétaires. Ces derniers, tels que les frais de démolition, de finition ou les coûts de transaction, jouent un rôle décisif dans la décision de rénover ou de reporter les travaux. Ignorer ces coûts peut mener à des projections irréalistes de taux de rénovation, incompatibles avec les cycles réels de rénovation des bâtiments.

La synergie entre l'isolation des maisons et l'installation de pompes à chaleur constitue une autre lacune majeure. L'efficacité des pompes à chaleur est étroitement liée au niveau d'isolation des bâtiments, et des incompatibilités techniques peuvent survenir dans des maisons mal isolées. Bien qu'une bonne isolation soit essentielle pour permettre des installations rentables et efficaces, il n'existe pas de consensus sur le niveau minimal d'isolation requis. Une étude récente menée sur deux ans au Royaume-Uni, portant sur 750 pompes à chaleur, a montré des installations réussies même dans des maisons anciennes datant d'avant 1945, avec une isolation minimale coûtant moins de 1 000 € (System, 2024). Ces résultats mettent en évidence la nécessité d'obtenir des données empiriques supplémentaires pour clarifier ces exigences.

Bien que les évaluations techniques les plus avancées intègrent désormais des co-bénéfices tels que la réduction de la pollution de l'air et les impacts systémiques sur l'énergie (Zeyen et al., 2021; Mandel et al., 2023), peu d'études considèrent les avantages pour la santé des occupants des maisons inefficaces. Ces dernières exposent leurs résidents à des risques accrus de maladies graves, telles que le syndrome coronarien aigu, la pneumonie ou d'autres infections respiratoires (Gillingham et al., 2021; Symonds et al., 2021). En France, une étude estime que les logements consommant théoriquement plus de 378kWhEF/m^2/an engendrent un coût social de 135 000€ par cas de maladie grave, soit en moyenne 7 500 € par logement concerné (Dervaux and Rochaix, 2022). Ces risques sont particulièrement élevés chez les ménages à faible revenu. Intégrer ces bénéfices sanitaires dans les analyses renforcerait la pertinence des rénovations énergétiques pour les ménages les plus vulnérables. Cependant, des recherches empiriques supplémentaires sont nécessaires pour quantifier précisément ces effets.

4.2 Les frictions de marché ou les anomalies comportementales empêchent-elles la diffusion de la rénovation énergétique ?

Depuis au moins trois décennies, les études techniques soutiennent l'adoption généralisée des technologies d'efficacité énergétique, affirmant que leurs avantages à long terme surpassent largement leurs coûts (McKinsey, 2009). Cette conviction en l'existence de mesures d'atténuation rentables mais sous-exploitées a conduit les chercheurs en efficacité énergétique à investiguer ce qu'on appelle l'écart d'efficacité énergétique — c'est-à-dire la différence entre le niveau économiquement optimal d'efficacité énergétique et le niveau réellement observé. Historiquement, cet écart a été évalué en estimant des taux d'actualisation anormalement élevés pour expliquer les décisions d'investissement observées (Train, 1985). Depuis l'article fondateur de Jaffe and Stavins (1994), une abondante littérature s'est consacrée à l'identification des causes de cet écart. Les explications proposées incluent des défaillances de marché classiques, des biais comportementaux liés à l'économie comportementale, ainsi que des erreurs de perception des analystes concernant la rentabilité des investissements en efficacité énergétique (Figure 0.3).

Les défaillances de marché et les biais comportementaux créent une divergence entre les décisions optimales d'un point de vue social et celles prises par les individus, justifiant ainsi l'intervention des pouvoirs publics. En revanche, si l'écart d'efficacité énergétique apparent résulte uniquement de coûts cachés ou d'erreurs d'évaluation de la part des analystes, alors il n'y a pas d'écart réel, et aucune intervention publique n'est nécessaire. L'objectif central de cette littérature a été de distinguer les situations où une intervention politique est légitime de celles où les décisions individuelles, bien que divergentes, ne reflètent pas nécessairement une défaillance de marché.

De nombreuses revues de littérature exhaustives se sont penchées sur ce sujet (Allcott and Greenstone, 2012; Gillingham and Palmer, 2014; Gerarden et al., 2017). Dans cette section, je résume brièvement les principales conclusions de la littérature concernant les défaillances de marché et les anomalies comportementales dans le secteur du chauffage résidentiel. Lorsque cela est possible, je mets l'accent sur les preuves issues du contexte français ou européen, qui constitue le cadre principal de cette thèse.

Défaillances de marché

Défaillances du marché de l'énergie Un écart entre les investissements optimaux et réels dans l'efficacité énergétique résulte de l'alignement défectueux entre le prix de l'énergie et son coût social marginal. Des coûts inférieurs incitent les ménages à investir trop peu, tandis que des coûts plus élevés les incitent à investir trop.

L'un des arguments les plus répandus est que les prix de l'énergie ne reflètent pas les externalités négatives associées à son utilisation. L'exploitation des combustibles fossiles génère des polluants environnementaux, y compris des émissions de gaz à effet de serre (GES), qui ne sont souvent pas pleinement internalisés dans les prix de l'énergie. En Europe, bien que l'électricité et les grands réseaux de chauffage urbain soient soumis à une tarification carbone via le système d'échange de quotas d'émission de l'UE (EU ETS), les émissions issues de l'utilisation directe de combustibles fossiles dans le secteur résidentiel ne sont que partiellement intégrées. En France, par exemple, la taxe carbone résidentielle est fixée à 45 €/tCO_2, bien en deçà de la valeur sociale estimée du carbone, qui est d'au moins 150 €/tCO_2 en 2024 (Quinet, 2019; EPA, 2022). Cette sous-évaluation limite l'intégration des bénéfices environnementaux dans les décisions d'investissement en efficacité énergétique, réduisant ainsi les incitations à adopter des technologies efficaces.

Par ailleurs, les décisions de rénovation énergétique influencent le système énergétique dans son ensemble, en générant des externalités positives ou négatives, notamment sur les infrastructures électriques. Cependant, le prix de détail de l'énergie, souvent réglementé par les pouvoirs publics, est basé sur des coûts moyens plutôt que sur des coûts marginaux. Cela entraîne fréquemment une déviation des prix par rapport aux signaux économiques optimaux, avec des prix parfois trop élevés ou trop faibles selon les périodes. L'absence de tarification en temps réel accentue cette inefficience, les ménages ne pouvant adapter leurs décisions d'investissement aux variations temporelles des coûts de l'énergie.

Asymétries d'information sur les marchés du crédit : rationnement du crédit Dans une enquête récente menée en France sur la rénovation énergétique, les contraintes financières ont été identifiées comme le principal obstacle à l'investissement (MTE, 2020). Bien que les prêts puissent contribuer à atténuer cette barrière, ils demeurent relativement coûteux par rapport à ceux soutenant d'autres actifs verts, tels que les véhicules (Giraudet et al., 2021b), et leur efficacité reste limitée en raison des asymétries d'information.

Les banques, incapables d'évaluer précisément le risque lié à ces investissements, ont tendance à utiliser le revenu des ménages comme un indicateur approximatif et imposent des ratios d'endettement maximum. Cependant, bien que le revenu soit corrélé au risque, ces deux variables ne sont pas identiques, ce qui peut conduire à exclure des ménages à faible revenu mais financièrement stables de l'accès au crédit (Stiglitz et Weiss, 1981). Ce phénomène de rationnement du crédit est particulièrement problématique pour les ménages souhaitant réaliser des investissements à fort potentiel d'économies d'énergie et à faible risque de défaut de paiement, mais disposant d'un historique de crédit défavorable (Palmer et al., 2012).

Ainsi, les asymétries d'information dans le secteur financier non seulement freinent l'adoption des mesures d'efficacité énergétique, mais créent également une iniquité dans l'accès au financement, limitant les opportunités pour les ménages modestes de bénéficier des avantages des rénovations énergétiques.

Asymétries d'information sur les marchés immobiliers : dilemme du propriétaire-locataire Si les marchés immobiliers fonctionnaient parfaitement, chaque euro d'économies d'énergie cumulées actualisées se traduirait par un euro de gain en capital à la vente ou d'augmentation annuelle du loyer (Myers, 2019). Cependant, ce mécanisme est limité par la nature partiellement non observable de la performance énergétique. Il est souvent difficile d'évaluer avec précision le niveau d'isolation ou d'autres caractéristiques liées à l'efficacité énergétique. Dans ce contexte, les acheteurs, qu'ils soient acquéreurs ou locataires, hésitent à payer davantage pour des avantages perçus comme incertains.

L'introduction du diagnostic de performance énergétique (DPE) en Europe en 2007 visait à pallier ce problème. Ce dispositif fournit également une base précieuse pour des évaluations empiriques de la "valeur verte" des logements. Une synthèse d'environ 30 études (21 portant sur les ventes et 9 sur les locations) révèle que le label DPE est bien intégré dans les prix de vente des maisons, avec un ratio proche de 1:1. Cependant, l'intensité de cette relation varie selon l'équilibre entre l'offre et la demande sur le marché local. En revanche, pour les loyers, le lien entre le label DPE et les prix est beaucoup plus faible (Giraudet, 2020).

Ce faible impact sur les loyers contribue à un sous-investissement chronique dans l'efficacité énergétique du parc locatif privé (Gillingham et al., 2012; Melvin, 2018; Myers, 2020; Lang et al., 2021b; Petrov and Ryan, 2021). Ce phénomène, connu sous le nom de problème des incitations fractionnées ou dilemme du propriétaire-locataire, reflète une situation où les coûts des rénovations énergétiques sont supportés par les propriétaires, tandis que les bénéfices, sous forme de factures d'énergie réduites, reviennent principalement aux locataires. Cette asymétrie incite les propriétaires à ne pas investir dans des améliorations énergétiques, perpétuant ainsi l'inefficience énergétique dans ce segment du marché immobilier.

Problèmes de coordination dans les logements collectifs Le taux de rénovation énergétique dans les maisons multifamiliales est généralement inférieur à celui observé dans les maisons unifamiliales (MTE, 2020). Ce phénomène s'explique principalement par deux problèmes de coordination propres à ce type d'habitat.

Dans les copropriétés, les rénovations énergétiques nécessitent souvent une décision collective prise par l'assemblée des copropriétaires. Cette situation est typique d'un problème de bien public : les avantages individuels perçus par chaque copropriétaire ne sont pas nécessairement proportionnels à leur contribution financière. Par exemple, un copropriétaire occupant un appartement au rez-de-chaussée pourrait considérer que les bénéfices d'une isolation thermique de la toiture sont moindres pour lui, comparés à ceux d'un résident situé au dernier étage.

Une solution théorique serait d'ajuster les contributions à l'investissement selon une règle de type Lindahl, comme cela se fait pour le financement des ascenseurs, où la contribution augmente avec l'étage. Cependant, dans le cas des rénovations énergétiques, cette règle n'est généralement pas appliquée. Par exemple, l'isolation du toit est souvent financée sur la base de la part de propriété, ce qui peut désavantager les copropriétaires situés aux étages intermédiaires, où les bénéfices perçus sont plus faibles.

En copropriété, les propriétaires n'ont pas un contrôle total sur les flux de chaleur qui traversent les limites de leur logement. Par conséquent, même si des décisions collectives sont prises, les gains énergétiques peuvent être partiellement annulés par des externalités thermiques. Ces flux de chaleur, qu'ils soient positifs ou négatifs, réduisent l'efficacité individuelle des investissements. Par exemple, la chaleur produite dans un logement mal isolé peut se dissiper dans les appartements voisins, diminuant ainsi les avantages pour le propriétaire ayant financé des travaux d'isolation.

Ces deux obstacles, le problème de bien public et les externalités thermiques, expliquent pourquoi les copropriétés tardent souvent à entreprendre des rénovations énergétiques. Ces défis soulignent la nécessité de mécanismes financiers et réglementaires adaptés pour encourager la coordination entre copropriétaires et maximiser les bénéfices collectifs des rénovations.

Anomalies comportementales

En plus des défaillances de marché, le comportement des agents économiques peut s'écarter de la rationalité parfaite postulée par les modèles microéconomiques standard. Ces écarts, appelés échecs comportementaux, se manifestent lorsqu'il existe une divergence systématique entre l'utilité au moment de la décision, appelée utilité de décision, et l'utilité ressentie lorsque les conséquences de la décision se matérialisent, connue sous le nom d'utilité expérimentée (Gillingham and Palmer, 2014).

Il est essentiel de différencier les préférences, comme les préférences temporelles standard ou les préférences face au risque, des biais comportementaux, tels que le biais de présent ou le biais du statu quo. Alors que les préférences peuvent dissuader les individus d'adopter des technologies économes en énergie, elles conduisent à des décisions rationnelles du point de vue de leurs objectifs personnels. Par conséquent, les politiques cherchant à contrer ces préférences ne rendraient pas nécessairement les individus mieux lotis.

En revanche, les biais comportementaux, comme le biais de présent ou le biais du statu quo, peuvent amener les individus à prendre des décisions contraires à leurs intérêts à long terme. Ces biais sont définis comme des échecs comportementaux car ils créent un écart entre l'utilité de décision et l'utilité expérimentée (Gillingham and Palmer, 2014).

L'utilisation de politiques visant à corriger ces biais comportementaux suscite des débats, notamment en raison de leur dimension paternaliste (Gillingham and Palmer, 2014). Néanmoins, ces déviations comportementales influencent l'efficacité des instruments politiques traditionnels conçus pour pallier les défaillances de marché. Il est donc crucial de les intégrer dans la conception des politiques publiques.

Identifier ces biais dans des études empiriques reste un défi majeur, particulièrement lorsqu'il s'agit de les différencier des préférences. Idéalement, des données longitudinales détaillées sur les ménages, incluant des informations sur les prix de l'énergie et les coûts de rénovation, sont nécessaires. Cependant, de telles données sont rares et ne se prêtent pas toujours aux expérimentations.

Dans ce contexte, les expériences de choix discrets se sont avérées être un outil utile pour détecter les anomalies comportementales (Michelsen and Madlener, 2012; Newell and Siikamäki, 2015; Achtnicht and Madlener, 2014; Schleich et al., 2021). Ces enquêtes présentent aux participants plusieurs options d'investissement et leur demandent d'en choisir une, permettant ainsi d'évaluer une variété de facteurs influençant leurs décisions. Cependant, une limite majeure de ces approches réside dans le fait que les choix déclarés peuvent différer des comportements réels.

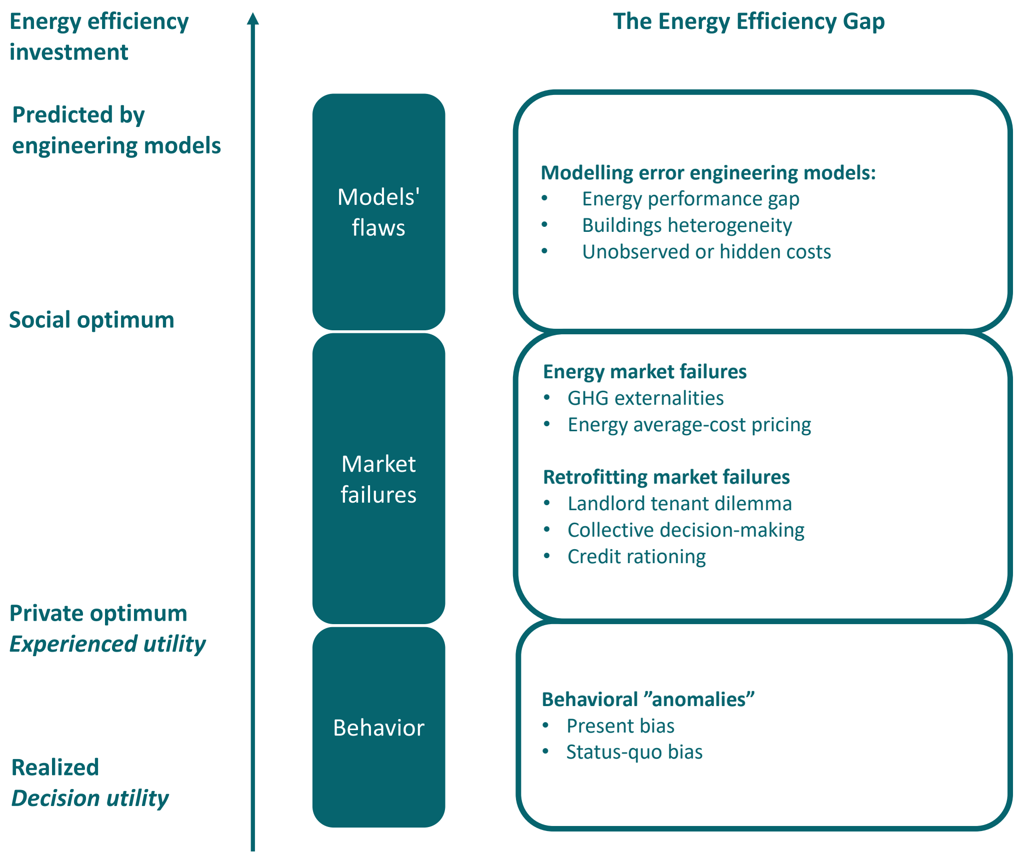
Une partie importante de la littérature s'intéresse à la manière dont les consommateurs actualisent les économies futures liées aux investissements en efficacité énergétique. Plusieurs études montrent que les consommateurs sont myopes lorsqu'ils évaluent l'isolation des maisons, exigeant des rendements plus élevés que ceux des marchés financiers (Stolyarova, 2016; Schleich et al., 2019). Ce biais de présent est souvent corrélé au revenu, les ménages à faible revenu manifestant une préférence pour le présent plus marquée que les ménages plus aisés (Stolyarova, 2016).

D'autres biais, comme l'inattention aux prix de l'énergie, peuvent également conduire à une sous-estimation des économies futures (Lang et al., 2024). De plus, l'aversion aux pertes peut inciter les propriétaires à minimiser les bénéfices potentiels des rénovations, réduisant ainsi la probabilité d'investissement (Schleich et al., 2019). Enfin, le biais du statu quo empêche souvent les ménages de changer leur système de chauffage, même lorsque des alternatives plus rentables sont disponibles (Stolyarova, 2016; Lang et al., 2021a).

Lacunes de la recherche

Une explication majeure de l'écart d'efficacité énergétique réside dans l'externalité carbone. Tant que les coûts sociaux de la consommation d'énergie ne seront pas intégrés dans les prix, les investissements dans l'efficacité énergétique resteront insuffisants. Ce principe a constitué la justification principale de nombreuses politiques d'efficacité énergétique à travers le monde. En plus de cette externalité, d'autres facteurs ont été identifiés, tels

Figure 0.3 – Composantes de l'écart d'efficacité énergétique considérées dans cette thèse.



que les erreurs de modélisation (Metcalf and Hassett, 1999), le dilemme propriétaire-locataire (Gillingham et al., 2012), les anomalies comportementales (Allcott et al., 2014), l'effet de rebond (Chan and Gillingham, 2015), le risque moral dans la qualité des travaux (Giraudet et al., 2018b) et les asymétries d'information dans la valorisation de l'efficacité énergétique (Myers, 2020). Cependant, seuls certains de ces facteurs ont été étudiés de manière empirique. Ces frictions sont généralement analysées individuellement et rarement en combinaison avec l'externalité carbone. À notre connaissance, une seule étude a examiné plusieurs frictions simultanément, en considérant les erreurs de modélisation, les asymétries d'information et l'effet de rebond (Christensen et al., 2021). Ainsi, l'écart d'efficacité énergétique a principalement été étudié dans des contextes de second ou de troisième meilleur, tandis que le monde du « nième meilleur » décrit dans le cadre de Jaffe and Stavins (1994) demeure largement inexploré.

4.3 Quels sont les impacts des politiques d'efficacité énergétique dans le secteur résidentiel ?

Aborder simultanément plusieurs défaillances de marché nécessite de recourir à une combinaison d'instruments. Cependant, leur mise en œuvre ne peut être justifiée qu'à travers une évaluation globale prenant en compte leur efficacité, leur rapport coût-efficacité, leurs impacts sur le bien-être et leurs effets distributifs. En effet, les programmes visant à promouvoir les économies d'énergie peuvent souffrir d'une conception inadéquate, d'une mise en œuvre déficiente ou d'un ciblage inapproprié des défaillances de marché ou comportementales pertinentes, ce qui peut entraîner des résultats non rentables. J'offre un aperçu du mix optimal de politiques dans un cadre théorique de premier meilleur, avant d'examiner les preuves empiriques concernant les instruments d'efficacité énergétique. Mon analyse se concentre sur l'évaluation des programmes de rénovation énergétique, plutôt que sur les rénovations elles-mêmes.

Premier meilleur mix de politiques

La solution économique fondamentale à l'externalité des émissions de gaz à effet de serre (GES) consiste à établir un prix du carbone égal au dommage marginal causé par ces émissions. Dans le domaine de la consommation résidentielle d'énergie, cet instrument est unique en ce qu'il agit simultanément sur la consommation d'énergie et sur les décisions d'investissement, contrairement aux politiques d'efficacité énergétique ou aux réglementations, qui n'influencent que le premier canal (Goulder and Parry, 2008). Cependant, la présence de défaillances de marché supplémentaires et d'anomalies comportementales justifie le recours à un mélange de politiques. Allcott et al. (2014) soutiennent qu'en présence de telles défaillances, une politique optimale consisterait à combiner une taxe énergétique inférieure au dommage marginal avec des subventions spécifiquement ciblées sur les défaillances comportementales. Cette approche repose sur leur constat selon lequel les consommateurs sous-évaluant le plus les coûts énergétiques sont également les moins sensibles aux taxes énergétiques. Une politique optimale viserait donc ces consommateurs désavantagés tout en limitant les distorsions pour ceux présentant moins de biais.

Cependant, la mise en œuvre de politiques de premier meilleur est souvent entravée par des contraintes pratiques ou politiques. Premièrement, les prix du carbone sont rarement fixés à leur niveau socialement optimal et ne couvrent pas toujours tous les secteurs concernés, lorsqu'ils sont appliqués. Par exemple, en France, le gouvernement a gelé le taux de la taxe carbone résidentielle en réponse au mouvement des Gilets jaunes

(Douenne and Fabre, 2022). Deuxièmement, lorsque les distorsions comportementales sont hétérogènes au sein de la population, le mix de politiques optimal devrait idéalement être adapté à chaque individu. Or, ces distorsions ne sont pas systématiquement corrélées avec des caractéristiques observables par le gouvernement, ce qui rend impossible un ciblage parfait. Allcott et al. (2014) montrent que dans de tels cas, les subventions devraient être basées sur le taux marginal moyen d'internalité, plutôt que sur le taux d'internalité moyen, bien que cette approche ne permette pas non plus un ciblage optimal. Ces défis rendent les politiques de premier meilleur politiquement difficiles à mettre en œuvre, nécessitant ainsi des approches de second meilleur adaptées par les décideurs publics.

Instruments de politique de second meilleur

Les mesures politiques les plus courantes dans le secteur du logement comprennent des incitations financières (taxes et subventions), des instruments réglementaires (normes et interdictions) ainsi que des mesures d'information (certificats de performance énergétique, campagnes de sensibilisation, etc.). Dans cette thèse, je me concentre exclusivement sur les deux premières catégories d'instruments, qui visent à corriger les défaillances de marché décrites précédemment.

Tarification du carbone Une question centrale liée à la tarification du carbone concerne la manière dont les recettes doivent être recyclées et utilisées. L'approche économique standard recommande de dissocier le signal de prix du mécanisme de recyclage des recettes, en préconisant idéalement un retour des fonds sous forme forfaitaire. En France, cette séparation est effectivement appliquée en raison des règles budgétaires qui interdisent au gouvernement d'affecter directement les recettes de la taxe carbone à des usages spécifiques. Néanmoins, le gouvernement accorde un paiement forfaitaire aux ménages à faible revenu, destiné soit à couvrir les dépenses énergétiques, soit à financer des investissements en efficacité énergétique, indépendamment des recettes issues de la taxe carbone. Ce mécanisme de redistribution forfaitaire peut considérablement réduire l'effet régressif de la taxe dans le contexte du chauffage résidentiel (Bourgeois et al., 2021).

Subventions Les programmes de subventions ont été largement utilisés en France pour promouvoir l'efficacité énergétique, car ils offrent un signal d'investissement plus visible que les taxes sur le carbone. Cela peut encourager une réponse plus forte de la part des ménages qui sous-évaluent les économies d'énergie (Allcott et al., 2014; Chan and Globus-Harris, 2023). Cependant, une préoccupation majeure concernant ces programmes est la présence de bénéficiaires non additionnels — des ménages qui auraient investi dans des rénovations énergétiques même en l'absence de subventions (Boomhower and Davis, 2014). Ces bénéficiaires non additionnels créent des effets distributifs négatifs, où les contribuables financent des investissements qui n'auraient pas nécessité d'aide, ce problème étant particulièrement fréquent lorsque les subventions sont uniformes.

Ce problème peut être partiellement atténué en ciblant les subventions là où elles sont le plus nécessaires, bien que cela soit limité par les caractéristiques observables des ménages. Une approche efficace consiste à se concentrer sur les ménages à faible revenu, dont les décisions d'investissement sont souvent entravées par plusieurs frictions. Une autre stratégie consiste à privilégier une conception des subventions basée sur des montants fixes par unité plutôt que sur une approche ad valorem, cette dernière étant vulnérable aux distorsions de prix dans des situations de concurrence imparfaite (Nauleau et al., 2015). Par ailleurs, des subventions mal conçues peuvent inciter à des investissements non rentables d'un point de vue social, notamment lorsque les gouvernements surestiment les bénéfices des rénovations énergétiques, ce qui peut survenir en cas d'écart significatif entre la performance énergétique théorique et réelle.

En France, le crédit d'impôt pour la transition énergétique (CITE) illustre bien ce phénomène. Une étude a estimé que 85% des bénéficiaires étaient non additionnels, laissant seulement 15% d'investisseurs additionnels (Nauleau, 2014). Cependant, cette mesure de la marge extensive (le nombre d'investissements additionnels) néglige les effets sur la marge intensive (l'ampleur des investissements). Par exemple, Risch (2020) ont montré que les participants non additionnels du CITE ont augmenté leurs dépenses de 22%, tandis que le prêt à taux zéro français (EPTZ) a généré un impact élevé sur la marge extensive (+22%) mais un impact faible sur la marge intensive (+3%) (Eryzhenskiy et al., 2023). Ces analyses reposent souvent sur des méthodes quasi-expérimentales, qui soulèvent des préoccupations quant à la validité interne en raison de la non-comparabilité potentielle des groupes de traitement et de contrôle. Giandomenico et al. (2022) ont constaté que les économies rapportées par des études utilisant une validité interne élevée sont systématiquement plus faibles, suggérant que les méthodes quasi-expérimentales peuvent surestimer les bénéfices des programmes par rapport aux essais contrôlés randomisés (RCT).

À ce jour, seuls deux RCT ont évalué les effets des programmes de rénovation énergétique aux États-Unis. Fowlie et al. (2018) ont examiné un programme d'isolation dans le Michigan, ciblant les ménages à faible revenu. Ils ont constaté une réduction de la consommation d'énergie de 10% à 19%, principalement pour le gaz naturel. Cependant, les investissements étaient non rentables, les coûts étant environ deux fois supérieurs aux économies d'énergie réalisées. Même en incluant des estimations optimistes du confort thermique et des réductions des externalités, les investissements n'offraient aucun bénéfice net, que ce soit pour les ménages ou pour la société. Ces résultats reposaient sur un coût social du carbone de 38€/tCO_2 et une durée de vie de 16 ans pour l'isolation, des hypothèses conservatrices selon la littérature actuelle.

De manière complémentaire, Allcott and Greenstone (2024) ont utilisé des RCT pour évaluer un programme de subventions dans le Wisconsin, combinant un modèle structurel et des expériences de terrain pour simuler des scénarios politiques contrefactuels. Ils ont montré que ce programme réduisait le bien-être en raison de prévisions erronées des économies d'énergie, entraînant des investissements socialement non rentables, même avec un coût social du carbone élevé (190€/tCO_2), un taux d'actualisation social de 3% et une durée de vie de 20 ans pour les mesures d'efficacité énergétique. Cependant, leur analyse a également révélé que des programmes de subventions mieux conçus, alignés sur les réductions d'externalités, pourraient générer des effets positifs sur le bien-être.

Instruments réglementaires Les instruments réglementaires, tels que les mandats technologiques (par exemple, la rénovation obligatoire) et les interdictions (comme celles visant les logements locatifs inefficaces ou les chaudières à combustibles fossiles), sont généralement considérés comme moins rentables que les politiques basées sur les prix. Ces mesures ne tiennent souvent pas compte de l'hétérogénéité des ménages, imposant des exigences uniformes qui peuvent ne pas correspondre à la rentabilité individuelle (Hepburn, 2006; Goulder and Parry, 2008). Même lorsque ces réglementations ciblent des investissements apparemment rentables, comme les rénovations obligatoires pour les logements les moins performants ou les pompes à chaleur en tant que systèmes de chauffage les plus efficaces, leur application uniforme néglige souvent les coûts cachés supportés par les ménages, ce qui réduit leur rentabilité globale.

Cependant, les normes peuvent présenter des avantages économiques dans des contextes où des biais comportementaux empêchent les consommateurs de répondre rationnellement aux signaux de prix. Par exemple, Tsvetanov and Segerson (2013) utilisent un modèle théorique intégrant la tentation et montrent que les normes de produits peuvent aboutir à de meilleurs résultats en termes de bien-être que les politiques basées sur les prix. Ces normes limitent la capacité des consommateurs à céder à la tentation d'acheter des produits énergétiquement inefficaces à bas coût, favorisant ainsi des choix plus alignés sur des objectifs à long terme.

Lacunes de la recherche

Globalement, bien que la littérature économétrique tende à montrer que les programmes de subventions à l'efficacité énergétique réduisent le bien-être, ces résultats sont très sensibles aux hypothèses et aux facteurs inclus dans l'évaluation (Fowlie et al., 2018; Allcott and Greenstone, 2024). Premièrement, la plupart des études se concentrent sur des estimations de rentabilité ou de coût d'abattement, qui ne font qu'approcher l'impact sur le bien-être et négligent souvent les avantages non énergétiques de la rénovation énergétique qui ont été montrés comme expliquant une partie significative de la motivation (Wekhof and Houde, 2023). Deuxièmement, lorsque les études tiennent compte des impacts sur le bien-être, elles ne prennent généralement pas en compte d'autres barrières à l'investissement en efficacité énergétique. Dans un environnement de marché et de comportement hautement imparfait, les externalités de GES ne sont qu'une des raisons justifiant la mise en œuvre de la politique. Troisièmement, le coût social du carbone et l'horizon d'investissement sont des variables exogènes clés qui peuvent influencer de manière significative les conclusions. En outre, les politiques sont généralement évaluées individuellement, tandis que les gouvernements comptent souvent sur de multiples instruments. Évaluer une stratégie globale nécessite une meilleure compréhension de la manière dont les politiques interagissent.

De plus, le faible nombre de rénovations énergétiques par rapport aux objectifs a poussé les gouvernements à mettre en œuvre des mesures plus agressives, telles que les instruments réglementaires. Notamment, le consensus sur l'efficacité des pompes à chaleur suggère la nécessité d'interdire les nouvelles chaudières à combustibles fossiles. Malgré son impact potentiellement massif et sa nature controversée, cette mesure a été peu étudiée. En particulier, aucune évolution de la politique d'efficacité énergétique ne considère la robustesse des instruments pour atteindre la neutralité carbone dans des conditions d'incertitude (Goulder and Parry, 2008).

4.4 Comment modéliser l'impact des politiques d'efficacité énergétique ?

L'écart entre les objectifs et les réalisations des investissements en efficacité énergétique met en évidence la nécessité de mieux intégrer les décisions d'investissement dans les évaluations ex ante des politiques pour une planification plus efficace. Divers modèles d'équilibre partiel appliqués au secteur résidentiel, souvent désignés comme modèles de stock de bâtiments, ont été développés au cours des dernières décennies (Mundaca et al., 2010; Langevin et al., 2020) (Figure 0.4). Les avancées dans les bibliothèques de données sur les bâtiments et les systèmes d'information géographique (SIG) ont permis la création de modèles bottom-up détaillés, capables de représenter avec précision les caractéristiques hétérogènes du parc immobilier. Ces modèles permettent d'estimer la consommation énergétique des bâtiments tout en intégrant de manière endogène les transformations structurelles du parc immobilier, telles que les démolitions, les constructions et les rénovations.

La plupart de ces modèles ont été utilisés pour explorer les voies d'atténuation à long terme, soit en s'appuyant sur des scénarios exogènes (Sandberg et al., 2021; Mastrucci et al., 2021; Berrill et al., 2022), soit en minimisant les coûts du système énergétique (Zeyen et al., 2021; Mandel et al., 2023). Bien que ces approches fournissent des estimations quantitatives du potentiel d'atténuation et des évolutions technologiques nécessaires, elles ne répondent pas à la question cruciale de savoir comment ces objectifs peuvent être atteints à travers des politiques réalistes. De plus, la dépendance de ces modèles aux estimations d'économies d'énergie issues de simulations techniques, plutôt que d'observations empiriques, entraîne une surestimation fréquente des économies d'énergie et de la rentabilité des investissements (Christensen et al., 2021).

Par ailleurs, certaines études, souvent associées aux Modèles d'Évaluation Intégrée (IAM), utilisent des modèles *logit* multinomiaux basés sur le coût total des technologies pour simuler de manière endogène la diffusion des technologies d'efficacité énergétique (Knobloch et al., 2021; Levesque et al., 2021). Toutefois, une limite majeure de ces modèles de dynamique de système réside dans leur représentation simplifiée des aspects techniques, reposant sur une approche top-down pour modéliser le secteur du bâtiment. Comme mentionné précédemment, l'hétérogénéité des coûts et des bénéfices des investissements ainsi que les diverses frictions du marché rendent les résultats de ces approches moins fidèles à la réalité.

Modèles multi-agents dynamiques et de micro-simulation

Quelques études, principalement menées à l'échelle nationale, tentent de combiner des détails technologiques avec les décisions d'investissement des ménages (Giraudet et al., 2012; Charlier et al., 2018; Giraudet et al., 2021a; Camarasa et al., 2022; Müller et al., 2024). Ces modèles utilisent souvent des approches de choix discrets, comme les modèles logit multinomiaux, pour représenter la diversité des décisions des ménages, tout en intégrant des barrières à l'investissement calibrées de manière empirique. Ils servent généralement à évaluer si les politiques actuelles permettent d'atteindre les objectifs climatiques et à comparer le rapport coût-efficacité de différents instruments politiques.

Cependant, cette approche présente plusieurs limites. Tout d'abord, bien que ces modèles utilisent un cadre bottom-up, les détails techniques qu'ils incluent sont souvent encore trop simplifiés pour représenter avec précision l'isolation des habitations et les systèmes de chauffage dans un même modèle (Giraudet et al., 2021a; Charlier et al., 2018). Deuxièmement, ces modèles intègrent souvent un nombre limité de frictions de marché, voire aucune (Charlier et al., 2018; Müller et al., 2024), ce qui peut conduire à des conclusions trop optimistes. Lorsqu'ils incluent des frictions, ils reposent fréquemment sur des taux d'actualisation implicites (Schleich et al., 2016), une approche qui peut mal représenter les véritables barrières à l'investissement et aboutir à des analyses politiques incohérentes. Par exemple, cette méthode risque de sous-estimer l'impact des taxes sur l'énergie sur les décisions d'investissement, en particulier lorsque les barrières relèvent de coûts non observés.

Enfin, ces modèles manquent souvent d'une base théorique rigoureuse, car ils s'appuient sur des fonctions ad hoc pour représenter les décisions d'investissement, sans alignement avec un cadre cohérent d'utilité (Giraudet et al., 2021a). Cela limite leur capacité à évaluer l'impact des politiques sur le bien-être social, les confinant à une analyse des économies d'énergie ou des émissions évitées. De plus, la justification économique des paramètres estimés reste souvent floue malgré leur importance, rendant l'interprétation des résultats difficile (Branger et al., 2015).

Modèles basés sur les agents

Au cours de la dernière décennie, les modèles basés sur les agents (ABM) ont connu des avancées significatives grâce à un meilleur accès aux données et à des capacités informatiques accrues (Rai and Henry, 2016). Ces modèles intègrent des facteurs psychologiques et sociaux dans les processus décisionnels des agents, en s'appuyant sur des théories issues de la recherche psychologique. Des études récentes ont appliqué les ABM pour analyser les décisions d'investissement en rénovation énergétique (Sachs et al., 2019; Chersoni et al., 2022; Niamir et al., 2024). Contrairement aux modèles multi-agents classiques de l'économie de l'énergie, les ABM simulent explicitement les interactions entre agents, leur accès à l'information, ainsi que l'influence des réseaux sociaux, des normes sociales et des pairs sur les décisions de rénovation.

Malgré leurs atouts, la complexité de l'estimation des paramètres influencés par ces interactions limite leur application à des évaluations de politiques globales. Ces modèles se révèlent toutefois particulièrement utiles pour explorer l'impact de comportements spécifiques des ménages. En outre, bien que les ABM soient capables de prédire les dynamiques potentielles des rénovations énergétiques, ils sont moins adaptés à l'évaluation des impacts des mesures politiques sur le bien-être, ce qui restreint leur portée pour des analyses plus générales.

Modèles structurels

Enfin, les modèles structurels des décisions d'investissement en efficacité énergétique sont ancrés dans la théorie microéconomique du consommateur. Leur principal avantage, par rapport à d'autres techniques de modélisation, réside dans leur capacité à fournir des évaluations du bien-être des politiques (Dubin and McFadden, 1984; Davis, 2008; Allcott et al., 2014; Chan and Globus-Harris, 2023; Allcott and Greenstone, 2024). Sur le plan normatif, ces modèles ont été utilisés pour déterminer le mix politique optimal en présence de défaillances de marché et de biais comportementaux. Par exemple, Allcott et al. (2014) ont employé un modèle structurel pour identifier les politiques les plus efficaces dans des scénarios impliquant des internalités (biais comportementaux) et des externalités de GES. Plus récemment, Allcott and Greenstone (2024) ont combiné des expériences de terrain avec des modèles économétriques structurels afin d'évaluer les impacts sur le bien-être d'un programme d'efficacité énergétique dans le Wisconsin, en mettant en évidence l'importance d'intégrer des attributs non observés et des économies d'énergie réelles dans la fonction de bien-être.

Ces approches sont souvent considérées comme le standard pour les évaluations crédibles de l'efficacité énergétique. Cependant, elles tendent à se concentrer sur un seul programme politique à la fois, alors qu'en pratique, un mix de politiques plus large est généralement en place. En outre, elles traitent un nombre limité de frictions, laissant d'autres défaillances de marché non prises en compte, bien qu'elles puissent également influencer les décisions d'investissement des ménages. Enfin, ces modèles ne sont généralement pas conçus pour intégrer les changements structurels du parc immobilier au fil du temps, ce qui les rend moins adaptés pour évaluer si les politiques permettent de répondre aux objectifs climatiques à long terme.

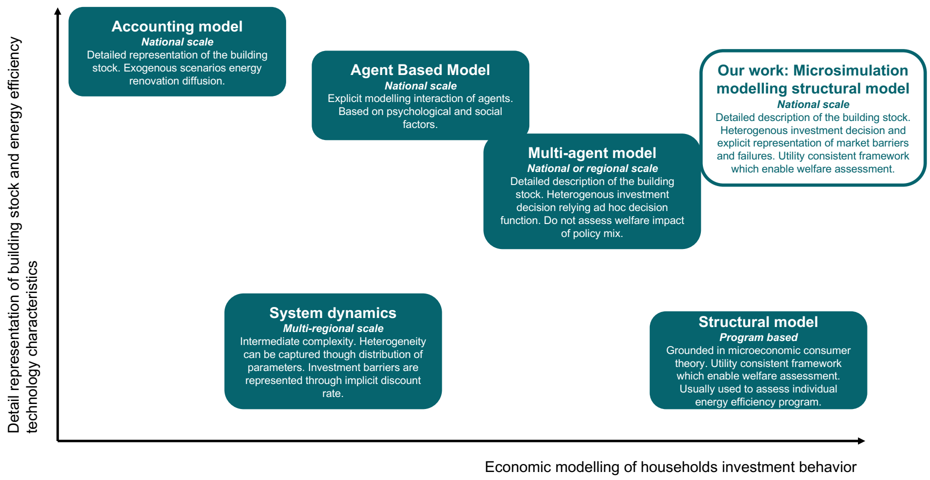
Lacune de la recherche

D'une part, les évaluations technico-économiques dans la littérature échouent souvent à représenter de manière adéquate les principaux mécanismes de marché et comportementaux, ce qui les rend inadaptées à l'évaluation des politiques réelles (Zeyen et al., 2021; Hummel et al., 2023; Mandel et al., 2023). Ces évaluations reposent généralement sur des analyses coûts-bénéfices étroites, qui tendent à surestimer les économies d'énergie et les coûts physiques tout en négligeant les co-bénéfices non énergétiques, pourtant cruciaux dans les décisions d'investissement.

D'autre part, les modèles structurels microéconomiques offrent un cadre cohérent d'utilité, permettant d'évaluer l'impact des politiques sur le bien-être. Cependant, ces modèles traitent généralement des frictions isolées ou évaluent des politiques de manière individuelle, sans tenir compte de la complexité des défaillances multiples de marché ou des interactions dans un mix politique (Allcott et al., 2014; Allcott and Greenstone, 2024). En outre, ils se concentrent principalement sur les impacts à court terme des politiques et ne capturent pas l'évolution structurelle à long terme du parc immobilier.

Ces lacunes dans la littérature soulignent la nécessité d'intégrer de manière plus complète les principales frictions qui freinent l'investissement en efficacité énergétique dans les évaluations politiques, afin d'améliorer la planification et l'efficacité des politiques publiques.

Figure 0.4 – Vue d'ensemble de la littérature de modélisation sur la diffusion de l'efficacité énergétique dans le secteur du bâtiment.



5 Cette dissertation

Cette dissertation regroupe quatre études de modélisation visant à évaluer les politiques d'efficacité énergétique. Son objectif principal est de développer un cadre de modélisation permettant une évaluation socio-économique approfondie d'une gamme de politiques d'efficacité énergétique résidentielle, dans des contextes caractérisés par des défaillances de marché et des anomalies comportementales.

Quatre avancées majeures par rapport à la littérature existante sont proposées : premièrement, un affinement de la description des technologies d'efficacité énergétique résidentielle, prenant en compte les complémentarités entre les niveaux d'isolation et la performance des systèmes de chauffage ; deuxièmement, une prise en compte explicite des principales barrières aux économies d'énergie, notamment les effets de rebond, le biais de présent, les attentes myopes des prix de l'énergie, les contraintes de crédit, le dilemme propriétaire-locataire et les problèmes de coordination dans les logements collectifs ; troisièmement, un cadre élargi pour l'évaluation du bien-être, intégrant le confort thermique, la réduction des factures de carburant, les bénéfices pour la santé, les co-bénéfices non énergétiques, ainsi que le coût d'opportunité des fonds publics ; quatrièmement, une intégration renforcée entre la demande et l'offre d'énergie dans le secteur résidentiel, essentielle pour capturer toutes les marges possibles de décarbonation.

Ces améliorations ont été appliquées à deux modèles distincts : Res-IRF, un modèle d'efficacité énergétique pour le secteur résidentiel français, et Message-ix Buildings, un modèle global de stock de bâtiments appliqué ici au secteur résidentiel de l'UE. Ci-dessous, je résume les contributions spécifiques de chaque chapitre :

Contributions par chapitre

Le premier chapitre, intitulé *Energy efficiency policy in an n-th best world: Assessing the implementation gap*, est un travail réalisé en collaboration avec Louis-Gaëtan Giraudet. Ce chapitre propose un modèle structurel détaillé de la demande énergétique pour le chauffage résidentiel, intégrant une large gamme de frictions freinant les investissements en efficacité énergétique. Ce cadre est utilisé pour analyser l'impact de ces frictions sur le bien-être, la consommation d'énergie et les émissions de CO_2 en France, avant d'évaluer les politiques actuellement en vigueur. Les résultats mettent en évidence le fossé de mise en œuvre des politiques, soulignant l'importance de mieux cibler les interventions dans les contextes où les frictions sont les plus significatives.

Le deuxième chapitre, intitulé *Meeting climate target with realistic demand-side policies in the residential sector in the EU-27*, réalisé en collaboration avec Alessio Mastrucci et Bas van Ruijven, étend le modèle de décision d'investissement développé dans le Chapitre 1 au niveau de l'Union européenne. Plus précisément, ce modèle est intégré à Message-ix Buildings, un modèle de renouvellement du stock de bâtiments. Grâce à ce cadre, j'effectue une évaluation quantitative complète d'un large éventail de mixes politiques axés sur la demande dans les 27 pays de l'UE.

Le troisième chapitre, intitulé *How to allocate mitigation efforts between home insulation, fuel switch and fuel decarbonization? Insights from the French residential sector*, réalisé en collaboration avec Célia Escribe, Louis-Gaëtan Giraudet et Philippe Quirion, s'attache à coupler le modèle structurel développé pour la France dans le Chapitre 1 avec un modèle de système énergétique. Ce cadre permet de capturer les arbitrages entre l'isolation des habitations, le passage à des systèmes de chauffage bas-carbone et la décarbonisation des combustibles de chauffage dans les stratégies d'atténuation. Plus précisément, ce modèle est utilisé pour analyser le rôle des subventions à l'isolation des maisons dans ces stratégies.

Le quatrième chapitre, intitulé *Banning new gas boilers as a hedge against the limited availability of renewable gas supply*, est un travail réalisé en collaboration avec Célia Escribe. Ce chapitre s'appuie sur le cadre développé dans le Chapitre 3 pour évaluer l'impact d'une interdiction de l'installation de nouvelles chaudières à combustibles fossiles, une mesure précédemment explorée dans le Chapitre 1 sans prise en compte de son impact sur le système énergétique. Dans ce chapitre, nous analysons en détail la robustesse de la mise en œuvre de cette interdiction en tenant compte d'un large éventail d'incertitudes.

Articles publiés et acceptés

Chapitre 3 : Escribe, C., **Vivier, L.**, Giraudet, L.-G, Quirion, P. *How to allocate mitigation efforts between home insulation, fuel switch and fuel decarbonization? Insights from the French residential sector.* Environmental Research Letters, 2024. *Contribution égale en tant que co-premier auteur avec Célia Escribe*
Chapter 4: Escribe, C.* and **Vivier, L.*** *Banning new gas boilers as a no-regret mitigation option.* Accepté dans Nature Communications. *Contribution égale en tant que co-premier auteur avec Célia Escribe*

Article sous revue

Chapitre 2 : Vivier, L. van Ruijven, B., et Mastrucci, A. *Meeting climate target with realistic demand-side policies in the residential sector in the EU-27.* En cours d'examen dans Nature Climate Change. Une version antérieure de cet article a reçu le Prix Levien IIASA.

Document de travail

Chapitre 1 : Vivier, L. et Giraudet, L.-G. *Energy efficiency policy in an n-th best world: Assessing the implementation gap.* Document de travail, 2024.

Autres contributions

Vivier, L. and Giraudet, L.-G., 2024. *Analyse socio-économique de la rénovation énergétique des logements.* Focus Conseil d'Analyse Économique.

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CHAPTER 1

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

Working Paper
Joint work with Louis-Gaëtan Giraudet

Abstract

The Energy Efficiency Gap refers to a set of market failures and behavioral anomalies deterring energy efficiency investment. These frictions tend to be studied in isolation, which introduces biases in the welfare assessment of energy efficiency policies. We set out to map the energy efficiency gap in the market for home energy retrofits by developing a utility framework distorted by multiple frictions – CO_2 externality, cold-related illness, credit rationing, landlord-tenant dilemma, free-riding in multi-family housing, present bias and status quo bias. Focused on France, the model features a detailed representation of both technology and household characteristics. The frictions are parameterized with the best available empirical estimates. We find that the CO_2 externality is dominated by health, rental and multi-family frictions in the ranking of justifications for energy efficiency policy. Taking into account all frictions moreover reverses the generally accepted conclusion that energy efficiency subsidies generate net social costs. Finally, the policy portfolio that prevails in France, which blends subsidies, taxes and regulations, only closes half of the energy efficiency gap. Its efficiency could be improved without spending more by better targeting low-income families, multi-family housing and rental housing.

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

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 and Stavins (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 tenet 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 and Hassett, 1999), landlord-tenant dilemma (Gillingham et al., 2012), behavioral anomalies (Allcott et al., 2014), the rebound effect (Chan and Gillingham, 2015), moral hazard in quality provision (Giraudet et al., 2018), information asymmetries in energy efficiency capitalization (Myers, 2020) and non-energy value (Wekhof and Houde, 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 multiple 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 and Stavins (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 and Missemer, 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 and Greenstone (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 and Greenstone, 2024). These state-of-the-art approaches have an unparalleled ability to produce internally valid friction estimates. 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, the welfare properties of which remain largely unknown. 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 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 options. The model therefore rests on 180,000 dwelling-household pairs. The energy performance of the dwelling can be upgraded by renovation investment, modelled as a discrete choice. Conditional on investment decision, households optimize their energy use in a utility framework. The energy performance gap is therefore endogenous to the model. Investment and utilization decisions are distorted by several frictions parameterized with the best available estimates – uninternalized CO_2 externalities, uninternalized health costs in the worst-performing homes, credit rationing, present bias and status quo bias. We add two more frictions through calibration – the landlord-tenant dilemma and free-riding in multi-family housing. Lastly, we take into account the residual non-energy value that rationalizes the gap between our predictions and observed investment levels. Our model thus allows us to assess all relevant dimensions of energy efficiency policy – investment cost, bill savings, increased comfort, reduced health costs, avoided CO_2 emissions, non-energy 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 CO_2 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, 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, a rental ban on worst-performing housing and 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 non-energy costs. Taking all policies together, we find they close about half of the French energy efficiency gap – about two-thirds along the energy savings dimension and one-third along the welfare dimension. Importantly, the remaining welfare gap is commensurate with current subsidy spending, suggesting actual schedules should be adjusted to increase their efficiency.

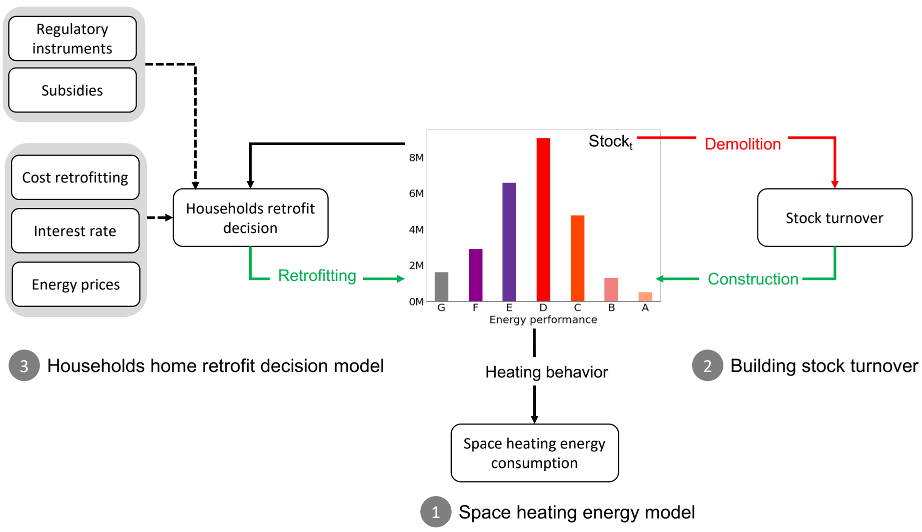
Our analysis purports to explore the complexities of a market distorted by multiple frictions. In doing so, it bridges a gap between microeconomic models and the building stock models used in numerical assessments of climate policy. In addition to the references listed above, our work therefore relates to that of Levesque et al. (2021); Mastrucci et al. (2021); Knobloch et al. (2021); Berrill et al. (2022); Müller (2015); Camarasa et al. (2022). These studies contain a high level of technological detail – with a broader scope in terms of energy usage and countries represented. They however rely on exogenous, or at best significantly less distorted, renovation processes. Although they produce valuable cost-effectiveness assessments, they are therefore unfit for welfare analysis.

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 4 discusses the results and Section 5 concludes.

2 Model

We develop a dynamic framework that is both technologically explicit and behaviorally rich. The behavioral part relies on micro-founded household decisions plagued with market failures and behavioral anomalies. The different processes are specified with the best available estimates for France. We provide below a concise description of the model, emphasizing its key processes and parameters. The overall structure is illustrated in Figure 1.1. The key variables and parameters are listed in Table 1.B.1. Additional information is provided in Supplementary materials 1.B.

Figure 1.1 – Schema model Res-IRF 4.0



2.1 Overview

The model simulates energy demand for space heating among French households. 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. Efficiency improvements result from the penetration of new vintages into the dwelling stock and the renovation of older vintages.

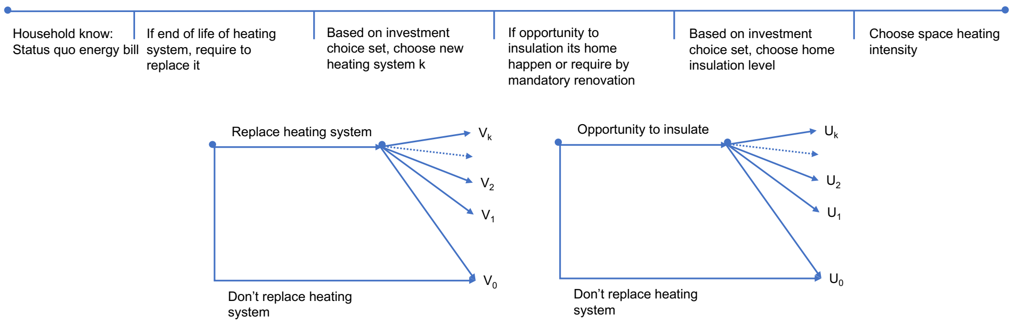
Stock turnover The construction of new dwellings is determined by an exogenous housing demand to fulfill, net of some exogenous dwelling decommissioning, assumed to fall in priority on the worst-performing dwellings. The performance of new vintages is then set to comply with the latest Building Code, 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. Six primary heating systems are considered – electrical heating, heat pump, fuel oil boiler, natural gas boiler, wood furnace and district heating. Secondary heating systems additionally feature in reduced forms, as detailed in Appendix 1.A.2. 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.[1] The resulting theoretical energy use is computed using the EN ISO 13790 methodology, as detailed in Appendix 1.A.2.

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. Moreover, 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 and Galvin, 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).

[1] These explicit technology specifications are a major improvement compared to the previous version of the model (Giraudet et al., 2021), which conflated all dwelling characteristics into an EPC rating. This improvement is instrumental in finely specifying policy instruments.

Figure 1.2 – Schema of structural model 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, which we refer to as 'segments' (see Table 2.1). These characteristics are specified using a unique dataset provided by French authorities (MTE, 2020b), discussed in greater length in Appendix 1.B.1.

Table 1.1 – Model dimension. Total number of dwelling-households pair is approximately 180,000. Thermal insulation is represented by the thermal transmittance (W/(m^2.K)).

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

2.2 Decision framework

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. Building on standard assumptions (e.g., Allcott and Greenstone (2024); Chan and Globus-Harris (2023)),[2] we assume utility to be quasi-linear. The constrained optimization program is:

$$\max_{x,m} \quad u(x,m) = x + h(m) \tag{1.1}$$
$$s.t. \quad \omega = x + p\eta \cdot m \tag{1.2}$$

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 (CRRA) function:

$$h(m_i) = A \cdot \frac{m_i^{1-\zeta_i}}{1-\zeta} \tag{1.3}$$

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 and Greenstone, 2024). The first-order conditions imply $u_m = p\eta_i$ and $x_i = \omega_i - p\eta_i \cdot m_i$, leading to:

$$m_i^* = \left(\frac{A}{p\eta_i \cdot \theta}\right)^{1/\zeta_i}. \tag{1.4}$$

where θ is the marginal value of the money described bellow.

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 1.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

[2] This assumption is reasonable when the good considered has a small budget share. Moreover, it allows one to express utility in monetary terms, which facilitates cost-benefit analysis.

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, contributing about one third of the energy performance gap.

Anticipating this adjustment,[3] 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:

$$X_{i,k} = V_{i,k} - K + \epsilon_{i,k}. \tag{1.5}$$

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. We set the interest rate to 3.9% and the rate of return on equity to 2.5% (Dolques et al., 2022; ADEME, 2018). The former provides an upper bound of financing costs and the latter a lower bound.

Non-energy 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 may absorb inconvenience, or unexpected money inheritance, which lowers capital costs.

Including such non-energy costs are crucial for modelling investment decisions. Non-energy benefits, as shown by Wekhof and Houde (2023), partially explain why households undertake energy renovations. Conversely, these non-energy costs also account for why households delay energy-saving investments until necessary renovations are needed, driving the low price elasticity of demand for energy renovations (Wekhof and Houde, 2023). This is consistent with estimates that energy renovation rates are ultimately constrained by building renovation cycles Aldenhoff and Kurzrock (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

[3] One could argue against this assumption. Indeed, Allcott and Greenstone (2024) find that households tend to make their decisions based on engineering forecasts, which typically overestimate energy saving. However, the evaluated program requires an energy audit, which is not the case for all programs in France. Perfect anticipation happens to be an effective heuristic, for the monetary value of taken-back savings provides a good proxy of the comfort gains implied by the rebound effect.

θ as a scaling factor so $\epsilon_{i,k}/\theta$ follows a standard type I extreme value law (Gumble law) of standard deviation $\pi^2/6$:

$$X_{i,k} = V_{i,k} - p_k \cdot (1 + r_{i,k}) + (\delta_{i,k} + \tilde{\epsilon_{i,k}})/\theta \tag{1.6}$$

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.[4] Given the extreme value error assumption, the probability $P_{i,k}$ of choosing investment option k is the standard logit choice probability (Train, 2009):

$$\tilde{X_{i,k}} = \theta \cdot (V_{i,k} - p_k \cdot (1 + r_{i,k})) + \delta_{i,k} \tag{1.7}$$

$$P_{i,k} = P(X_{i,k} > X_{i,j} \forall j, k) = \frac{\exp \tilde{X_{i,k}}}{\sum_j \exp \tilde{X_{i,k}}} \tag{1.8}$$

Estimating parameters δ_k and θ is inherently challenging. For one thing, the full choice set is rarely observed.[5] Notwithstanding this difficulty, estimates are typically obtained in specific programs, thereby lacking external validity (Allcott and Greenstone, 2024). To circumvent these problems, we compute unobserved 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 1.A.4.

Normalizing the value of not investing to zero, we obtain a mean unobserved value of insulation of €67,132 in private housing and €82,338 in social housing. It simply reflects the strong inertia associated with home energy retrofit, which only 3% of households undertake every year. As expected, the values are almost systematically positive to marginal investors. Overall, mean values 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.[6]

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 and Stavins, 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 and

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

[5] Allcott and Greenstone (2024) circumvent this difficulty by using energy audits, but this piece of information is not available to us.

[6] Unobserved values are more difficult to interpret regarding heating system, for there is no default option.

Palmer, 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.[7] Summarized in Table 1.2, the seven frictions modify the constrained optimization program as follows:

$$\max_k \tilde{X_{i,k}} = \theta \cdot (\lambda_i \cdot V_{i,k} - p_k \cdot (1 + r_{i,k}) + \delta_{i,k} + \epsilon_{i,k} + \phi_i^{\text{rental}} + \phi_i^{\text{MFH}}) \tag{1.9}$$

$$s.t : \alpha_{k,i} \cdot p_k \cdot (1 + r_{i,k})/\text{duration} < b \tag{1.10}$$

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.

Table 1.2 – Summary of the market and behavioral frictions contained in the model.

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 and Rochaix (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 penalty for switching fuel	Stolyarova (2016)	No penalty

Carbon dioxide externality. Energy use and, to a lesser extent, construction works generate CO_2 emissions that contribute to climate change. The associated social cost ζ has been estimated to be €150/tCO_2 in 2024, €250/tCO_2 in 2030 and €775/tCO2 in

[7] Another 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 nor examine instruments meant to eliminate them.

2050 in France (Quinet, 2019b). The externality associated with energy use is partially internalized through the EU-ETS price – fluctuating between €60 and €100/tCO_2 in the past two years, presumably passed-through onto wholesale fuel prices – and an additional €45/tCO_2 carbon tax applied to retail natural gas and fuel oil prices. The externality associated with construction works is not internalized at all.

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).

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 and Ryan, 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.[8] 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 whose annual social cost c_{health} has been assessed to be €7,500 (Dervaux and Rochaix, 2022). Detailed in Appendix 1.B.4, this estimate includes care costs, morbidity costs and mortality costs. While one might interpret it as an internality,[9] the prevalence of the problem among low-income points to financial constraints as a strong determinant. We therefore interpet it here as an uninternalized externality. Note that it can be seen as the recipient of other market

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

[9] Supporting 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 and Marmolejo-Duarte, 2024).

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 inertia parameter corresponding to a bias of €8,600 (Stolyarova, 2016).

2.4 Cost-benefit analysis

Our microfounded framework allows us to perform comprehensive cost-benefit analysis of energy efficiency programs. (Galvin, 2024).

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 non-energy benefits, environmental and health outcomes, and the opportunity cost of public funds. The social welfare function reads:

$$W = \sum_{i=1}^{N} \alpha_i \cdot [P_{i,k} \cdot (\underbrace{-c_k}_{\text{investment cost}} + \underbrace{E[\epsilon_{i,k} | k = \text{argmax}_j V_{i,j}]}_{\text{non-energy value}}) \tag{1.11}$$

$$+ \gamma \cdot (- \underbrace{\eta_i p \cdot m_i^*}_{\text{energy expenditure}} + \underbrace{h(m_i^*)/\theta}_{\text{thermal comfort}}]) \tag{1.12}$$

$$- \underbrace{\gamma \cdot \zeta \cdot Q}_{\text{environmental externalities}} - \underbrace{\gamma \cdot c_{\text{health}}}_{\text{health externalities}} + c_{\text{public money}} \tag{1.13}$$

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:[10]

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

$$\Delta W = \frac{\sum_{t=1}^{T} W_t(s) - W_t(s^{\text{ref}})}{(1+\gamma)^t} \tag{1.14}$$

$$\tag{1.15}$$

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

Non-energy 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).[11] For option k to household i, we compute it as the expected value of the error term, conditional on investment being made, $E[\delta_{i,k} + \overline{\tilde{\epsilon_{i,k}}} | V_{i,k} > V_{i,j}, \forall j \neq k]$.

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:

$$G = \sum_{i=1}^{N} \alpha_i \cdot P_{i,k} \cdot (s_k - \tau_k \cdot p_k) - \tau \cdot Q. \tag{1.16}$$

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:

$$c_{\text{public money}} = \mu \cdot G. \tag{1.17}$$

2.5 Model validation

Long-term sensitivity 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).

[11] Unobserved values could theoretically results from bias that overestimate the decision utility. Homeowners would make unprofitable investment because they overestimate the benefits of energy renovation when making the investment decision. We reject this assumption here and assert that homeowners tend to underestimate future benefits due to behavioral anomalies. In addition, we detail above many factors that were not included in the utility function which could explain the importance of unobserved value in energy renovation decision.

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 – the reduced VAT rate, MPR phases I, II and III and the White certificate obligation. Policy specifications are detailed in Appendix 1.E.1. Some of these instruments are discussed in greater length in Section 4.

The results displayed in Figure 1.3 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 reproduce. 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.[12] 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.

In addition, we compare simulated policy effects on both the extensive and intensive margins of insulation investments to empirical estimates when available (see Figure 1.E.5. We find a proportion of infra-marginal participants in MPR Phase I of 78% in 2018, similar to the 80% estimated by Nauleau (2014); 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.

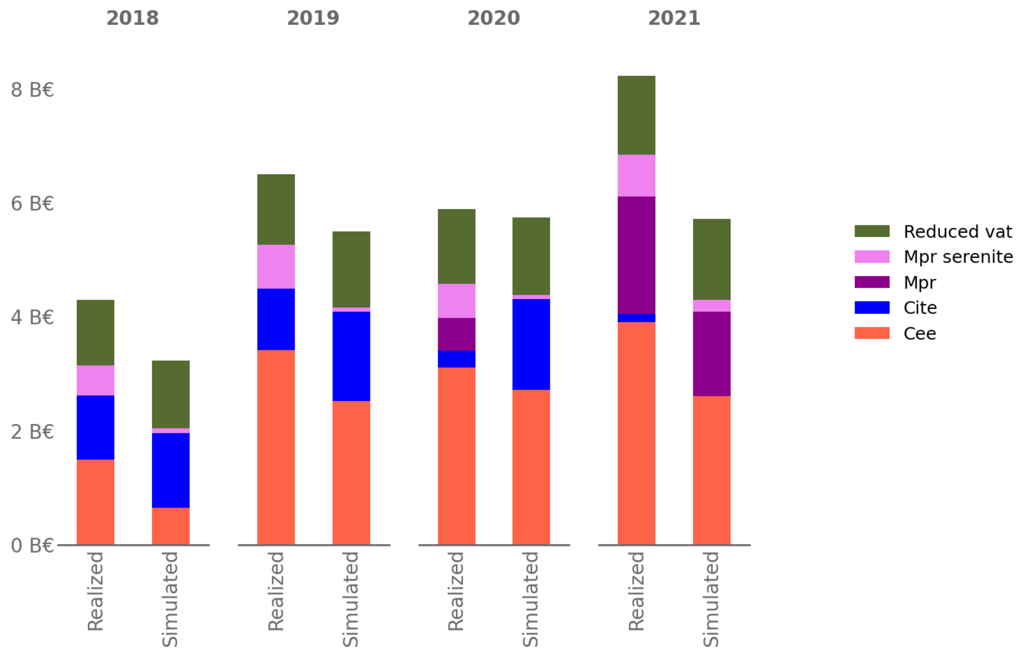
Overall, these results give confidence in the ability of the model to accurately simulate policy impacts.

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. Specifically, we want to assess the individual and joint contribution of each market and behavioral friction to suboptimal outcomes along three dimensions – energy use, CO_2 emissions and social welfare. Note that the former is

[12] One exception is MPR Phase II. This program awards subsidies for deep renovations, which combine insulation and heat pump adoption. Since we treat heat pump and insulation decisions sequentially, however, we ignore heat pump subsidies here, which understates the cost of MPR Phase II.

Figure 1.3 – Comparison of simulated ('Simulated') and actual evolution ('Realized') of public expenditure in France between 2018 and 2021.



only a proxy of the energy efficiency metric that featured in Jaffe and Stavins (1994b)'s original framework – arguably a more modern proxy, considering that CO_2 emissions reductions have become the central objective of energy efficiency policies.[13]

3.1 Method

We focus on the seven frictions reported in Table 1.2, excluding subsidy salience, which we only consider in policy assessment. To assess the joint contribution of the seven frictions, 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.

All simulations rely on the same exogenous inputs, including:

- Energy price annual growth rates 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

[13] As told by Giraudet and Missemer (2023), Jaffe and Stavins (1994b)'s framework first emerged amidst energy security concerns, before being revisited through the lens of climate change in the 2000s.

- The carbon content of electricity falls from 0.079 gCO_2/kWh to 0 gCO_2/kWh by 2050, that of district heating from 0.101 gCO_2/kWh to 0.033 gCO_2/kWh. 14 TWh of gas consumption for space heating is covered by renewable gas.

3.2 Contribution of individual frictions

Figure 1.4 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 non-energy benefits. One preliminary observation is that each friction affects all welfare components, which suggests that interactions between frictions are significant.

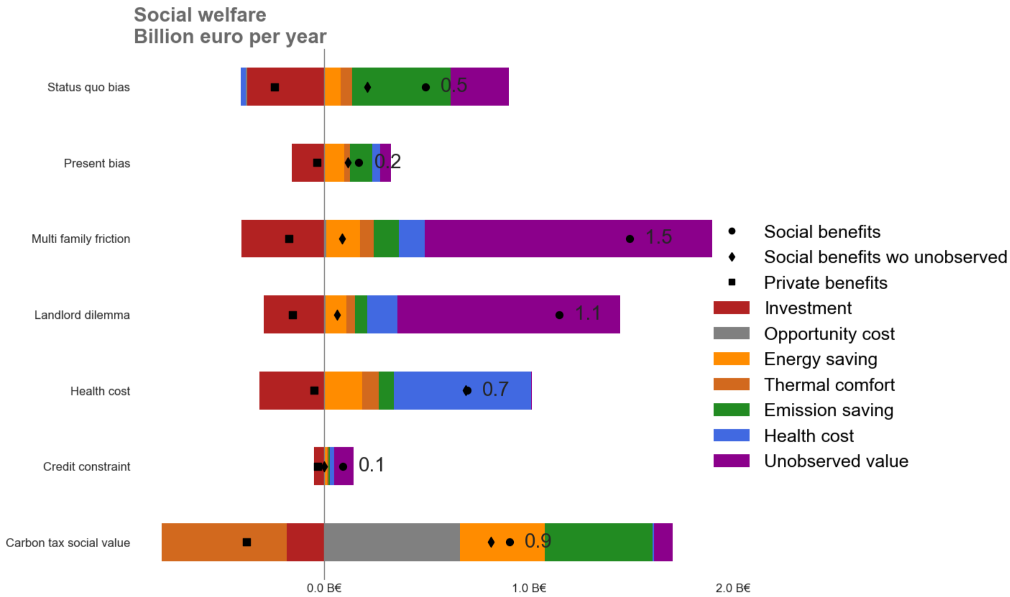
The figure displays the net cost-benefit balance along three perspectives – private (where only investment cost, bill savings, improved comfort and non-energy value are considered), social (where all costs and benefits are considered) and social without non-energy benefits. The private value is negative 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 CO_2 externality. The ranking changes dramatically when non-energy benefits are ignored, making the CO_2 and health externalities the two most critical problems. This highlights the crucial role played by hard constraints in rental and multi-family housing, which deny occupants significant benefits. The CO_2 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 1.5 plots social welfare against cumulative energy savings so as to produce the so-called Jaffe-Stavins diagram (Jaffe and Stavins, 1994b). 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. Figure 1.6, we produce the same diagram in the welfare-CO_2 space.

3.3 Interactions

The vast area covered by interactions in Figure 1.5 motivates closer examination. We proceed in two steps. First, we examine one-to-one interactions in Figure 1.7. We find that most interactions are mild and almost systematic and that interactions tend to be under-additive, with notable exceptions. Credit constraints exhibit an over-additive effect, especially when combined with health cost externalities or present bias—two market failures that disproportionately impact low-income households. This highlights the multiple frictions affecting investment decisions for low-income households and underscores the need for comprehensive policy mixes to address these issues holistically. Second, we plot all interactions in Supplementary Figure 1.C.1. This picture confirms that interactions

Figure 1.4 – 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 non-energy value. The square marker represents private benefits, simply balancing investment costs and bill savings plus comfort gains.



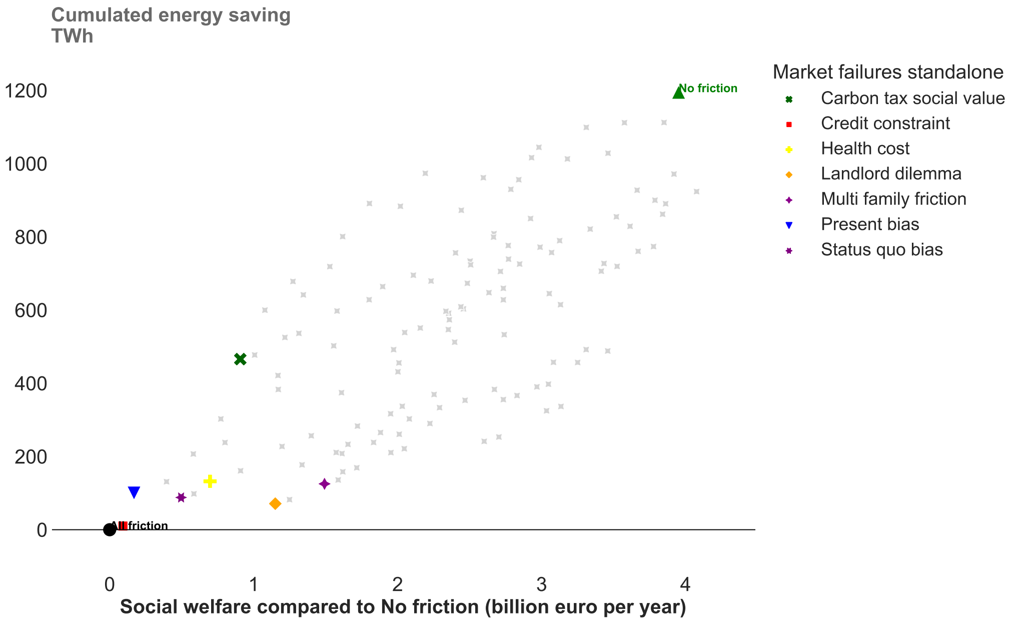
tend to be under-additive, with two notable exceptions – credit constraints, which are over-additive, and present bais, which is neutral.

Supplementary Figures 1.C.2, 1.C.4 and 1.C.3 display Sobol indices, which measure the total influence of a certain variable 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 1.5 in terms of both social welfare and emissions reductions. The small wedge between first-order and total-order metrics confirm that interactions are mild.

3.4 Stylized policy solutions

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 CO_2 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 and Palmer, 2014), but energy efficiency subsidies are known to provide an effective nudge against investment inertia (Allcott et al., 2014).

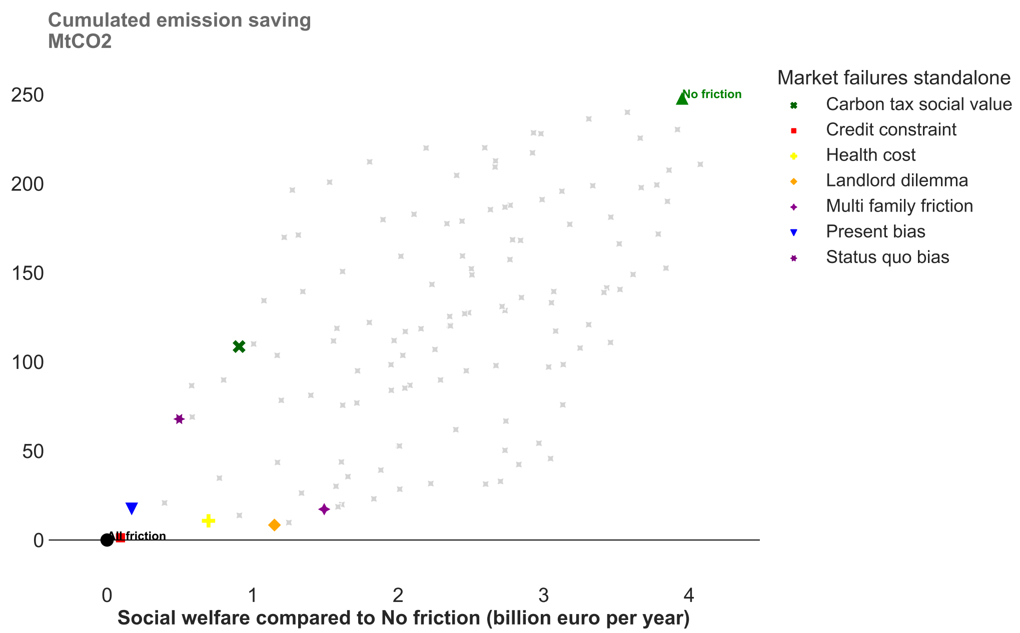
Figure 1.5 – Mapping of the Energy Efficiency Gap. Each dot represents a combination of frictions. Special markers in the legend refer to the standalone effect of remonving each friction, as shown in Figure 1.4.



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 and Fabre, 2022). Meanwhile, energy efficiency subsidies have long been the preferred approach, since as early as 1999 with the reduced value-added tax (see Appendix 1.E.1). 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 and Parry, 2008; Giraudet and Quirion, 2008; Chan and Globus-Harris, 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 CO_2 externality, the health externality, the landlord-tenant dilemma and multi-family frictions. Figure 1.8 exhibits patterns relatively similar to those of Figure 1.4 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 1.D.1 and 1.D.1 also confirm the under-additivity of policy solutions and simply results from the marginally decreasing returns from renovation. This emphasizes the impact overstatement that may result from failing to take into account subsidy interactions (Gillingham et al., 2018).

Figure 1.6 – Mapping Emission Efficiency Gap. Each dot represents a combination of frictions. Special markers in the legend refer to the standalone effect of remonving each friction, as shown in Figure 1.4.



Supplementary Figure 1.D.3 displays the Sobol indices. It shows that subsidies have a comparable effect in welfare terms. However, interactions are now strongly over-additive.

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. (2021); 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 1.3.

Carbon tax Carbon pricing is the textbook solution to the CO_2 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

Figure 1.7 – Marginal impact of market failures on welfare in interaction with another market failure.

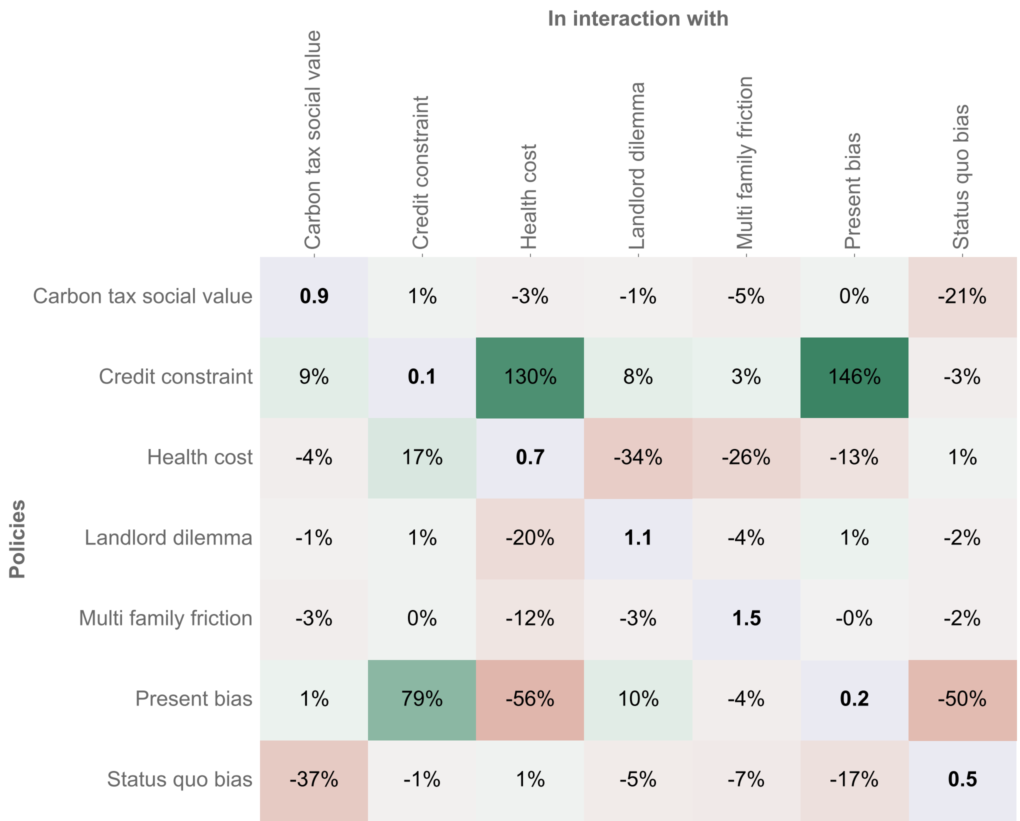


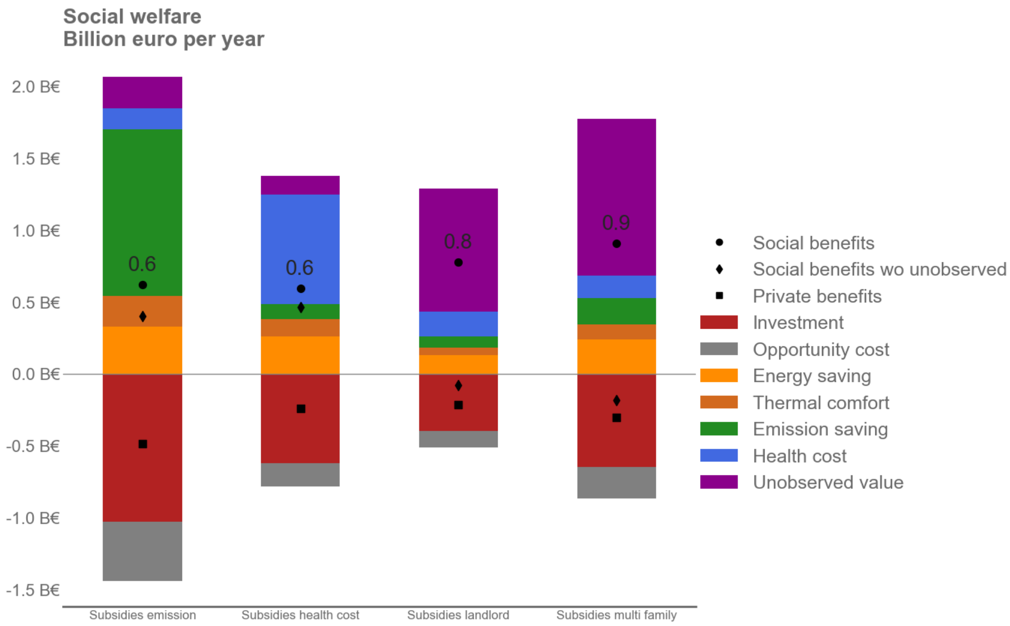
Table 1.3 – Policies considered

Policy	Instrument type	Justification	References
MPR subsidies	Incentive: energy efficiency subsidy (per-unit, targeted)	Externalities and public good; credit rationing; present bias	Nauleau (2014); 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); Douenne (2020)
White certificates	Hybrid energy efficiency subsidy/energy tax (targeted)	Externalities and public goods; credit rationing	Giraudet and Quirion (2008); **?**
Rental ban on inefficient housing	Regulation	Externalities	Vivier and Giraudet (2021)
Ban on new gas boilers	Regulation	Externalities	Escribe and Vivier (2024)

former channel.[14] This advantage however comes with unintended effects when other

[14]The 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 and Parry, 2008). The residential carbon tax activates the latter two.

Figure 1.8 – 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.



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).[15] In addition, earmarking revenue to low-carbon technologies make carbon pricing more acceptable (Douenne and Fabre, 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/tCO_2 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,

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

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/tCO_2 and gradually increasing to €85/tCO_2 in 2040 and €160/tCO_2 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 CO_2 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 and Globus-Harris, 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 and Davis, 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 1.E.1 and Table 1.E.1. Its earlier version was found to effectively stimulate investment on both the extensive and intensive margins (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 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 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 and Quirion, 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 unobserved non-energy 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 X 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 1.E.

Individual impacts Figure 1.9 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 unobserved value and 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 unobserved 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 non-energy 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 non-energy 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. It also emphasizes the need to factor in unobserved value in social welfare (Wekhof and Houde, 2023; Allcott and Greenstone, 2024).

Looking more specifically at each instrument, the carbon tax has a negligible effect on non-energy value. This is due to is 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 unobserved costs, they have very contrasted impacts on CO_2 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 1.4 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 the reduce CO_2 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).

Figure 1.9 – Impact on welfare of individual policies implemented in France compared to the 'No Policy' scenario, with costs and benefits discounted at a social rate of 3.2%.

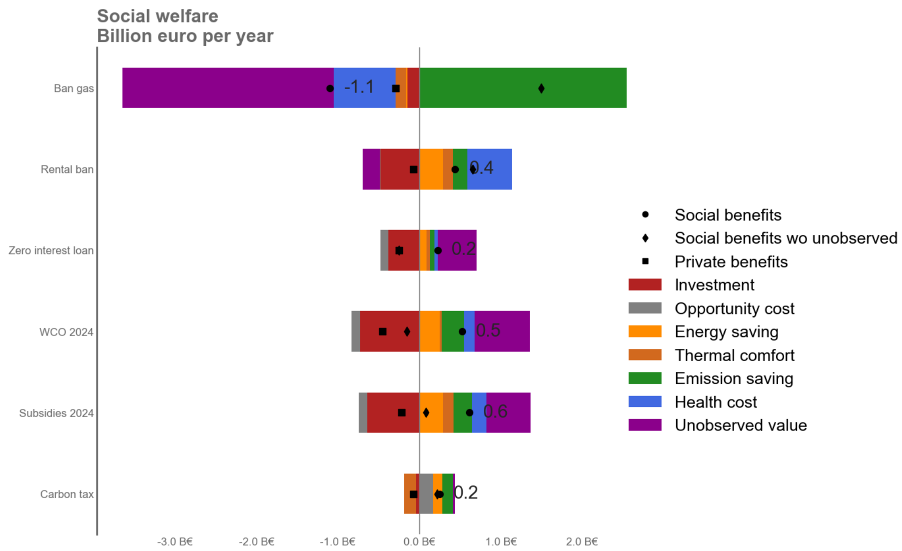


Table 1.4 – Cost-benefit and cost-effectiveness assessment of standalone policies.

	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

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 and Greenstone, 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;[16]
- **No friction, biased:** All frictions have been removed but households make decisions based on predicted energy savings.

Table 1.5 compares the welfare impact of policies across perspectives. In the most conservative 'No friction, biased' case, where no friction other than the CO_2 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 and Greenstone (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.

[16]Specifically, the ϕs 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 ($b = 0$).

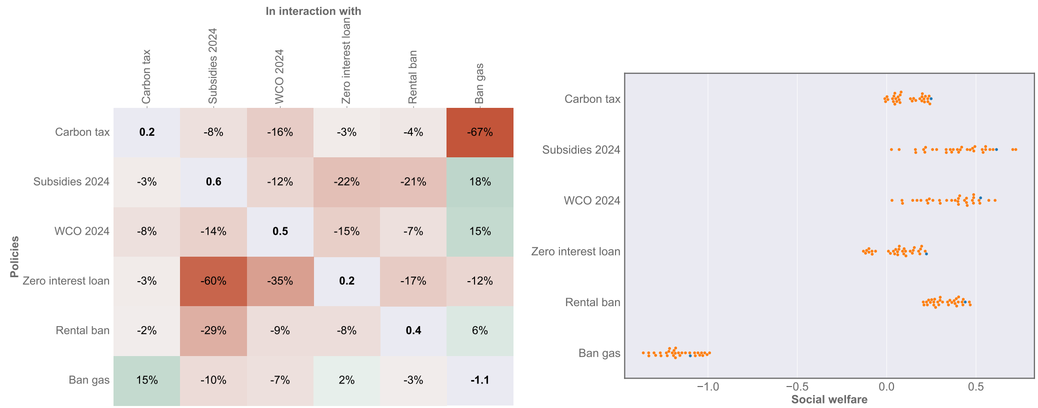
Table 1.5 – Cost-benefit impact of French policies (Billion €per year) under alternative perspectives. 'Biased' refers to households making their decision based on overstated engineering predictions. *Results were calculated using a previous version of the model, but this does not affect the merit order.*

	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

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 1.10a) and all-order interactions from the 64 possible policy combinations (Figure 1.10b). 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 1.10 – Net benefit-cost balance under various interactions.



(a) Assessment of individual policies implemented in France in interaction with other policies. Bold values corresponds to standalone assessment as described in Figure 1.9.

(b) Marginal welfare impact of individual policies in interaction with all possible combination of policies implemented in France. The orange dot refers to the standalone effect as described in Figure 1.10a.

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:** The baseline package includes the policies currently in place, namely MPR subsidies, ZIL, WCO, the carbon tax and the ban on rental housing;
- **Baseline Package + Gas Ban:** This package additionally includes the ban on new gas boilers considered at the European level for implementation in 2030;
- **SCC benchmark:** Here, the only instrument in place is a carbon tax set to the SCC (€150/tCO_2 in 2024, €250/tCO_2 in 2030 and €775/tCO_2 in 2050), the proceeds of whic are returned to households in a lump-sum manner (see Appendix 1.B.5). This package allows us the appraise how the supposedly first-best instrument – at least regarding the CO_2 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.'

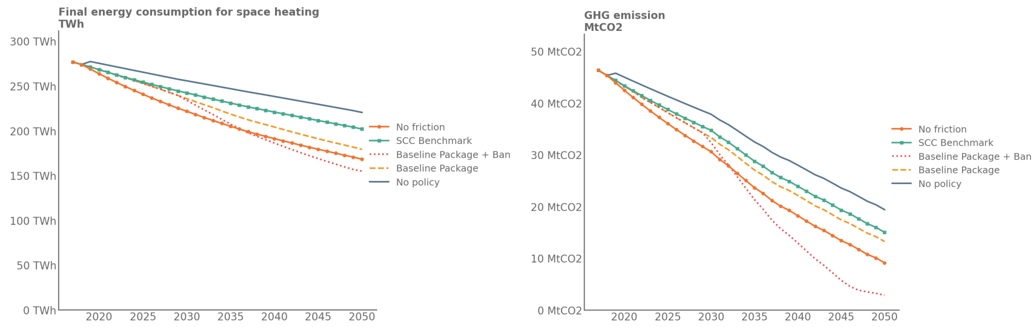
5.2 Environmental effectiveness

Figures 1.11a and 1.11b display pathways of energy consumption for space heating and the associated CO_2 emissions. Absent policies, energy use falls by 20% and CO_2 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 CO_2 emissions by 22 p.p. With 31 MtCO_2 in 2030, this scenario misses the 26 MtCO_2 mark corresponding to the 'Fit for 55' European target. With 10 MtCO_2 in 2050, it is not consistent with the carbon neutrality target either, estimated to involve 3 MtCO_2 from space heating by 2050 (ADEME, 2022). This 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 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 CO_2 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 CO_2 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 1.12 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

Figure 1.11 – Evolution of (a) final energy consumption for space heating and (b) the associated GHG emissions in Scope 2 in France.



(a) (b)

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 faction of labels A and B 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 1.13 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. 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, many low-income households, due to credit rationing, and non-insulated dwellings, due to technical infeasibility, continue using their direct electric systems, thus bearing high operating costs. Despite a general shift towards heat pumps, the overall increase in electricity consumption remains modest under all scenarios, with an increase of 20 TWh at most, only representing 4% of electricity consumption in 2024 (see Figure 1.F.2 in Appendix).

5.3 Social welfare

Figure 1.14 displays benefit-cost balances for the different scenarios, assessed against the 'No policy' counterfactual. Further details are provided in Appendix 1.F. 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 the non-energy costs discussed above.

5.4 Distributional impacts

Figure 1.15 displays variations in total household cost across several dimensions – income categories on the x-axis, capturing vertical inequalities, and housing type and occupancy

Figure 1.12 – Evolution of the energy performance of the housing stock, by EPC rating (G: least efficient; A: most efficient).

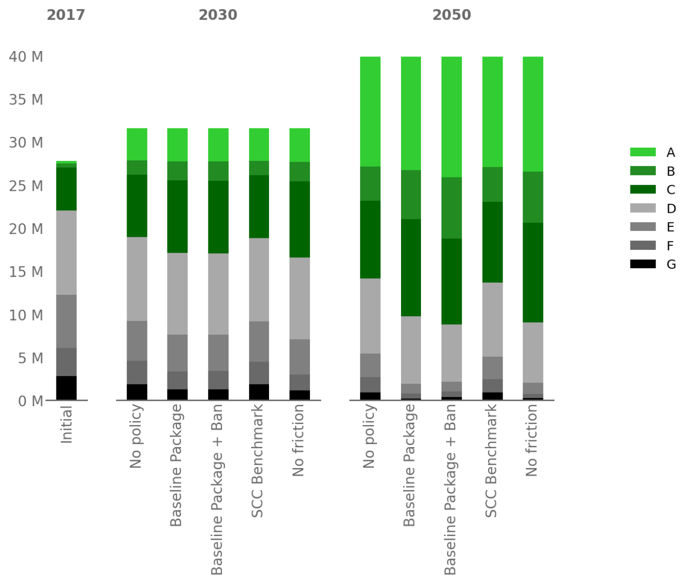
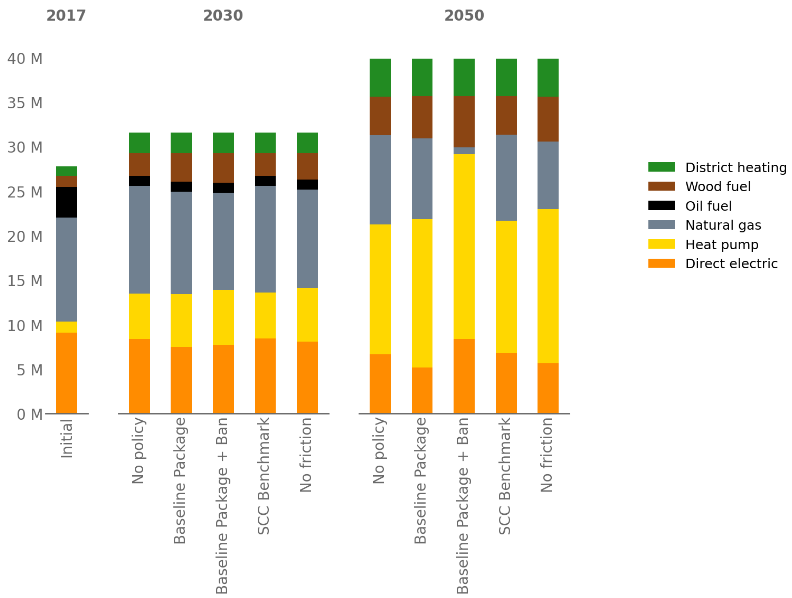
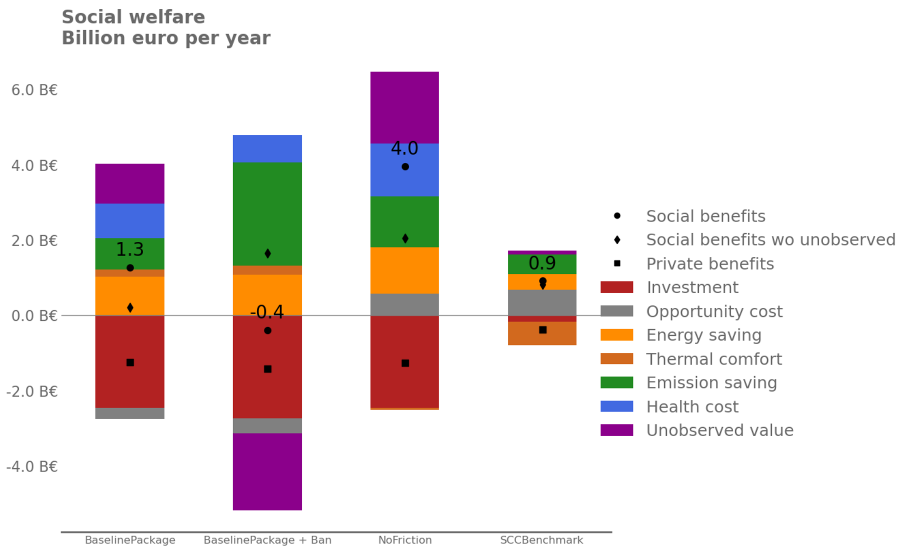


Figure 1.13 – Evolution of heating systems prevalence.



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 1.15a and as a fraction of income in panel 1.15b.

Figure 1.14 – Welfare effects compared to the 'No Policy' scenario. Benefits are accumulated over 20 years. Costs and benefits are discounted at 3.2% per year.



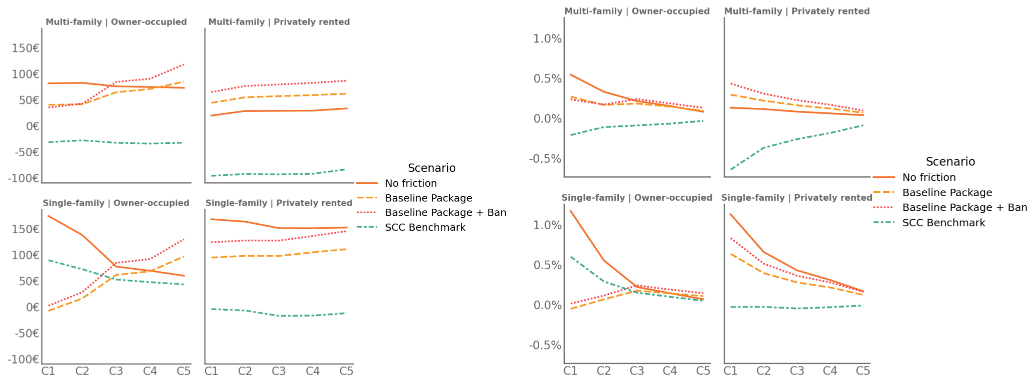
The 'No friction' benchmark involves higher total cost, primarily falling on low-income households living in larger home (owner-occupied). This illustrates inequalities inherent in energy consumption, which weighs disproportionately heavy on low-income households' expenditure. The only exception in is 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 policy solution introduced earlier).

5.5 First-best versus actual policy

We finally map the different packages within the Jaffe-Stavins diagram to visualize the implementation gap and compare actual and stylized policy solutions. Figure 1.16 and Table 1.6 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.

To further investigate subsidy designs, we follow Allcott and Greenstone (2024)'s approach and plot subsidy amounts against the frictions they are meant to address. Figure 1.18 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 1.18b). The residual misalignment can be attributed to uncorrected behavioral biases.

Figure 1.15 – Evolution of total spending in 2050 compared to the 'No policy' counterfactual, (a) in absolute terms and (b) as a fraction of income.



(a) (b)

Figure 1.16 – Implementation gap

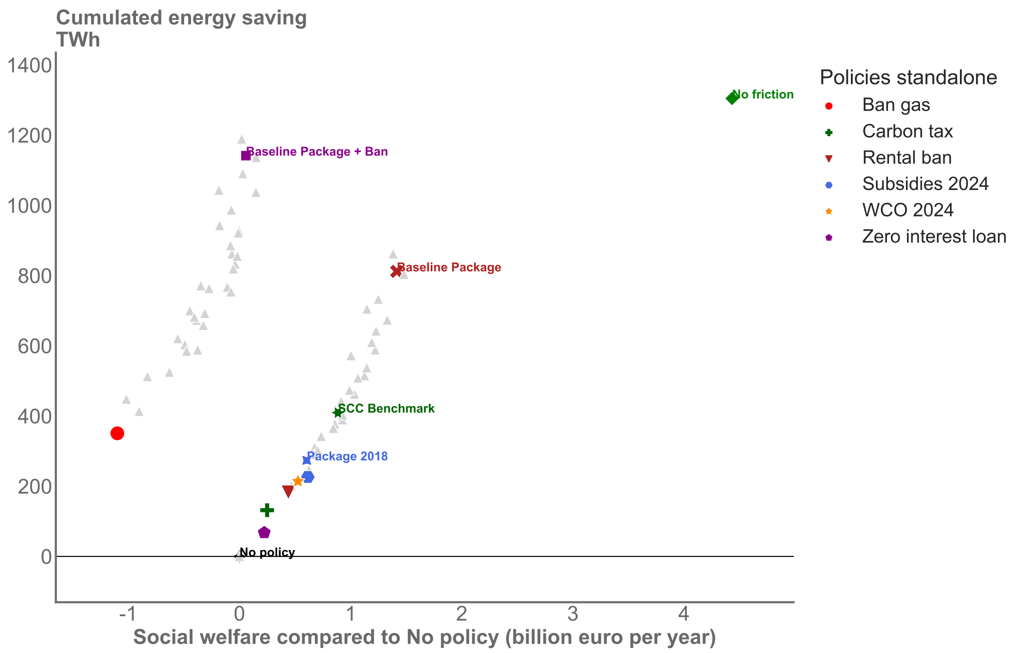


Figure 1.17 – Implementation gap

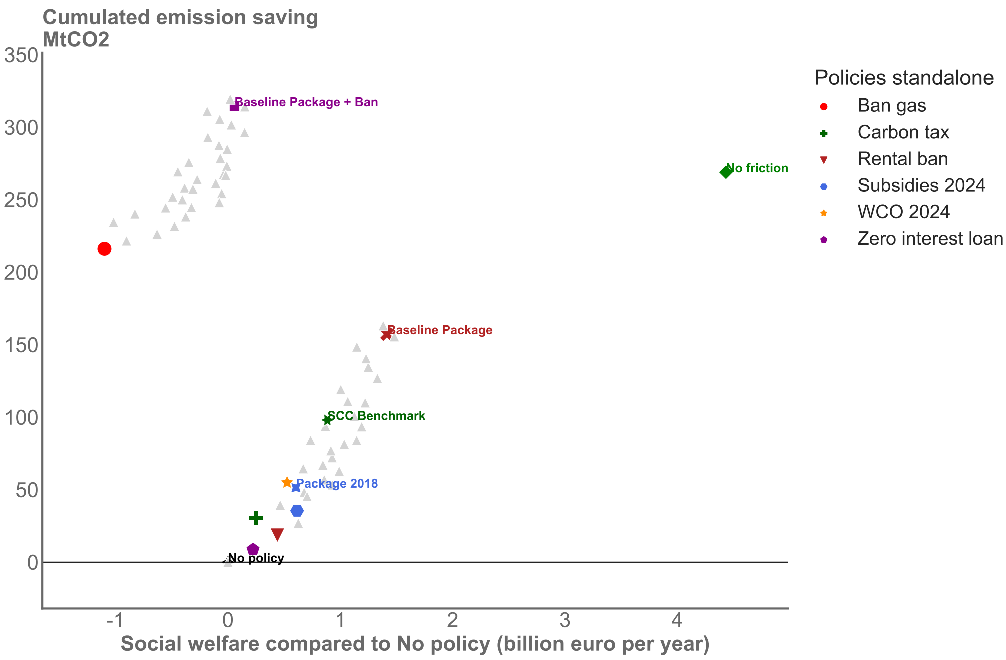
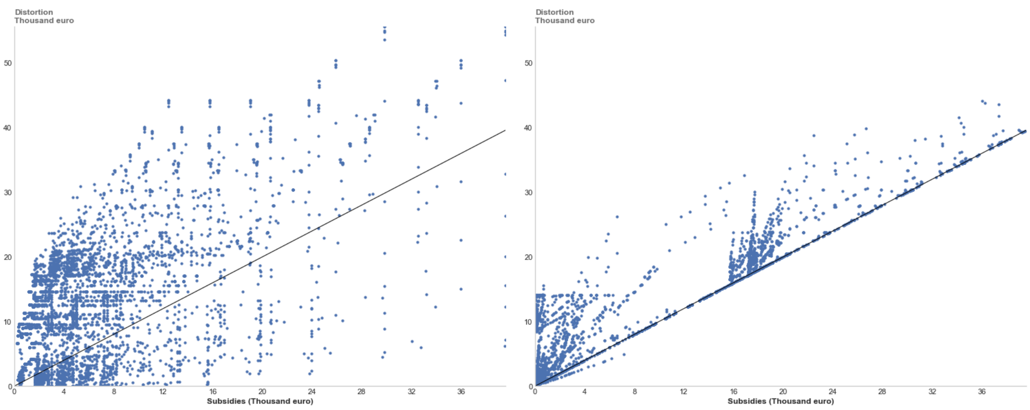


Table 1.6 – Detailed assessment of the implementation gap.

	No friction	Stylized policies	Actual policies
Cumulated Consumption (TWh)	7297.60	7696.16	7675.35
Cumulated Emission (MtCO2)	898.01	920.92	994.95
Consumption (TWh) 2050	168.19	182.80	179.16
Emission (MtCO2) 2050	9.12	9.14	13.23
Δ cumulated energy (TWh)	7297.60	7696.16	7675.35
Δ cumulated emission (MtCO2)	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/tCO2)	761.90	788.77	1380.89

Figure 1.18 – 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.



(a) Package 2024 **(b)** Second-best subsidy mix

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 and Greenstone (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 more positive assessment is also more basically due to parametric assumptions, including a higher social cost of carbon – growing from €150/tCO_2 in 2024 to €775/tCO_2 in 2050, against a €38/tCO_2 flat rate in Fowlie et al. (2018) and €172/tCO_2 in Allcott and Greenstone (2024) – and a longer time horizon – 20 years against 16 years in Fowlie et al. (2018) and similar to assumption retained by Allcott and Greenstone (2024).

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 non-energy 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 and Vivier (2024) 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 and Greenstone, 2024; Chan and Globus-Harris, 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 and Legendre, 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., 2024). 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. 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 – housing, 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 and Greenstone, 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.

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 CO_2 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 and Stavins (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 unobserved 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); 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 hating – about two thirds along the energy savings dimension and one-third on the welfare dimension. The welfare gap is however commensurate with current spending on subsidies. The current budget is therefore adequate, but subsidy schedules should be adjusted to make it more 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., 2024) and its robustness to uncertainty regarding low-carbon energy supply (Escribe and Vivier, 2024). 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.10405491 or on GitHub: https://github.com/CIRED/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**: Conceptualization, Funding acquisition, Writing - review & editing

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Appendix

1.A Supplementary Method

Price elasticity of energy consumption

$$e = \eta \left(\frac{A}{p\eta}\right)^{1/\zeta} = A^{1/\zeta}\eta^{1-1/\zeta}p^{-1/\zeta} \tag{1.18}$$

$$\frac{de}{dp} = -\frac{1}{\zeta}A^{1/\zeta}\eta^{1-1/\zeta}p^{-1/\zeta-1} \tag{1.19}$$

$$\epsilon = \frac{p}{e}\frac{de}{dp} = -\frac{1}{\zeta} \tag{1.20}$$

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:

$$m^* = \left(\frac{A}{p\eta}\right)^{1/\zeta} \tag{1.21}$$

$$x^* = \omega - p\eta \cdot m^* \tag{1.22}$$

$$v(p, \eta) = u(x^*, m^*) = \omega - p\eta \cdot m^* + h(m^*) \tag{1.23}$$

$$= \left(\omega - A^{1/\zeta}\eta^{1-1/\zeta}p^{1/\zeta}\right) + A\frac{\left(\frac{A}{p\eta}\right)^{\frac{1-\zeta}{\zeta}}}{1-\zeta} \tag{1.24}$$

$$= \omega + A\frac{\left(\frac{A}{p\eta}\right)^{\frac{1-\zeta}{\zeta}}}{1-\zeta} - A^{1/\zeta}\eta^{1-1/\zeta}p^{1/\zeta} \tag{1.25}$$

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.

$$V_{i,k} = v(p, \eta_k) - v(p, \eta_i) \tag{1.26}$$
$$V_{i,k} = \underbrace{p \cdot (e_i^* - e_k^*)}_{\text{bill saving}} + \underbrace{h(m_k^*) - h(m_i^*)}_{\text{thermal comfort}} \tag{1.27}$$

1.A.1 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:

$$\begin{aligned}
\text{Unobserved value}_{i,k} &= E[\delta_{i,k} + \overline{\epsilon_{i,k}} | V_{i,k} > V_{i,j}, \forall j \neq k] && (1.28)\\
&= E[\delta_{i,k} + \overline{\epsilon_{i,k}} | V_{i,k} = \max_j V_{i,j}] && (1.29)\\
&= \delta_{i,k} + E[\overline{\epsilon_{i,k}} | V_{i,k} = \max_j V_{i,j}] && (1.30)\\
&= \delta_{i,k} + \ln\big(\sum_j e^{v_{i,j}+\delta_{i,j}}\big) - (v_{i,k} + \delta_{i,k}) && (1.31)\\
&= \ln\big(\sum_j e^{v_{i,j}+\delta_{i,j}}\big) - v_{i,k} && (1.32)
\end{aligned}$$

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,[17] 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, $E[\hat{X}]$.

[17] which 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

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 $\hat{X}$.

Follwing 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:

$$\mathbb{E}[v_j + \epsilon_j | j = j^*] = \mathbb{E}[\hat{X}] = \ln\left(\sum_j e^{V_j}\right) + C \tag{1.33}$$

where C is an unknown constant the represent 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.

$$\mathbb{E}[\epsilon_j | j = j^*] = \ln\left(\sum_j e^{v_j}\right) - v_j \tag{1.34}$$

1.A.2 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 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:

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

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

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

cp_{air} is the volume-specific heat capacity of air in Wh/(m^2.K), $n_{air,use}$ is the average air change rate during the heating season, related to the utilization of the building in 1/h, $n_{air,inflitr}$ is the air change rate by infiltration in 1/h, A is the area of the building in m^2, 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).[18] The current version of our model does not consider energy usage for cooling purposes, while the estimation of water heating is based on default requirements and the heating system's efficiency. All parameters not directly observed have been obtained from the TABULA project documentation or default values derived from the 3CL method, and are meticulously outlined in the provided reference spreadsheet.

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

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.

1.A.3 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, $\hat{p_{i,t}}^{\text{k}}$ net of subsidies, $s_{i,t}^{\text{k}}$, 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.

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

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

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

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:

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

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

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

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 3.4 show the difference of average total cost for househol group I when the ban is implemented compared to the counterfactual scenario.

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

1.A.4 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); 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.

Table 1.A.1 – Parameter estimates used in investment decision utility function for heating system.

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

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.[19] 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 1.A.3.

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

Table 1.A.2 – Parameter estimates used in investment decision utility function for home insulation.

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 1.A.3 – Calibration results of reduced-form distortion to invest in home insulation. Values are expressed in euros.

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

1.B Supplementary Data

1.B.1 Overview

All data sources are comprehensively listed in Table 1.B.1, 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 1.B.1. 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

Table 1.A.4 – Calibration results of reduced-form distortion of specific home insulation measures

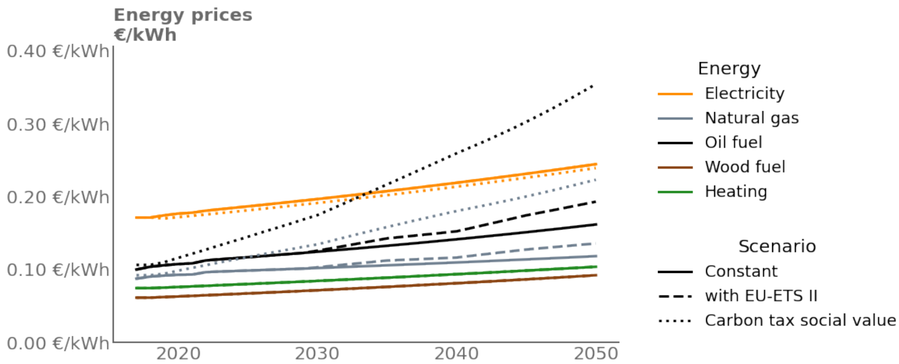
Insulation measure	Value
Wall, Floor, Roof	32,748
Floor, Roof	70,423
Wall, Floor	75,889
Wall, Roof	23,657
Wall	28,104
Roof	8,585
Floor	87,104
Wall, Floor, Roof, Windows	24,136
Floor, Roof, Windows	32,708
Wall, Floor, Windows	40,331
Wall, Roof, Windows	45,535
Wall, Windows	60,433
Roof, Windows	54,051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

Table 1.A.5 – Simulation result for base year.

Variable	Value
Stock (Million)	28.05
Surface (Million m2)	2393.48
Consumption (TWh)	273.90
Consumption (kWh/m2)	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 (MtCO2)	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 (MtCO2/year)	0.99

the Ukraine crisis, where price increases were withheld, underline this unpredictability. We have therefore decided to base our analysis on the latest officially available data and to carry out sensitivity analyzes on the fluctuations in fuel prices. The projections for the housing market, including demolition rates, construction of new buildings and their specifications (such as housing type, heating system and energy efficiency), are derived from the national reference scenario of ADEME (2022). We also use this scenario to configure the parameters of the energy system, including the share of renewable gas available for space heating of residential buildings and district heating connections. Our model assumes that the emission content of electricity decreases from 2030 and reaches 0 gCO_2/kWh by 2050. In our reference scenario, we use business-as-usual data and critically examine the impact of key variables through sensitivity analysis.

Figure 1.B.1 – Energy prices with taxes used in the reference scenario in Res-IRF 4.0. Source: DGEC.



Initial building stock

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

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

Table 1.B.1 – List of data sources used in Res-IRF. * means data are not publicly available.

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); 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	Enertech et al. (2022)
Capex heating system	RTE and ADEME (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 and Rochaix (2022)
Social value of carbon - Value of climate action	Quinet (2019b)
Social discount rate	Ni and Maurice (2021)
Thermal module data	Loga (2013); Arquin et al. (2020)

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.

1.B.2 Technical data

Table 1.B.2 – Cost analysis from Observatoire BBC field study (Enertech et al., 2022). The costs for the wall insulation correspond to exterior insulation. For the roof, the costs correspond to an average value for the insulation costs of converted attics, lost attics and crawl spaces. Costs are consistent with findings from ADEME (2020) and Enertech et al. (2022) studies. Model excludes ventilation costs, audit and accompanying expenses, and non-energy related renovation costs.

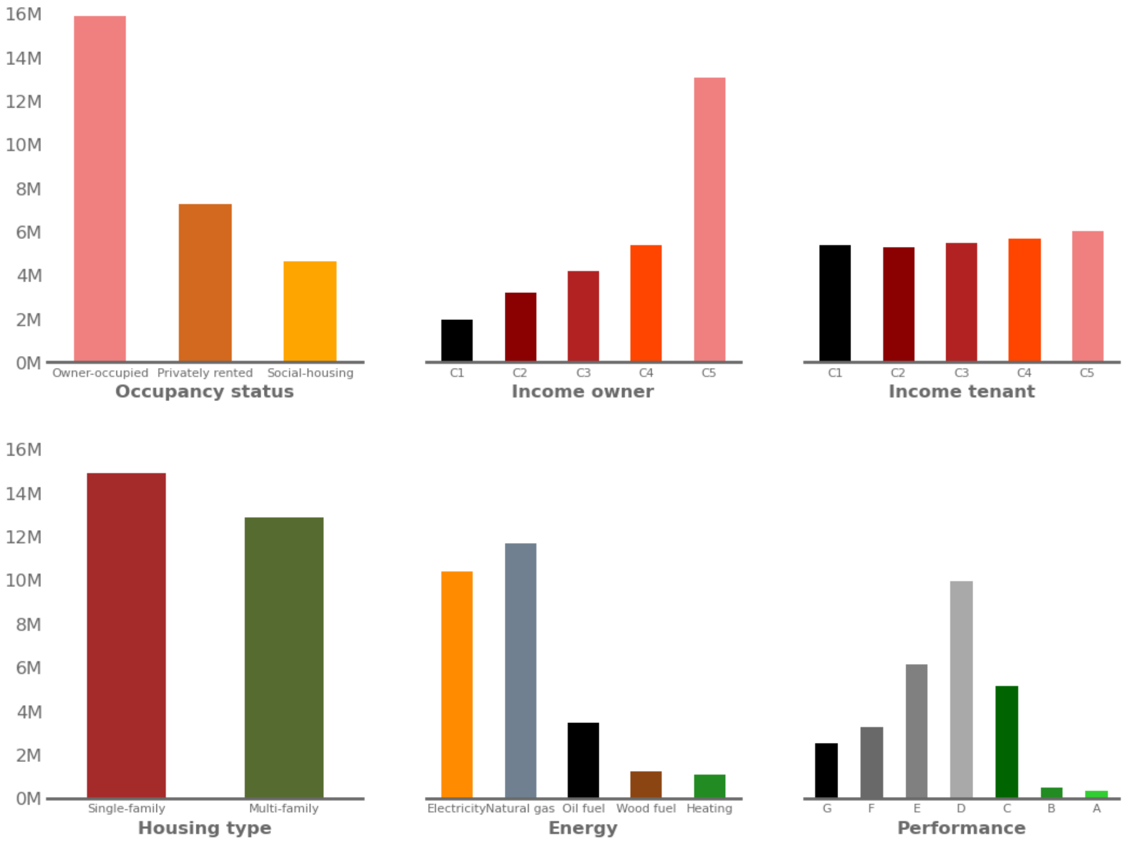
Insulation component	Cost (euro/m^2)	U-value (W/(m^2.K))
Wall	160	0.2
Floor	53	0.3
Roof	83	0.2
Windows	542	1.3

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 1.F.1.

Table 1.B.3 – Data derived from RTE and ADEME (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).

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

Figure 1.B.2 – 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.



1.B.3 Flow of renovation and heating-system installation

Table 1.B.4 – 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).

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

1.B.4 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

Table 1.B.5 – Share of insulation measures in total renovation in 2019 in France. 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%

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.

Table 1.B.6 – Share of buildings with health risk by energy performance certificate (Dervaux and Rochaix, 2022)

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

Table 1.B.7 – Probability of heath-risk and social cost by income class of the tenant(Dervaux and Rochaix, 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 1.B.8 – Carbon tax and social cost of carbon. In the 'Carbon tax' policy scenario, the carbon tax is levied on the social value of carbon (Quinet, 2019b)

	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

1.B.5 Carbon tax and social cost of carbon

1.B.6 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 MtCO2e by 2050 for all buildings, which corresponds to around 3 MtCO2e 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.

1.C Mapping the energy efficiency gap

Figure 1.C.1 – Marginal impact of market failures on welfare when interacting with all possible combinations of market failures.

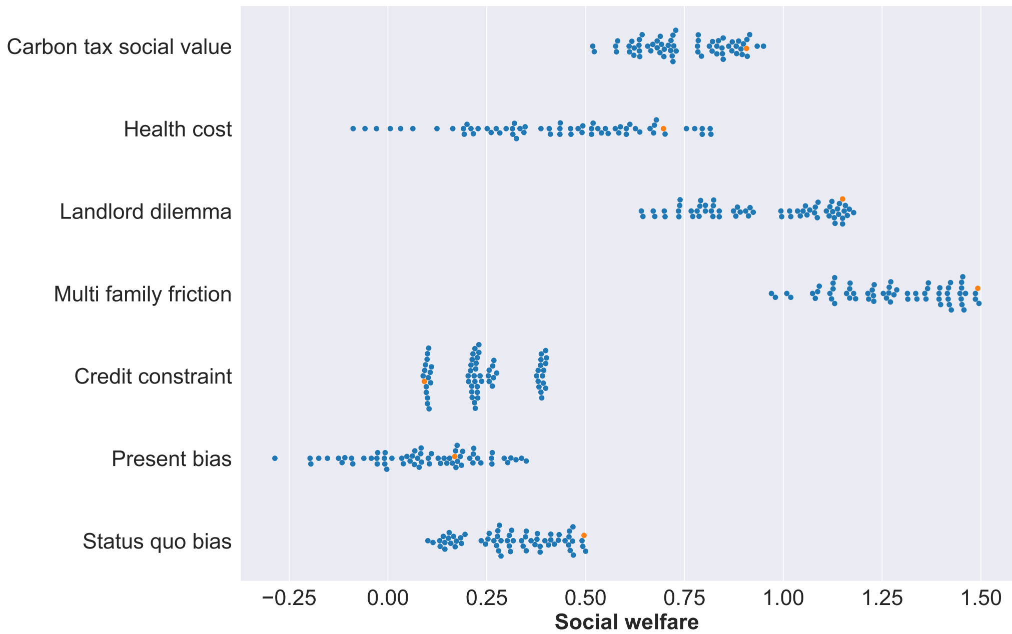


Figure 1.C.2 – Assessment of most influential market failures on social welfare.

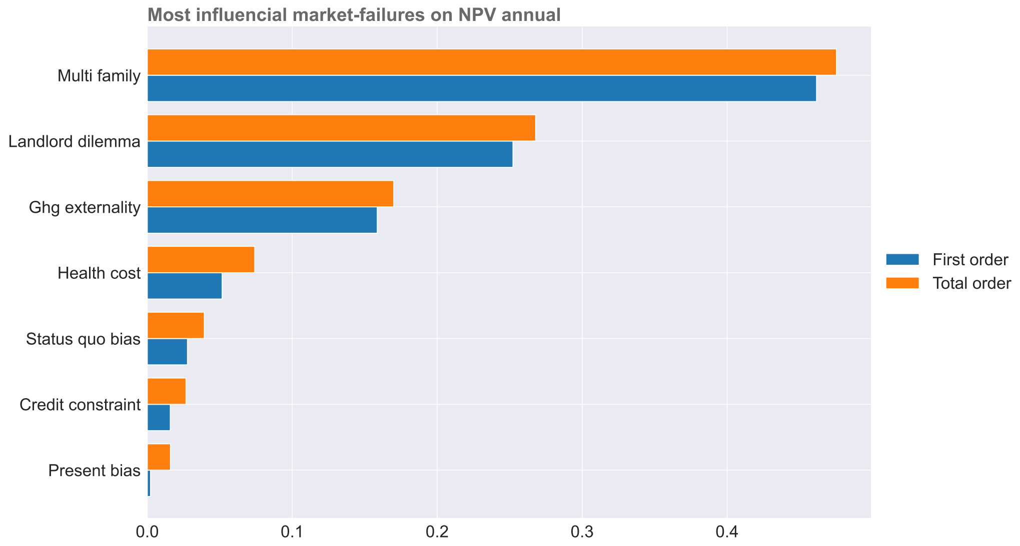


Figure 1.C.3 – Assessment of most influential market failures on energy reduction.

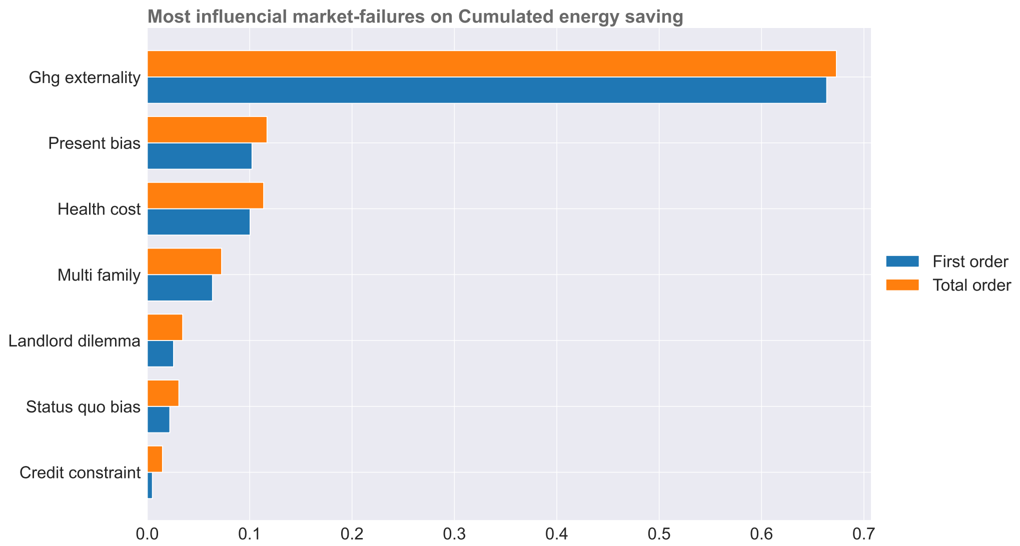
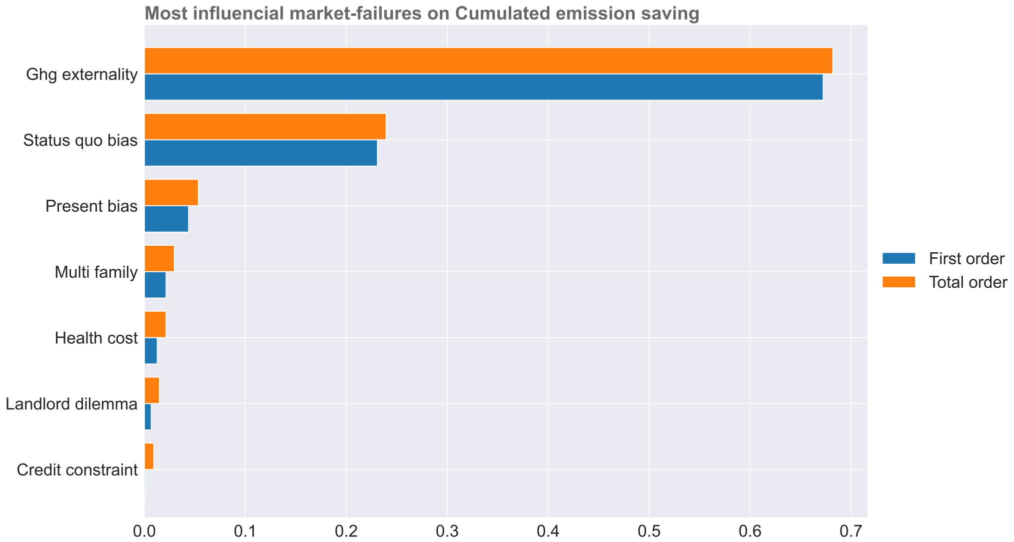


Figure 1.C.4 – Assessment of most influential market failures on emission saving.



1.D Stylized policy solutions

Figure 1.D.1 – Interaction one at a time between subsidies.

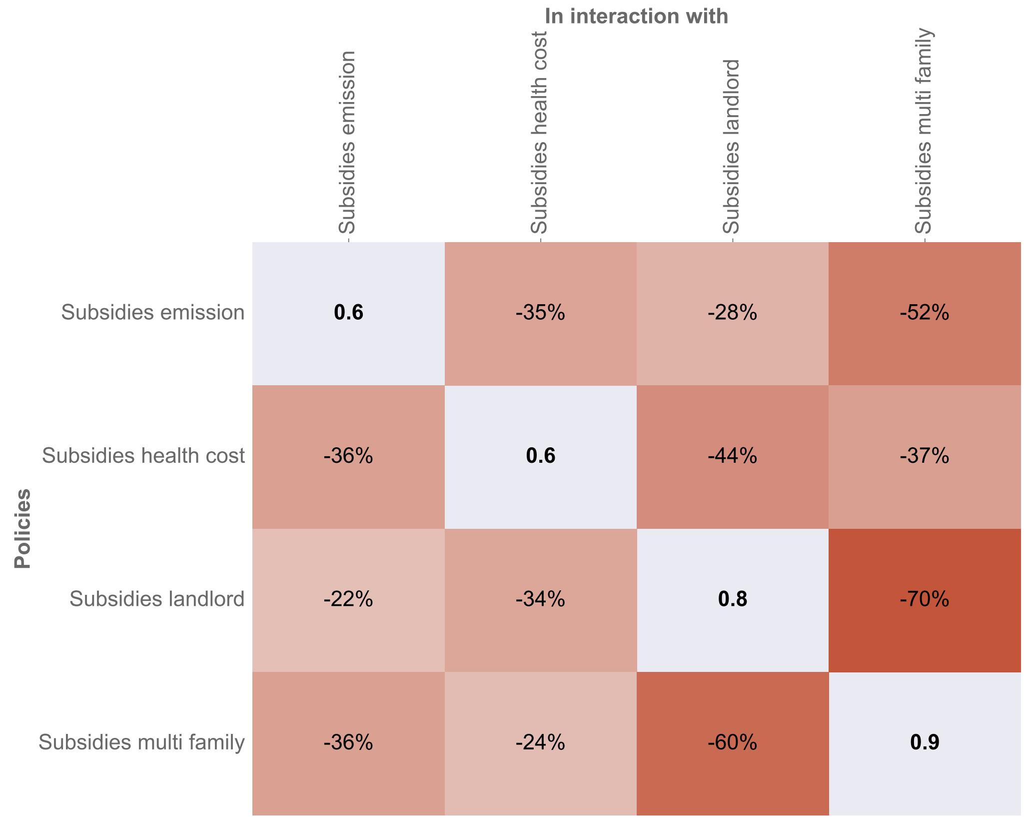


Figure 1.D.2 – Marginal social welfare impact of market failures when interacting with all possible combination of market failures.

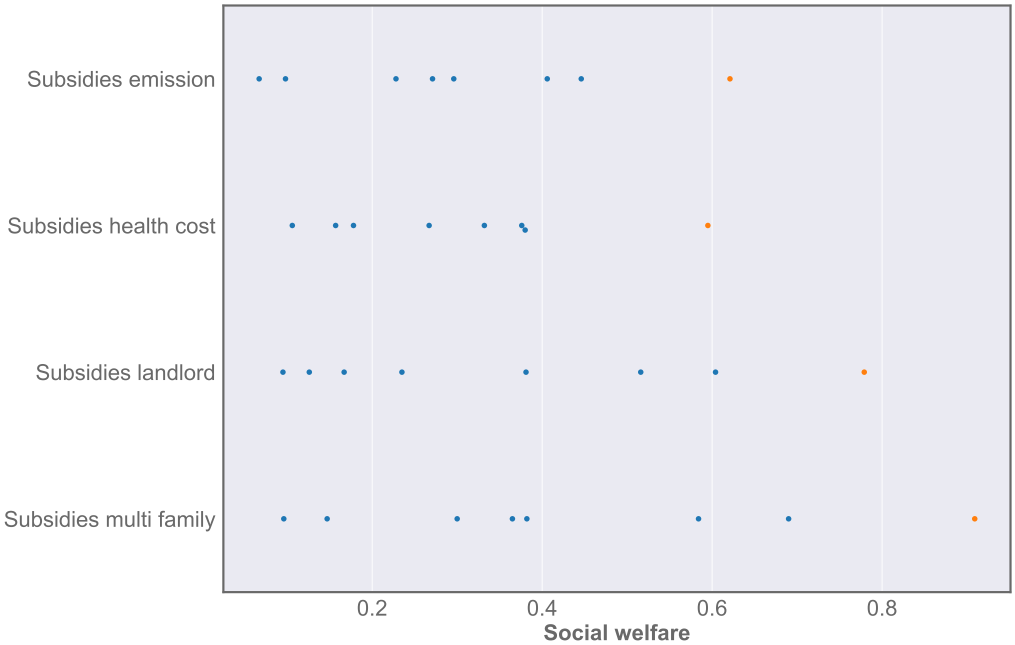


Figure 1.D.3 – Assessment of most influential market failures on social welfare.

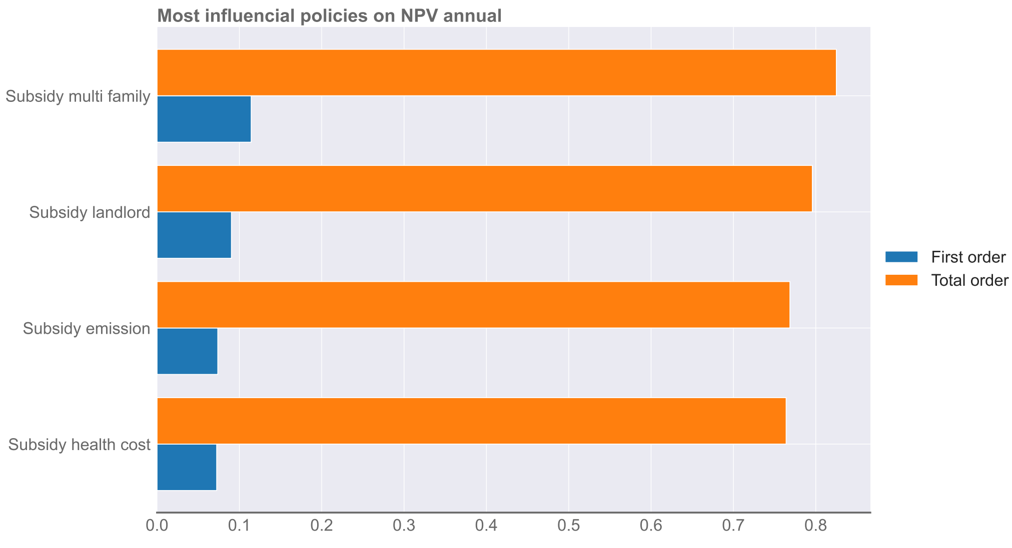


Figure 1.D.4 – Assessment of most influential market failures on energy reduction.

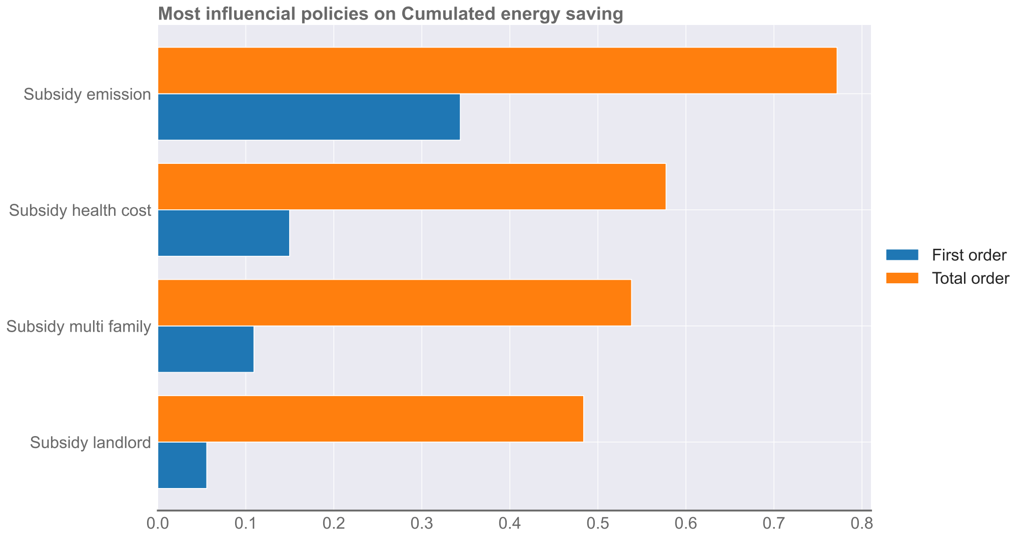
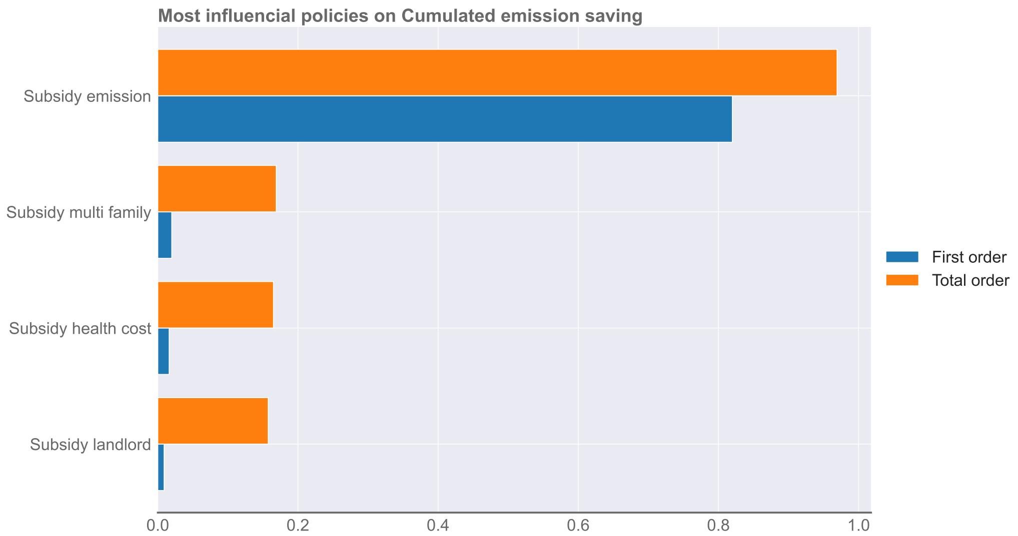


Figure 1.D.5 – Assessment of most influential market failures on emission avoided.



1.E Actual policies

1.E.1 Description of actual policies

Figure 1.E.1 – Description of implementation of energy efficiency policies in the residential sector in France.

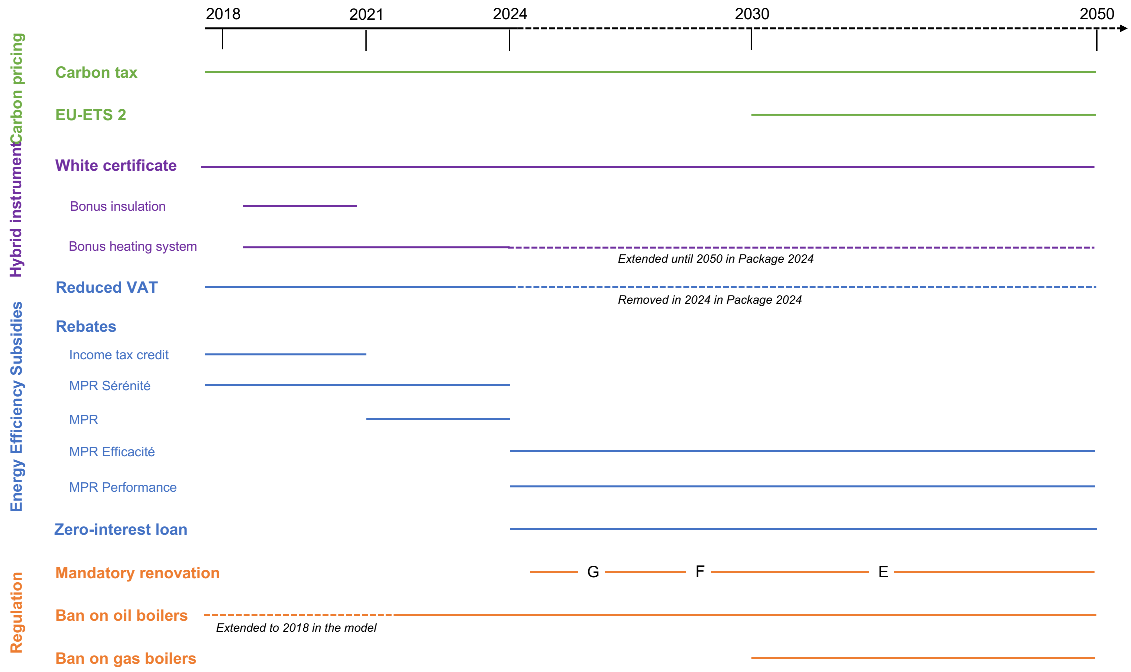


Table 1.E.1 – Description of the main policies implemented in France. Policy packages are a mix of these instruments. 'Package 2024' is the 'Baseline Package'.

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 1.B.5 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 bellow 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.

1.E.2 Results

Table 1.E.2 – Welfare impact of policies implemented in France. C. tax stands for Carbon tax complemented with EU-ETS 2 when the model does not include any friction.

	C. tax	**Subsidies**	**WCO**	**ZIL**	**Rental ban**	**Ban gas**
Consumption (TWh)	-68.76	-288.77	-119.63	-86.21	-70.54	-212.36
Emission (MtCO2)	-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/tCO2)	123.23	1240.21	916.58	1897.69	1423.66	22.19

Figure 1.E.2 – Most influential policies in reducing energy consumption.

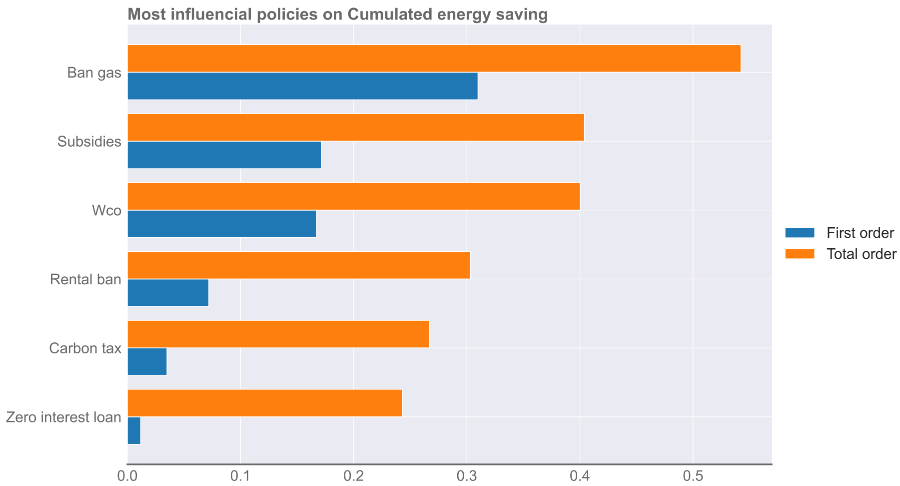


Figure 1.E.3 – Most influential policies in avoiding GHG emission.

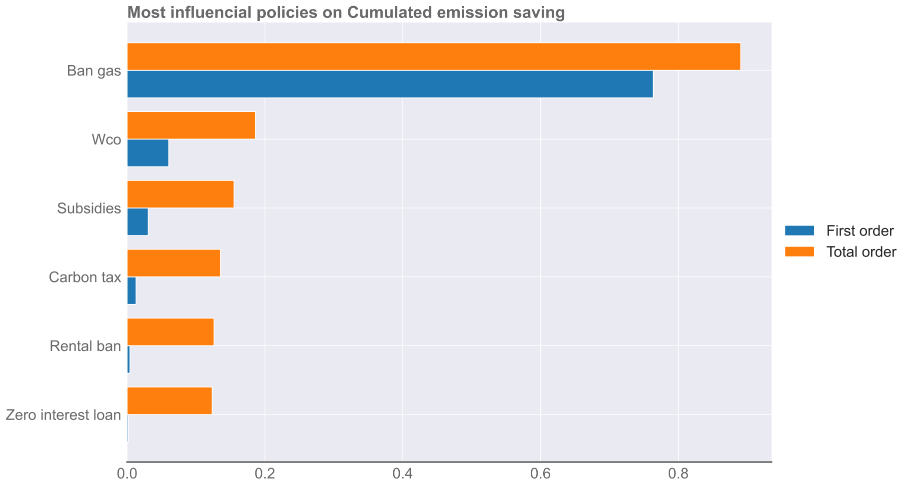


Figure 1.E.4 – Most influential policies on health cost.

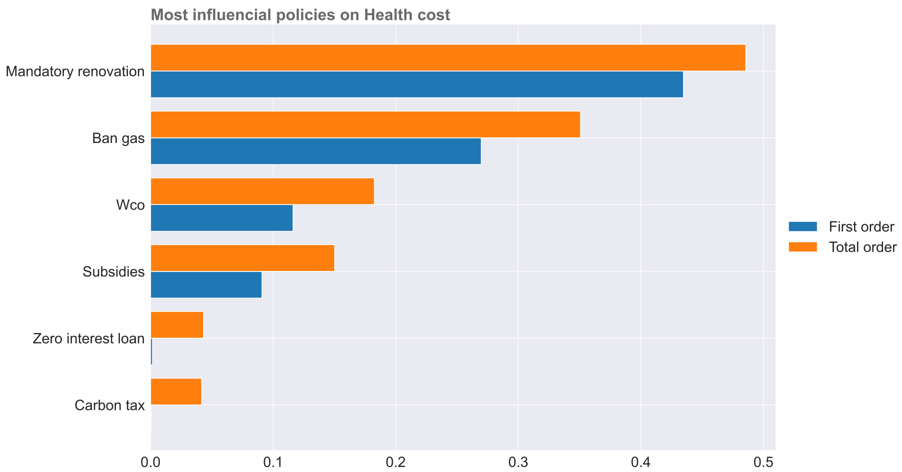


Figure 1.E.5 – Simulated extensive margin of home insulation subsidies.

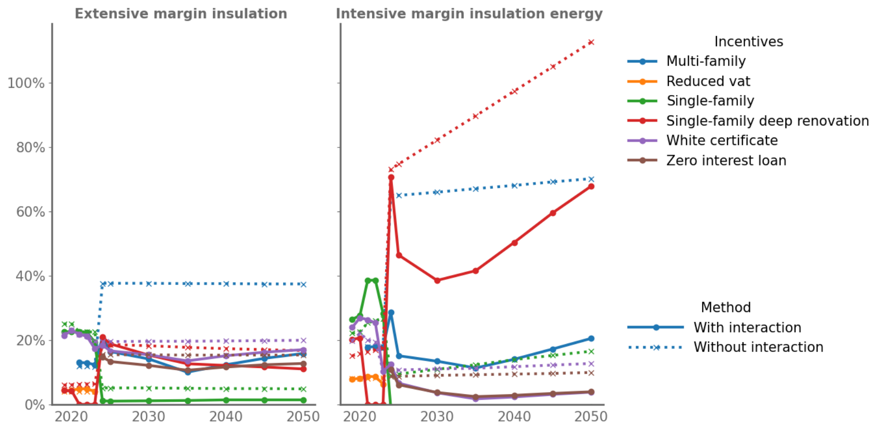
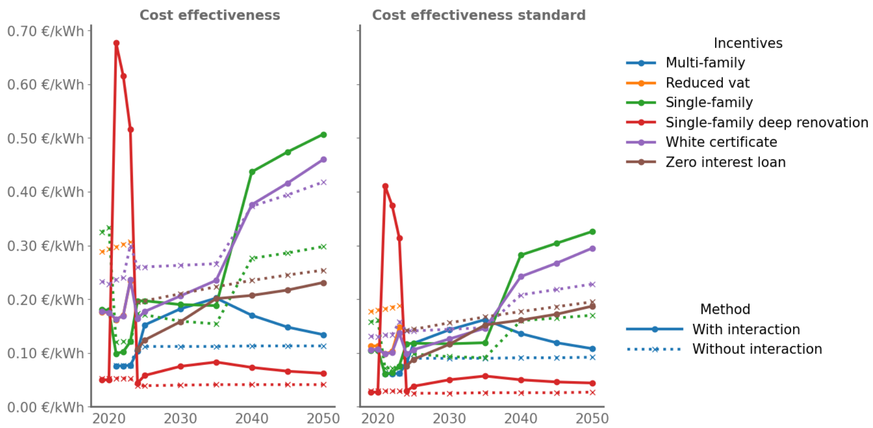


Figure 1.E.6 – Cost-effectiveness of home insulation subsidies



1.F Assessing the implementation gap

Table 1.F.1 – Simulation results in 2030.

	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 1.F.2 – Simulation results in 2050.

	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%

Figure 1.F.1 – Mapping the French energy efficiency gap

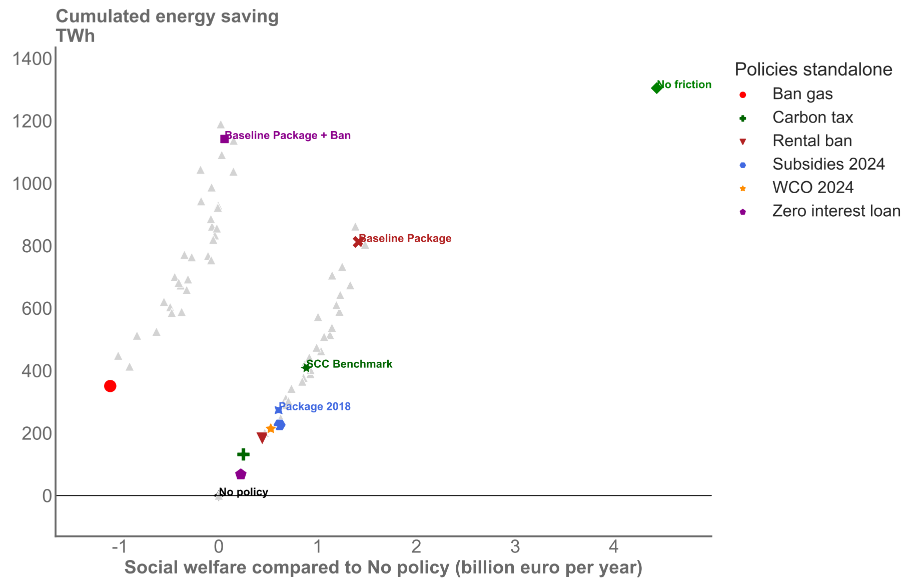


Figure 1.F.2 – Evolution of residential space heating consumption in France.

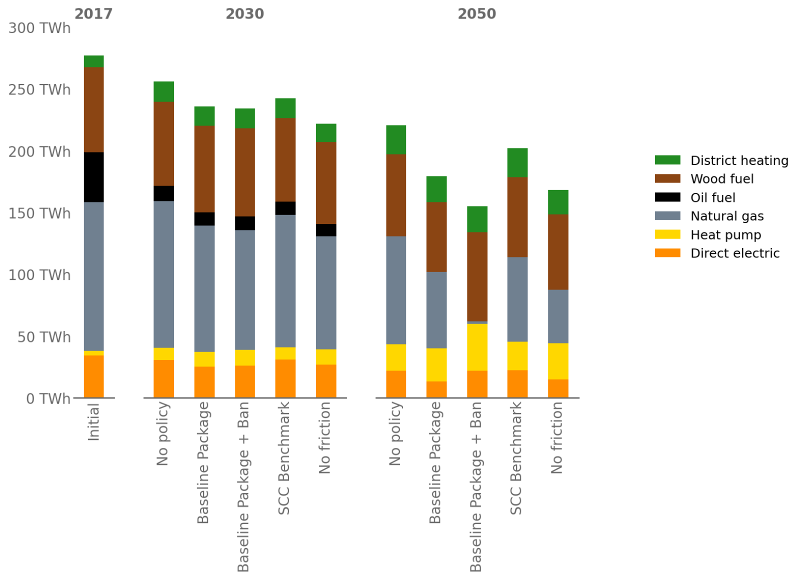


Figure 1.F.3 – Evolution of total investment in home renovation and heating system in France.

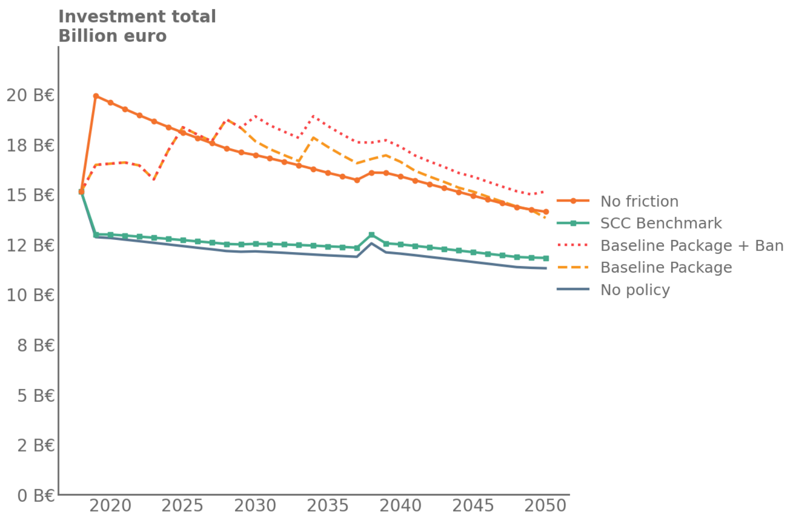


Figure 1.F.4 – Policy cost. To simplify the figure we aggregate all subsidies under the name 'Direct subsidies'. The calculation of the public cost of the zero-interest loan is based on an interest rate of 1.5% paid by the authorities to the bank (Eryzhenskiy et al., 2023).

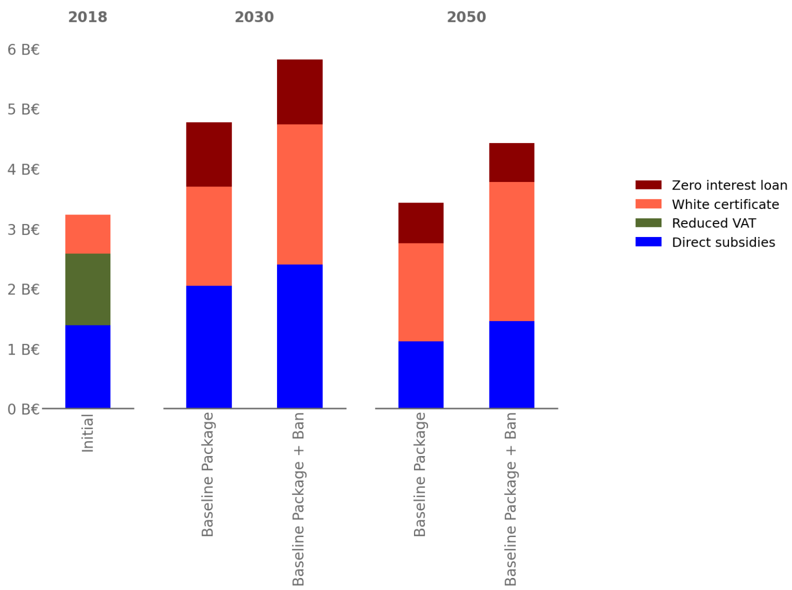
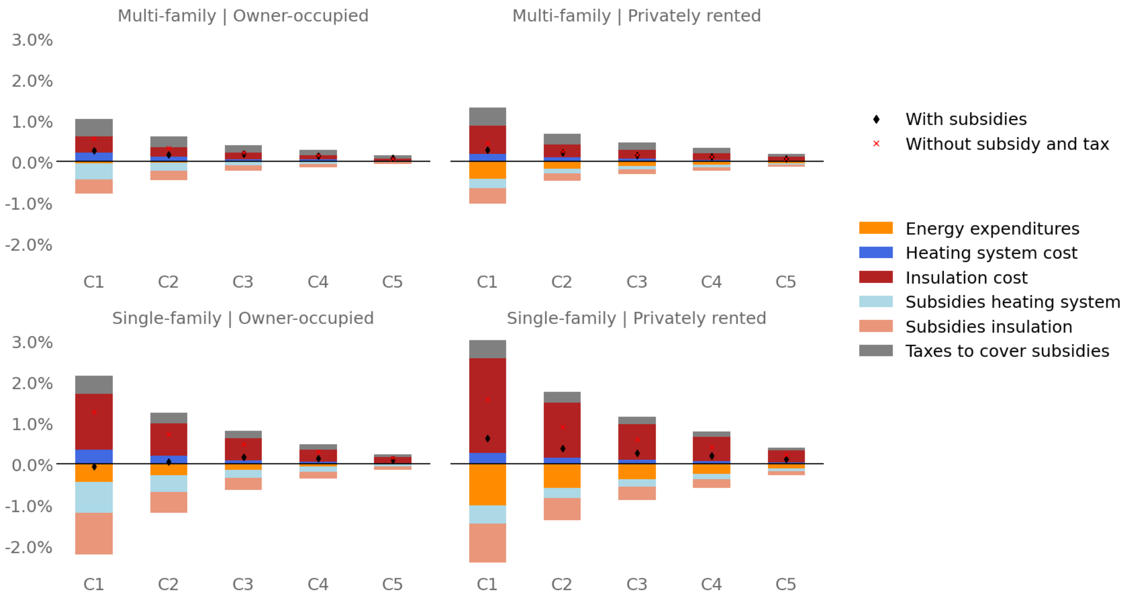


Figure 1.F.5 – Ratio of households energy expenditures (including energy efficiency investment) on income in the '2024 Package' compared to 'No policy'.



1.F.1 Sensitivity analysis

Table 1.F.3 illustrates the variation on energy consumption, emissions and energy poverty in 2050 when varying main inputs of the model. In particular, household income growth rates significantly impacts energy poverty levels. Lower income growth exacerbates fuel poverty, while higher growth alleviates it. Similarly, changes in energy prices also play a decisive role. Higher energy prices lead to a decrease in consumption and emissions, but also escalate energy poverty. The emission content of electricity is key; constant emission rates significantly increase overall CO_2 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.

Table 1.F.3 – Sensitivity analysis of the most important inputs in 2050. Consumption in TWh, GHG emission in $MtCO_2$, 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.

Parameters	**Consumption (TWh)**	**Emission (MtCO2)**	**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

1.F.2 Building stock models

Table 1.F.4 – Previous development of Res-IRF.

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 1.F.5 – Description of the model following Nägeli et al. (2022)

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 1.F.6 – 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.

CHAPTER 2

Meeting climate target with realistic demand-side policies in the residential sector in the EU-27

Previous version of this paper received the IIASA Levien Award
Joint work with Alessio Mastrucci

Abstract

The EU has established an ambitious policy framework for demand-side mitigation in buildings towards net-zero targets. Here, we conduct a comprehensive quantitative assessment of 384 demand-side policy mixes for residential space heating that complement supply-side decarbonization efforts. We show that the implementation of EU Emissions Trading System 2, even when combined deep decarbonization of energy supply, falls short of climate targets. We emphasize the need for ambitious subsidies for heat pumps as a critical component of this strategy. Conversely, a large-scale 'Renovation Wave' modestly contribute to decarbonization, is not a cost-effective strategy at the EU level and require significant increases in public spending. We advocate for the implementation of a carbon tax, paired with substantial subsidies for heat pumps and carefully calibrated incentives for home insulation. This approach supports the decarbonization of the residential sector, limits the strain on the electricity grid, and alleviates energy poverty.

Keywords: climate change mitigation, residential sector, energy mix, policy assessment.

1 Introduction

In the European Union (EU), residential space heating accounts for 17% of total final energy consumption, with approximately 75% still relying on fossil fuels (Eurostat, 2023). Urgent action is needed to achieve carbon neutrality by 2050 (Cabeza et al., 2022). Given that the majority of buildings that will be standing in 2050 are already constructed (Eurostat, 2023), it is imperative to reduce greenhouse gas (GHG) emissions in the existing residential space heating sector.

Decarbonizing this sector involves both supply-side actions to decarbonize heating fuel and demand-side actions to reduce energy service demand, improve energy efficiency, and shift to low-carbon heating system (Escribe et al., 2024). Traditionally, modeling studies have focused on energy supply decarbonization (Creutzig et al., 2018), but recent research has investigated the role of demand-side policies in the residential sector (Levesque et al., 2021; Mastrucci et al., 2021; Camarasa et al., 2022; Mandel et al., 2023). These studies shed light on potential technological transitions, but not on the actual policy measures needed to achieve them. Indeed, many regional-level studies rely on simplified policies, such as exogenous scenarios (Berrill et al., 2022; Zhong et al., 2021) or shadow carbon pricing (Zeyen et al., 2021; Hummel et al., 2023; Mandel et al., 2023), thereby overlooking that decisions are made by heterogeneous households facing various investment barriers. Commonly cited barriers in the residential sector include split incentives between landlords and tenants, friction in multi-family dwellings, credit constraints, and behavioral anomalies (Gillingham and Palmer, 2014; Allcott, 2016; Gerarden et al., 2017). In addition, when investments are made, the actual energy savings are far below the theoretical energy savings calculated using engineering methods (Fowlie et al., 2018; Allcott and Greenstone, 2024) due to a combination of overestimation of pre-retrofit energy consumption, the rebound effect and quality issue (Christensen et al., 2021). Technological models that overlook these barriers therefore lead to overly optimistic role of energy efficiency technologies (Zeyen et al., 2021; Mandel et al., 2023). Moreover, this approach often lacks practical guidance for policymakers on translating research findings into tangible policy instruments (Pollitt et al., 2024). Therefore, while decarbonizing the energy supply side is crucial for meeting climate targets in the residential sector (Zeyen et al., 2021; Berrill et al., 2022), there is still limited evidence on the desirable demand-side policy mixes to implement.

In the EU-27, the EU Green Deal introduces a new European Emissions Trading Scheme (ETS), ETS 2, which will price emissions in the residential sector by 2027 (Commission, 2019). Additionally, energy directives set non-binding objectives, calling on EU-27 member states to implement national instruments to achieve these goals. Specifically, the EU Commission proposes a ‘Renovation Wave’ to double the energy renovation rate by 2030 and promote a ‘Heat Pump Action Plan’ to transition from fossil-fuel boilers to heat pumps (Commission, 2020). However, while existing EU studies focus on technically optimal solutions (Zeyen et al., 2021; Hummel et al., 2023; Mandel et al., 2023), few assess the impact of the expected policy mix. When such assessments are made, they are often limited by the number of policies considered (Knobloch et al., 2021; **?**) or by the heterogeneity of households (Knobloch et al., 2021; Levesque et al.,

2021) and countries (Fotiou et al., 2024) studied. Consequently, little is known about the environmental, economic, and distributional impacts of comprehensive and feasible policy mixes in the residential sector. Specifically, questions remain about whether these policies will achieve carbon neutrality, if the benefits will outweigh the costs, the impact on energy poverty, the amount of public spending necessary to trigger energy-efficiency investments given existing barriers, and how these impacts will vary across countries.

Here, we perform a comprehensive quantitative assessment of 384 demand-side policy mixes, including carbon taxes, subsidies for low-carbon heating systems and home insulation, to complement the decarbonization of the supply side in the residential space heating sector of the EU-27 by mid-century. We systematically evaluate the environmental effectiveness, social costs, and energy poverty of these policies. Specifically, we calculate social cost that includes benefits from bill saving, avoided emissions and variation of thermal comfort and estimate energy poverty based on energy expenditure-to-income ratio. We conclude by comparing four possible policy mixes, one of which includes all measures, while three others aim to minimize social costs under specific constraints. To achieve this, we develop an innovative bottom-up framework for the European residential sector that is both technologically explicit and behaviorally rich. We use up-to-date data on building stock combined with recent data on heating system replacement dynamics and energy renovation to provide credible numerical projections at country level. Building on **?**, our framework endogenously simulates space heating energy use and investment decisions at the household level, considering the main barriers to energy efficiency investment. The model accounts for both the 'prebound effect', where heating energy consumption is consistently lower than the calculated energy ratings of buildings (Galvin and Sunikka-Blank, 2016) and the rebound effect, by including a price elasticity of energy demand (Labandeira et al., 2017; Ruhnau et al., 2023). Investment barriers are derived from the literature or calibrated to reflect lower renovation rates in privately- rented and multi-family dwellings. By integrating household behavior into a high-resolution model at the EU level, this study introduces a new perspective that compares the impact of policy instruments between different countries in the EU-27. Results show that current dynamics combined with supply-side decarbonization lead to a 60% reduction in emissions from 2015 level, but the ETS 2 alone is insufficient to meet climate targets. Subsidies for heat pumps are needed in most EU countries to reduce greenhouse gas emissions. In contrast, additional subsidies for home insulation should only be granted in a few EU countries and should primarily benefit low-income households.

2 Method

2.1 Model

The model simulates space heating energy demand in the residential sector for all EU-27 member states, calculating energy use based on the building's energy performance and occupant behavior. Energy use evolves over time through efficiency improvements and heating system replacements induced by existing demand-side policies within a recursive framework starting in 2015 to 2050 with a time step of 5 years. Efficiency improvements result from the introduction of new building vintages into the dwelling stock and the renovation of older vintages.

This model is an extension of the MESSAGEix-Buildings framework (Mastrucci et al., 2021) soft-linked to the MESSAGEix-GLOBIOM Integrated Assessment Model (IAM). In this analysis, we enhance the framework by providing a more detailed description of the building sector for all EU-27 member states, incorporating up-to-date and granular data. Additionally, we include household decision-making models regarding home energy renovations and heating system replacements, based on Vivier and Giraudet (2024).

Stock turnover New construction is determined iteratively to meet housing demand, accounting for the demolition of existing buildings. Building demolition is modeled using a Weibull distribution and calibrated at the country level. The number of households is determined by population and household size projections following SSP2 projections (Riahi et al., 2017). We assume that the energy performance of new buildings complies with stringent building codes and remains constant over time. The distribution of dwelling types in new buildings and the average living area are adjusted to align with projections for the entire building stock, also consistent with SSP2 projections (Riahi et al., 2017).

Technology The energy performance of dwellings is determined by dwelling archetypes (single or multi-family), the insulation level of envelope components, and renovation status. Specifically, we consider five building construction periods—pre-1945, 1945-1990, 1990-2015, post-2015—and associate each with a specific energy performance level based on the TABULA database (Loga, 2013). We also define two energy renovation depths: standard and deep renovation, following **?** definitions. Standard renovation achieves approximately 40% energy savings, while deep renovation achieves 60%. We consider seven main heating systems: direct electric heating, heat pumps, gas boilers, oil boilers, coal boilers, solid biomass boilers, and district heating. This results in 210 distinct dwellings archeypes in each of country of the EU-27.

As with any technology, energy renovation is theoretically subject to cost reductions through technical progress. The only available study reports learning rates—cost reductions associated with a doubling of cumulative production—of 32% for heat pumps, 10% for other heating systems, 18% for insulation, and 15% for air conditioners (Weiss et al., 2010). However, due to the non-standardized nature of renovations and their labor intensity, it is unlikely that these cost reductions will be additive. The overall impact of technical progress on energy renovation remains to be seen, with expected innovations being as much organizational as technological. Nevertheless, we account for potential cost reductions in heat pumps starting in 2030 due to technical progress and increased market competition.

Household heterogeneity The characteristics of a dwelling are combined with the socio-economic characteristics of their owner and, if rented, their tenant. This adds 15 dimensions to the dwelling stock—three occupancy statuses (owner-occupied, privately rented, social housing) and five socio-economic categories for occupants.

Combining all these characteristics results in a total of 3,150 building archetypes across EU-27 member states (see Table 2.1). These characteristics are specified by merging various databases, detailed in the Supplementary Information.

Table 2.1 – Model dimensions in the EU implementation. Overall, the building stock is segmented into 3,150 building archetypes by EU-27 member states or 58,320 in total.

Dimension	Values
Country	27 EU member states
Location	2 urban / rural
Income class	3, teritiles
Occupancy status	2, owner-occupied / rented
Housing type	2, single-family / multi-family
Period of construction	5, 1945, 1946-1990, 1990 - 2010, 2010
Level of energy performance	3, no renovation, standard renovation, deep renovation
Main space heating system	6, coal, oil, gas, solid biomass, district heating, direct electric, and heat-pumps

Energy use for space heating In this analysis, we calculate the space heating energy consumption of residential buildings using a simplified version of the calculation methodology in accordance with the standard EN ISO 13790, as described in the TABULA methodology (Loga, 2013). We rely on average heating degree-days by country. Building on Vivier and Giraudet (2024), we employ a heating intensity function to address the well-known discrepancy between theoretical energy consumption, as determined by engineering methods, and actual energy consumption (Christensen et al., 2021). The heating intensity function is calibrated to match observed energy consumption in 2015 (Eurostat, 2023) and to replicate a short-term energy service price elasticity of space heating demand of -0.2, consistent with the literature (Douenne, 2020; Labandeira et al., 2017). This function captures the increase in heating intensity following energy renovations, as a result of lower energy service price, commonly known as the rebound effect. Building on Vivier and Giraudet (2024), we estimate the monetary value of variations in thermal comfort.

Energy efficiency investment At each time step, our model endogenously represents investments in building envelope insulation and heating systems (see Figure 2.B.3). Heating system replacements are triggered by the breakdown of existing systems, while energy renovation decisions are assessed every five years. Investment decisions are based on microeconomic consumer theory, with detailed specifications provided in the Supplementary Information. In summary, household utility for adopting energy-efficiency technologies depends on the net cost of the technology, inclusive of available subsidies, bill savings, and thermal comfort improvements. The model then simulates the probability of households making an investment based on discrete choice models (Train, 2009).

The model is calibrated to align with observed technology adoption patterns across EU-27 member states. We use renovation surveys to estimate energy renovation rates

(European Commission et al., 2019) and JRC-IDEES data to determine the market share of heating system replacements (Commission and Centre, 2024). Calibration parameters encompass unobserved costs or benefits, such as existing policies, technical constraints, and potential sources of error, acknowledging that financial considerations are not the sole determinants of investment decisions (Wekhof and Houde, 2023; Tvinnereim, 2023). Recent surveys indicate that motivations for renovation often extend beyond energy savings, encompassing non-energy renovations, environmental concerns, and comfort enhancements. Furthermore, we calibrate the decision model to respond to reductions in investment costs with an average price elasticity of -1 for both heat pumps and energy renovations, as estimated from econometric assessments of a French tax credit initiative that offsets 30% of energy renovation costs, resulting in a 70% rate of non-additional renovations (Nauleau, 2014; Risch, 2020).

We exclude certain options deemed unrealistic: oil, coal, and electricity are not considered as energy sources for new constructions or replacements in renovated homes; biomass is allocated exclusively to single-family homes, while district heating is restricted to multifamily buildings in new constructions. Switching from gas boilers and district heating to solid biomass, and from low-carbon to fossil-fuel heating systems, is precluded due to incompatibilities.

In addition to the discrete choice models, we assume that households will invest in energy renovations or prematurely replace their heating systems if they can recoup the costs within three years. This benchmark is derived from modeling assumptions by Knobloch et al. (2021) regarding heating system choices.

Market and behavioral barriers Building on Vivier and Giraudet (2024), we include several market and behavioral barriers to investments in energy-efficiency technologies.

Empirical evidence often observes under-investment in energy efficiency in rental housing compared to owner-occupied housing, frequently attributed to the split incentive problem (Gillingham et al., 2012; Melvin, 2018; Lang et al., 2021; Petrov and Ryan, 2021). To capture this barrier, we include a reduced-form distortion calibrated to the estimated renovation rate in rental housing. Similarly, although less studied, friction in multi-family housing may also impede energy efficiency investments. We address this by including a reduced-form distortion calibrated to the estimated renovation rate in multi-family housing.

There is substantial evidence that consumers fail to rationally weigh the future benefits of energy efficiency investments, a phenomenon known as present bias, which tends to decrease with income (Hartner et al., 2017). We account for this bias in both energy renovation and heating system investment decisions, using findings from Hartner et al. (2017). Additionally, we include a status quo bias in the household utility function to reflect the preference for retaining existing heating systems, partly explaining the inertia in switching to low-carbon technologies. This bias is informed by a discrete choice experiment conducted in France (Stolyarova, 2016) and utilized in Vivier and Giraudet (2024). The study's willingness-to-pay value of €4,300 for maintaining the same system was incorporated as a bonus in our model's utility function and extrapolated to other EU member states using the cost index factor.

2.2 Cost-benefit analysis and energy poverty

Our model enables a comprehensive cost-benefit analysis of demand-side policies by accounting for a wide range of effects. The impact of a policy is measured by comparing social cost with those of the 'Baseline' scenario. Specifically, we include:

- Investment costs: This encompasses both the incremental costs associated with energy renovations and the costs related to heating system replacements.
- Energy expenditures: We calculate the reduction in energy expenditures resulting from the implemented measures.
- Thermal comfort: We estimate the variation of thermal comfort value from the implemented measures.
- Environmental benefits: The benefits derived from the reduction in CO_2 emissions are quantified based on their social value, as defined by EPA (2022).

Investment costs are annualized using a social discount rate of 2%, aligning with the rate used to compute the social cost of carbon. All costs and benefits from the 2015-2050 period are aggregated, with future values discounted accordingly.

Additionally, we address energy poverty by considering the number of households with a heating energy expenditure-to-income ratio exceeding a country-specific threshold. This threshold is calibrated to match the observed energy poverty rate in the base year of 2015 (Supplementary 2.B.3).

2.3 Policy scenarios

Our analysis rely on various policy instruments.

First, carbon pricing is the textbook solution to addressing the CO_2 externality. In the context of residential energy use, it stands out by encouraging both energy efficiency investments and reductions in energy consumption, unlike other policies that only promote the former (Goulder and Parry, 2008). Carbon pricing raises crucial revenue, especially important with restricted public funds, but it may also increase the burden on low-income households if not associated with tailored redistribution measures. The ETS 2, set to begin in 2025, is the concrete implementation of carbon pricing on fossil fuel use (including natural gas, oil, and coal) in the residential sector. However, this implementation falls short of the socially optimal level (EPA, 2022), which is estimated to be €171/tCO_2 in 2025 and to reach €279/tCO_2 in 2050. In our modeling, we introduce two contrasting carbon pricing scenarios, assuming that the industry will fully pass this tax on to consumers. Our first scenario aligns the carbon price with the ETS price to mimic the plausible implementation of the ETS 2. The second scenario aligns the carbon price with the social cost of carbon, reflecting the first-best policy solution.

Second, heat pumps are key low-carbon heating systems for reducing space heating emissions, offering the dual benefits of higher efficiency compared to conventional boilers and relying on electricity, which is less costly to decarbonize. Consequently, heat pumps play a significant role in mitigation scenarios, despite their higher investment costs compared to fossil fuel boilers. This importance is underscored by the EU Commission's new Heat Pump Action Plan. While carbon pricing can incentivize the switch to heat pumps, it may be inefficient if set too low or if households undervalue future bill savings (Allcott et al., 2014). To address this, governments can introduce subsidies, improve market competition or promote innovation, all leading to reduce consumer upfront cost. In our modeling, we introduce subsidies proportional to emissions avoided to align subsidies with externality reduction (Allcott and Greenstone, 2024). These subsidies are based either on the full social cost of carbon (High) or on half of this cost (Medium). Additionally, we account for potential reductions in heat pump costs by incorporating a learning rate of 32%, representing the expected percentage reduction in the average upfront cost of the technology as its installed capacity doubles.

The Renovation Wave aims to double the renovation rate in the EU-27 and has been reinforced in the revised Energy Performance Building Directives (Commission, 2020). The directives promote deep renovations—defined as those achieving at least 60% energy savings—to maximize the energy-saving potential during the rare opportunities for home renovation. However, recent ex-post assessments have raised concerns about the actual realization rate of energy renovations. Quality defects, such as poor-quality materials and installation errors, often result in lower-than-expected energy savings. This issue is exacerbated by the partly unobservable nature of energy performance, which creates information asymmetries between homeowners and contractors (Giraudet et al., 2018). Based on assumptions from U.S. studies, we estimate that quality defects account for 25% of the discrepancy between actual and predicted energy savings (Christensen et al., 2021). Furthermore, market failures such as credit constraints, the landlord-tenant dilemma, frictions in multi-family housing, and present bias hinder the development of energy renovations. These issues particularly affect privately-rented, multi-family, and low-income owned dwellings, leading to untapped energy-saving potential. In this modeling, we explore three main policies to promote energy renovation. First, we introduce four types of subsidies that vary in amount and targeting. Specifically, we design subsidies to either double the number of renovations in each EU-27 member state (High) or achieve half of these additional renovations (Medium). Subsidies can also target standard or deep renovations, with the latter complemented in reducing hidden costs associated with deep renovations that are calibrated in the model rationalize their lower occurrence. Second, we examine the impact of policies aimed at maximizing the realization rate of energy renovations. Addressing this issue could involve intensive ex-post inspections conducted by public services rather than relying on companies. Finally, we implement a policy that removes all market failures and behavioral anomalies, simulating a set of measures in the real estate market, credit market, or through information campaigns designed to reduce inattention to energy prices.

2.4 Limitation

Here, we draw attention to key data limitations of our approach.

Despite incorporating a wide range of segments, our model uses a simplified representation of heating systems, including only one type of heat pump and fossil boiler. The study bases heat pump costs on water/air technology, assuming most dwellings with existing hydraulic systems will retain them. Water/air heat pumps offer greater thermal comfort and can be used for water heating. This level of detail is sufficient to capture the trends in mitigation scenarios. First, the efficiency differences between standard and advanced fossil boilers are small (typically ranging from 0.7 to 0.9, with an average efficiency of 0.8 used in our model), and their stock is limited by 2050. Second, heat pump costs decrease through learning in policy scenarios that explore the impact of reduced heat pump costs. To accurately capture technological changes in district heating networks, a separate model, akin to those used for electricity generation changes, would be required. This is beyond our current model's capabilities. However, we treat district heating as a technology available to urban households, with its diffusion accounted for through household investment decisions. This approach is simplistic, as heating network decisions are usually made by public authorities, not individuals. As these technologies become more economical, their penetration could increase. We have ensured that district heating consumption does not increase excessively compared to the base year. The technical representation of our framework is reasonable as our findings are consistent with detailed engineering studies (Commission et al., 2023).

Our framework does not fully capture the synergies between home insulation and heating systems, particularly heat pumps. First, better insulation and reduced energy needs can lower the size and cost of heating systems. However, fixed costs, including installation, make up the larger share of total costs, so this effect is limited. Second, heat pumps are less efficient in poorly insulated dwellings, and some studies suggest they cannot function properly without sufficient insulation. This view has recently been challenged, with evidence that minimal insulation (costing less than €1,000) may be adequate for installing heat pumps in the worst-performing dwellings. Specifically a study spanning almost two years analysed the performance of 750 heat pumps in the UK and demonstrates that a successfully installation even in these older pre-1945 properties (System, 2024). In our modeling, we do not restrict heat pump installations in poorly insulated dwellings, as we do not include light energy renovations that could make such installations feasible. We believe our findings are reasonable since we assume an average heat pump efficiency of 2.5, which is at the lower end of the efficiency range.

Our assessment of energy renovation focuses on investment costs and benefits related to energy cost savings, avoided emissions, and increased thermal comfort due to higher heating intensity. However, other costs and benefits not included in this scope could impact our findings. On the one hand, non-energy auxiliary costs, such as transaction costs for searching contractors or gathering subsidy information, can hinder energy renovations but are rarely considered in cost-benefit analyses. These hidden costs are likely significant but vary across households (Fowlie et al., 2015). Households already undertaking general home renovations incur lower marginal costs for installing insulation due to overlapping expenses like scaffolding or painting. While our investment decision framework implicitly includes such costs through calibration parameters, they are not explicitly factored into the cost-benefit analysis. This assumption is reasonable because households that decide to invest in energy renovations typically do so because they face lower hidden costs. Moreover, even in scenarios with the highest rates of energy renovation, the rates remain below those of light energy renovations (European Commission et al., 2019). Therefore, these households are likely to undertake more extensive renovations when they already plan smaller ones, making our model consistent with observed behavior. On the other hand, households may value extra benefits from energy renovations, such as improved acoustics, aesthetics, or the satisfaction of reducing emissions (Wekhof and Houde, 2023; Tvinnereim, 2023). Recent studies also highlight substantial health benefits from improved home energy performance, especially in poorly performing dwellings occupied by low-income households (Gillingham et al., 2021; Dervaux and Rochaix, 2022). Furthermore, reducing energy use enhances energy security. Failure to include these impacts could underestimate the socio-economic outcomes of energy retrofits, but is unlikely to change our global results as the health benefits are located in dwellings suffering from energy poverty, consistent with our proposal for targeted energy renovation.

We do not include all costs, such as administrative expenses or information campaign costs, associated with the successful implementation of the policy, thereby minimizing the overall cost of the policy. Specifically, we do not consider policies aimed at inducing innovation in heat pumps or creating market competition that could lower heat pump costs. Similarly, we do not account for the cost of ex-post inspections necessary to improve the realization rate of energy renovations. As a result, our findings may overestimate the cost-benefit outcomes of our first and second-best scenarios, which do not factor in these additional costs but benefit from improved renovation quality. To isolate these effects, we first assess the standalone impact of subsidies for energy renovation without quality improvements, then compare this with a counterfactual scenario that includes quality improvements induced without subsidies, and finally build a 'Minimum cost national, constraint' scenario that excludes these quality improvements.

3 Demand-side policy scenarios

We project a 'Baseline' scenario, aligned with an SSP2 scenario, extending current dynamics of energy renovation and heating system replacement, alongside a fully functioning Emissions Trading Scheme (ETS), leading to zero emissions from electricity and district heating energy by 2050. This scenario implicitly includes all existing demand-side policies in EU-27 member states, serving as a counterfactual to assess additional demand-side policies. We evaluate 360 policy mixes, which result from the combination of the implementation of six main demand-side policies, categorized into carbon pricing, direct promotion of heat pumps, and direct promotion of energy renovation (Table 2.2).

The ETS 2, starting in 2027, targets fossil fuel use in the residential sector and addresses the CO_2 externality by encouraging energy efficiency investments and consumption reductions. We model two carbon pricing scenarios: one aligned with the ETS price (Pietzcker et al., 2021) and another with the social cost of carbon (EPA, 2022). In addition, we design two subsidies level for heat pumps (High and Medium) to offset higher upfront costs, that we align with externality reduction potential. We also include learning rates to account for potential cost reductions in heat pumps, reflecting technical progress and increased market competition. To achieve the 'Renovation wave', we explore three main policies to promote energy renovations. First, we introduce subsidies that vary in amount and targeting. Specifically, we design subsidies to either double the number of renovations in each EU-27 member state (High) or achieve half of these additional renovations (Medium). Subsidies can also target standard or deep renovations. Second, we examine the impact of policies aimed at maximizing the realization rate of energy renovations. Addressing this issue could involve intensive ex-post inspections. Finally, we implement a policy that eliminates all market failures and behavioral anomalies. This policy therefore simulates a series of measures in the real estate market, the credit market and through information campaigns to reduce households' inattention to energy prices. Further descriptions of the scenarios are provided in the Methods.

Table 2.2 – Residential demand-side policies studied. A total of 360 policy combinations are analyzed, each complementing supply-side policies aimed at fully decarbonizing electricity and district heating by 2050. Heat pump subsidies are proportional to emissions avoided. High means value is equal to social of carbon and medium half of the social value of carbon. Energy renovation subsidies are designed to either double the renovation rate (High) or increase it by 50% (Medium).

	Policy instruments	**Implementation**
	Carbon pricing	
1	Residential carbon tax	No, Aligned on ETS price, Aligned with social value of carbon
	Direct heat pumps promotion	
2	Subsidies for installation of heat pump	No, Medium, High
3	Innovation policy and market competition reducing heat-pump price	Price constant, Learning-by-doing
	Direct energy renovation promotion	
4	Subsidies for energy renovation - subsidy targeting	No, Medium, High Standard renovation, Deep renovation
5	Improvement renovation quality (ex-post control)	Increasing realization rate of energy renovation
6	Policies tackling market-failures in energy renovation investment decision - credit constraint, landlord-tenant dilemma, friction multi-family and behavioral anomalies	Yes, No

4 The multifaceted effects of demand-side policies

The 'Baseline' scenario reduces emissions by 58% by 2050 compared to 2015 level, falling short of the climate targets of a 95% reduction. Driven by current energy renovation efforts and the installation of heat pumps, energy use is projected to decrease by 40%, while electricity use is expected to increase by 77% compared to 2015 level due to shifts to heat pumps.

Fig.2.1 shows the environmental impact and social cost of demand-side policies compared to the 'Baseline' scenario. The implementation of ETS 2 is expected to reduce emissions by 63%, while a more ambitious carbon tax reduces emissions by 73%. Both policies have a positive socio-economic impact, despite reducing household thermal comfort which lowers their heating intensity in response to the increased fossil fuel prices. Carbon pricing alone does not significantly trigger energy renovations or the replacement of heating systems, as households are subject to credit constraints and tend to underestimate energy savings (Allcott et al., 2014). An adverse effect of carbon pricing is an increase of energy poverty by up to 2% compared to the 'Baseline'.

Implementing heat pump subsidies is the most effective strategy for reducing emissions, achieving reductions of up to 85% and cutting energy consumption by 70% by improving heating system efficiency from 0.8 (standard fossil fuel boilers) to 2.5. These measures result in a positive socio-economic outcome, with savings of up to €18 per household per year compared to the 'Baseline' scenario. However, if the value of avoided emissions is not considered, private costs increase by €18 due to higher electricity prices compared to natural gas. Consequently, there is no significant impact on energy poverty, and it leads to a substantial increase in electricity use.

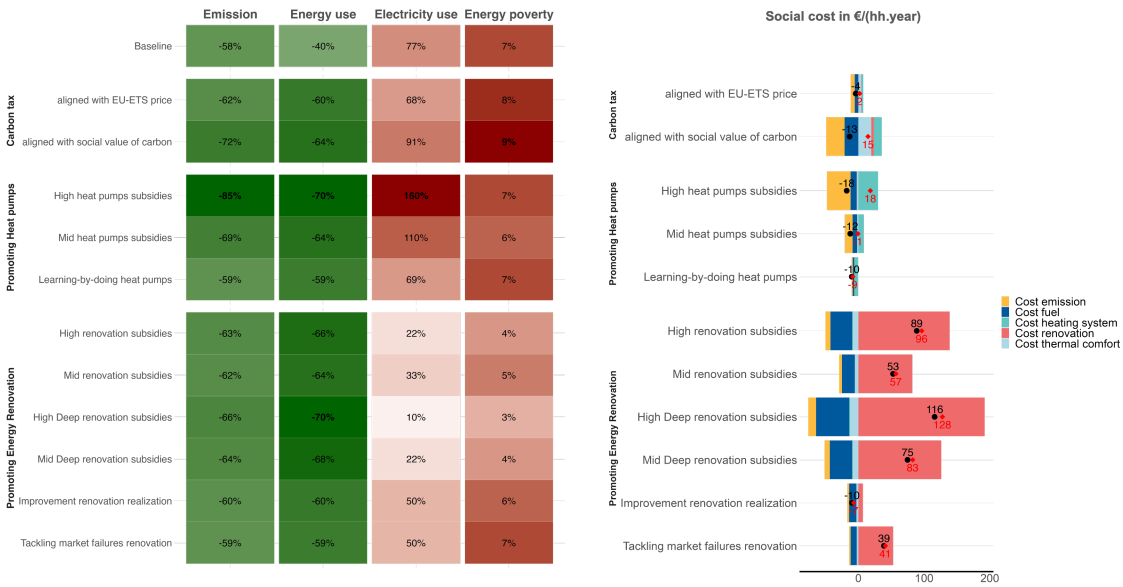
Measures to promote energy renovation have a modest impact, with the most ambitious scenario reducing emissions by an additional 7 percentage points compared to the 'Baseline' scenario. These measures also limit the increase in additional electricity demand to 19% by 2050. Our results suggest that the benefits of subsidies for energy renovations, including savings on electricity bills, improved thermal comfort and avoided emissions, do not outweigh the investment costs. This is consistent with engineering studies (Galvin, 2024) and ex-post policy evaluations that report negative impacts of energy renovations (Fowlie et al., 2018; Allcott and Greenstone, 2024). Market failures contribute to 19% of additional energy consumption compared to the 'Baseline' scenario in 2050 due to lower renovation rates in multi-family buildings and private rental housing. However, these measures significantly reduce energy poverty by 3 percentage points compared to the 'Baseline' scenario.

The Supplementary Fig.2.A.1 assesses the marginal impact of each policy in combination with others. It confirms that the promotion of heat pumps has by far the largest impact on reducing emissions, accounting for around 80% of additional reductions compared to the 'Baseline' scenario. While subsidies for energy renovation are the most effective measures for reducing energy consumption and alleviating energy poverty, they also significantly increase overall social costs.

5 Ambitious heat pumps subsidy to meet climate targets

Fig.2.2 illustrates the emission savings, electricity variations, and social cost impacts of 380 policy mixes at the EU-level. Only the implementation of higher heat pump subsidies, combined with a reduction in heat pump costs, gets close to the climate targets by 2050. Panel C of Fig.2.2 highlights key differences in the ambition required to meet carbon neutrality across EU-27 member states. For instance, countries like Sweden and Finland do not require additional policies, whereas others like France need full policy implementation to meet the 95% emission reduction target. Supplementary Fig.2.A.3 illustrates that this

Figure 2.1 – Impact of standalone demand-side policy implementation on emissions, energy use, and social cost compared to the baseline scenario by 2050. Each row displays the impact of a single standalone policy. In the left panel, percentage refers to variation compared to 2015 level. In the right panel, black dots represent the social cost compared to the 'Baseline', while red diamonds indicate the private cost compared to the 'Baseline', excluding monetized benefits from avoided emissions. Policies are grouped into carbon pricing, direct promotion of energy renovation, and direct promotion of heat pumps.



A. Variation compared to 2015 level

B. Social cost compared to the Baseline

difference is explained either by a low share of fossil fuel boilers in countries like Sweden, Finland, and the Baltic states due to the initial low stock in 2015, or by projections driven by current dynamics of heating system replacement in countries such as the Czech Republic and Poland. In contrast, Spain and Germany may require more stringent measures, such as a ban on fossil boilers or higher levels of heat pump subsidies, to meet their targets (Escribe and Vivier, 2024). This is because residential electricity prices are significantly higher than gas prices—€0.30/kWh for electricity compared to €0.07/kWh for gas in Germany in 2015—making heat pumps less profitable and thus discouraging households from switching to them.

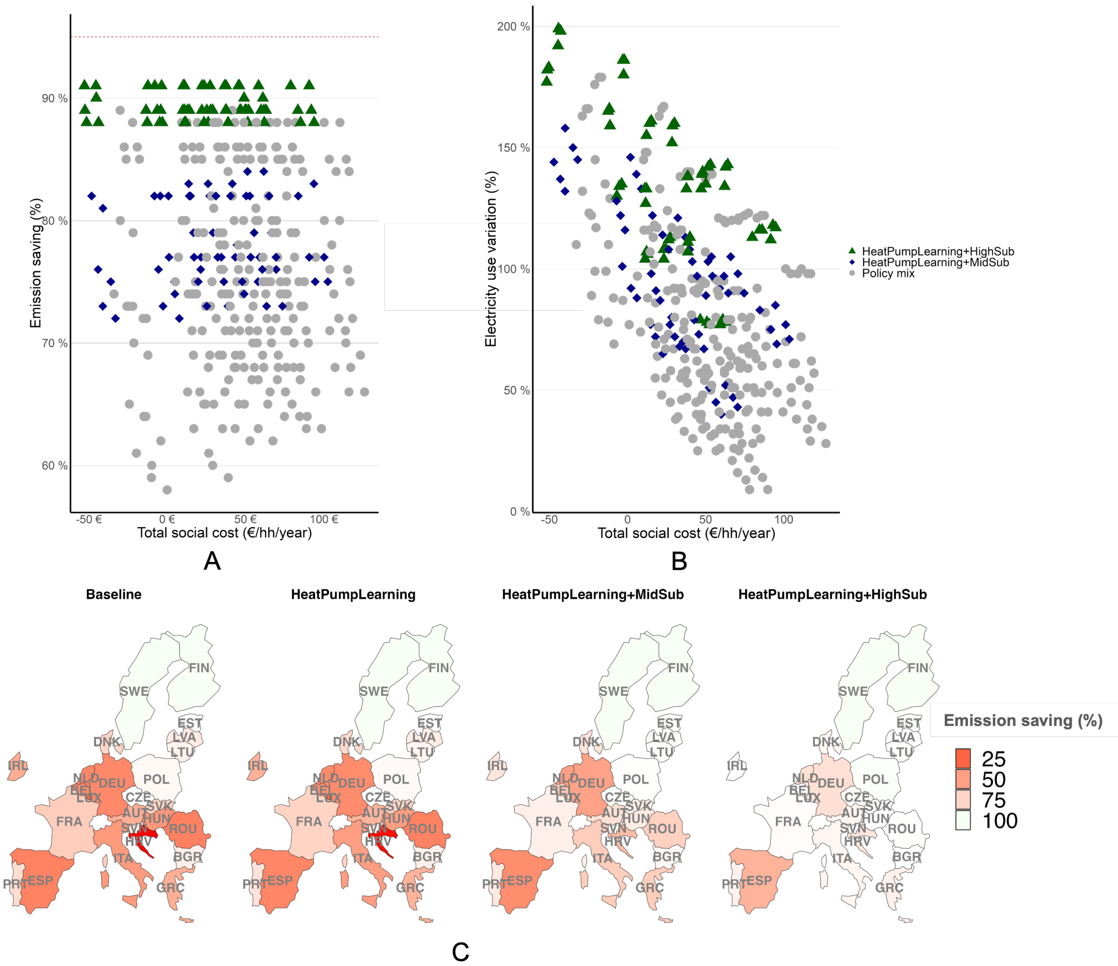
The promotion of heat pumps leads to an increase in electricity demand of +70% to +200% compared to the 2015 level (panel B Fig. 2.2), depending on other energy saving policies within the mix. The social cost increases as electricity demand decreases correlated to the level of energy renovation subsidies implemented. Reducing electrification requires energy renovation that appear not socially profitable in most cases. Our sectoral analysis assumes an exogenous energy supply system that can absorb the increased demand at a fixed marginal cost. However, the extensive electrification induced by the spread of heat pump diffusion put a strain on the electricity system, which in turn requires an increase in capacity and thus additional costs, especially as space heating reaches its peak values in winter, when the efficiency of heat pumps is at its lowest (Zeyen et al., 2021; Mandel et al., 2023; Escribe et al., 2024). The impact on the electricity system is difficult to estimate as heat pumps can add flexibility to the power system, reducing electricity curtailment in systems with high shares of variable renewable sources (Bloess et al., 2018). This is particularly beneficial in central and northern Europe, where wind generation aligns with the heating season, making heat pumps and wind power an effective combination (Zeyen et al., 2021). The adaptability of the electricity system heavily depends on national contexts (Thomaßen et al., 2021; Comission et al., 2023). Recent research in France shows that widespread heat pump adoption can be absorbed at a reasonable cost by the electricity system without additional energy saving policies (Escribe and Vivier, 2024), but further analysis should be systematically conducted at the EU level.

6 Targeted energy renovation policies

We then specifically investigate the role of energy renovation policies in complementing the necessary development of heat pumps. Panel A Fig.2.3 illustrates the marginal impact of different designs of subsidies for energy renovation (standard/improved realization rate and increased number or depth) on the total social cost for EU-27 member states. Energy renovation subsidies increase the social cost in most countries, averaging €50 per household per year. As previously observed, the benefits do not outweigh the investment costs. However, we find that improving realization rates significantly enhances the balance, while targeting deep renovations has varied impacts across EU member states but generally leads to more countries achieving a positive socio-economic balance. Our findings, however, do not support the implementation of a 'Renovation Wave' at the EU level. We highlight geographical differences, suggesting that such subsidies could be beneficial for specific countries, especially if they improve realization rates and target deep renovations. The marginal social cost of additional subsidies depends on a combination of factors including energy prices, renovation costs, energy use per dwelling and current dynamics of renovation. Austria, for example, had one of the highest renovation rates in the EU in 2015 at 1.9% per year. As a result, additional subsidies trigger energy renovations in the remaining dwelling stock, which are the less cost-effective projects. Conversely, Estonia has the highest energy consumption per square meter, averaging 214 kWh/m^2, making investments in energy savings highly profitable. Spain benefits from the lowest energy renovation costs, with energy renovations costing only €51/m^2, alongside a relatively high electricity price of €0.23/kWh. In Croatia, Slovenia, and the Czech Republic, energy consumption per square meter is also above average, and the costs for energy-efficient renovations are relatively low. Overall, numerous factors influence the socio-economic profitability of additional energy renovation efforts, highlighting the need for nationally-determined strategies rather than a uniform European approach.

Moreover, energy renovation subsidies offer two key advantages. First, they can significantly reduce electricity use by up to 25% at the EU level (Panel B Fig. 2.3). Reducing electricity consumption can limit the need for new power plants, thus avoiding

Figure 2.2 – Emission savings compared to 2015 level across policy scenarios. The climate goal is a 95% reduction in scope 2 emissions in the residential sector. The upper figure displays all policy mixes, highlighting scenarios that include heat pumps with learning-by-doing and subsidies (medium level in blue, high level in green). The lower figure displays variation across EU MS for 4 policy scenarios.



costs in the electricity system that could potentially lead to a positive balance (Zeyen et al., 2021; Boomhower and Davis, 2020; Mandel et al., 2023). Second, energy renovation subsidy is a key policy for reducing energy poverty. In most EU-27 countries, heat pumps, due to higher efficiency, lower household energy bills and thereby reduce energy poverty (panel C Fig.2.3). However, heat pumps do not alleviate energy poverty in Italy and may worsen it in Germany, where natural gas prices are typically less than half those of electricity. Our findings suggest implementing targeted energy renovation subsidies, focusing on countries with profitable economic balances and those facing electricity peak challenges due to heat pump diffusion. Additionally, they should prioritize low-income households to reduce energy poverty.

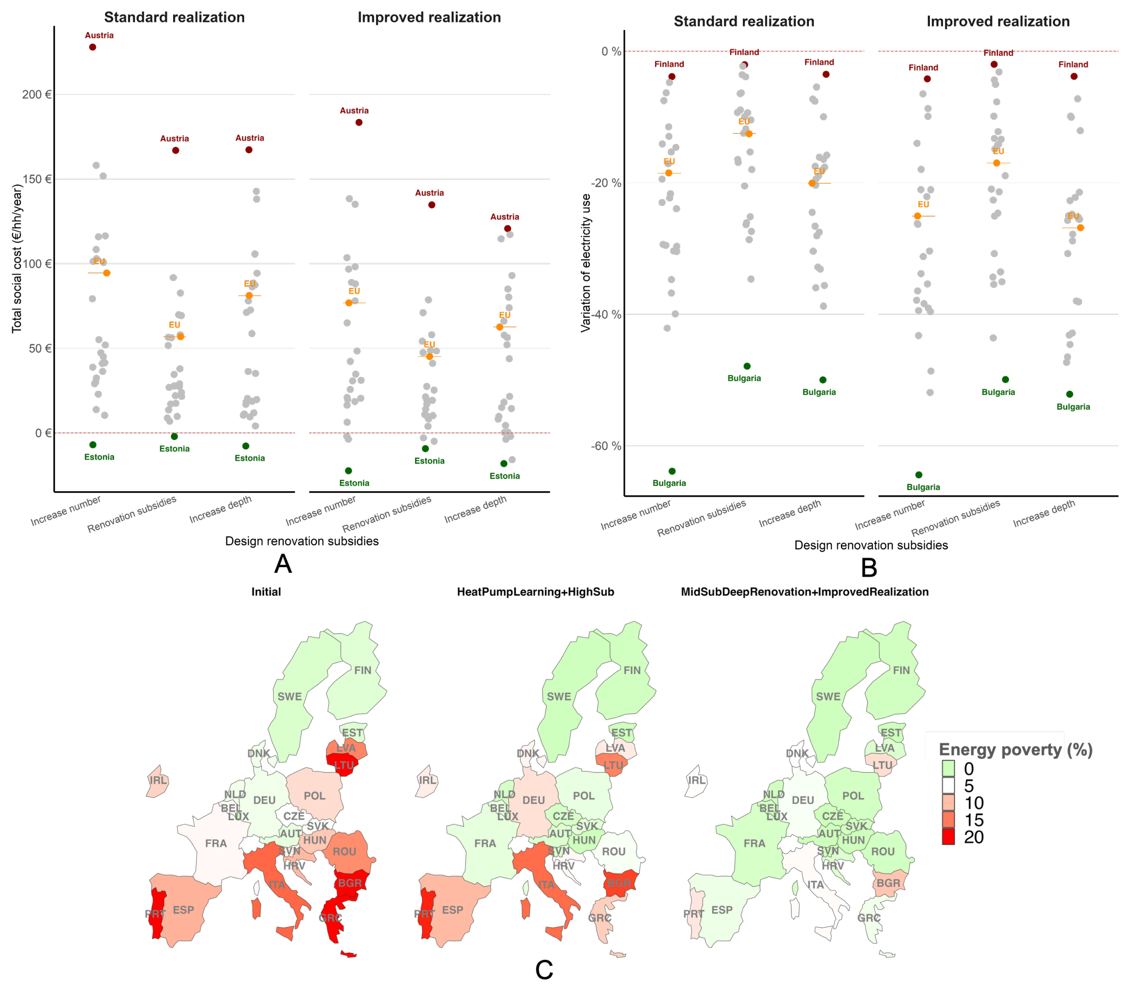
7 Optimizing national policy mixes to achieve EU climate goals

Lastly, we compare the effectiveness of four policy mixes in reducing emissions and improving energy efficiency across the EU-27. Each mix is based on a carbon price limited to the ETS price and excludes policies directly addressing energy renovation market failures. Three scenarios aim to minimize social costs under specific constraints. The 'Minimum cost national' mix aims to minimize social costs at the member state level, while 'Minimum cost national, constraint' scenario follows the same strategy but assumes that heat pump prices do not decrease and energy renovation realization rates does not improve. In contrast, the 'Minimum cost EU' policy mix minimizes social costs at the EU level. Lastly, the 'All policies' scenario illustrates the impact of implementing all subsidies at maximum levels, targeting deep renovations and improving energy renovation quality.

Panel A in Fig.2.4 shows that both the 'Optimal EU-level' and 'All policies' scenarios achieve a 90% reduction in emissions compared to 2015 level. In contrast, the 'Minimum cost national' scenario achieves an 82% reduction, while the 'Minimum cost national, constraint' scenario only reaches a 77% reduction (Table 2.A.1). The Panel B of the figure displays energy use by fuel carriers. In the 'Minimum cost national' scenario, 75% of buildings are heated with low-carbon systems such as district heating, biomass, and heat pumps, with 100 million heat pumps installed by 2050, representing approximately 50% of the dwelling stock. Residual emissions stem from gas demand and may be slightly overestimated, as renewable gas for space heating is not included in our scenarios. Given the limited availability and high uncertainty surrounding renewable gas (Escribe and Vivier, 2024), this assumption is justified and would not affect our qualitative findings.

We estimate that the 'Minimum cost national' path can be achieved with a budget of €10 billion at EU level to promote the installation of heat pumps (€248 billion in total), of which only half can be financed from the revenue the ETS 2 (Table 2.A.1). Main differences result from energy renovation policies. The 'All policies' scenario leads to a 67% energy saving compared to 2015 level, due to the renovation of 145 million buildings by 2050 (75% of the dwelling stock), compared to 80 million buildings in the 'Minimum cost national' scenario and about 65 million in the other scenarios that do not rely on additional energy

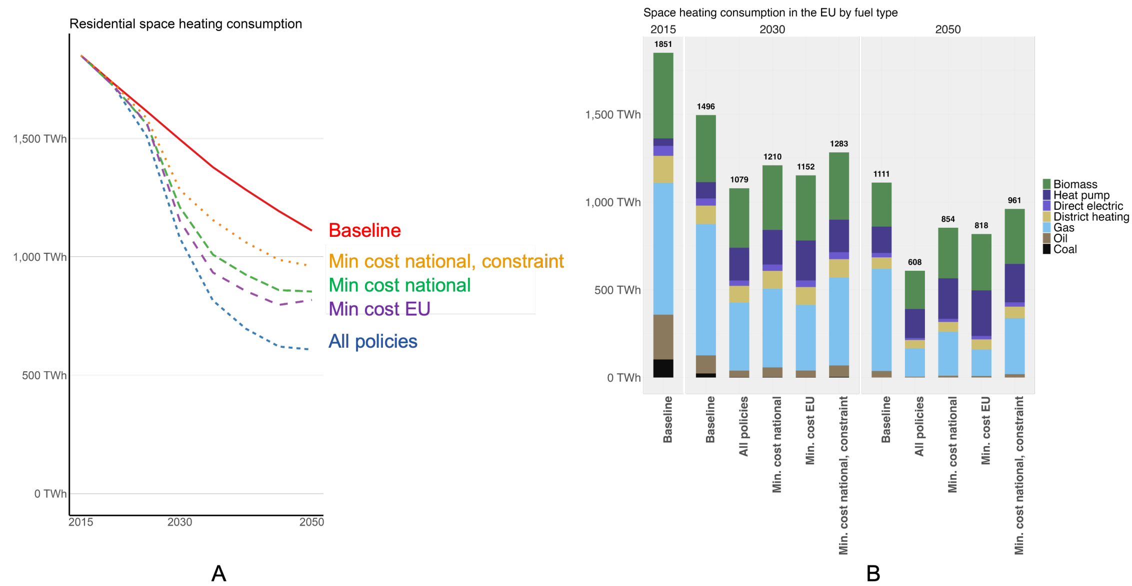
Figure 2.3 – Impact of different designs (standard/improved realization rate and increased number or depth) of energy renovation policies as a complement to ambitious heat pump policies. The upper figure presents the social cost compared the the 'Baseline' of renovation policies, with countries where benefits outweigh costs highlighted in green, and those where costs exceed benefits in red. The lower figure displays the share of energy poverty, with countries having less than 5% energy poverty highlighted in green, and those exceeding this threshold in red.



renovation subsidies at all. The ‘All policies’ scenario leads to €3,074 billion investments in energy renovation, covered at 73% by subsidies, which require an additional €2,034 billion (or €81 billion annually between 2025 and 2050) in public spending. In contrast, the ‘Minimum cost national’ would only require an additional €5 billion per year, 75% of which would be covered by public spending, to unlock the profitable potential.

Fig.2.5 presents the social cost of each policy mix compared to the ‘Baseline’. All scenarios result in a positive socio-economic balance. However, the impact is modest for the ‘All policies’ scenario, that reduces social cost by €6 but increases private costs by €45 per household per year due to non-beneficial investments in energy renovation. The ‘Minimum cost national’ scenario outperforms the ‘Minimum cost EU’ scenario, emphasizing the importance of tailoring energy renovations policies to national contexts. Scenarios modestly reduce energy poverty due to low promotion of energy renovation, except for the ‘All policies’ scenario, which reduces energy-poor households to 2% of total population by 2050.

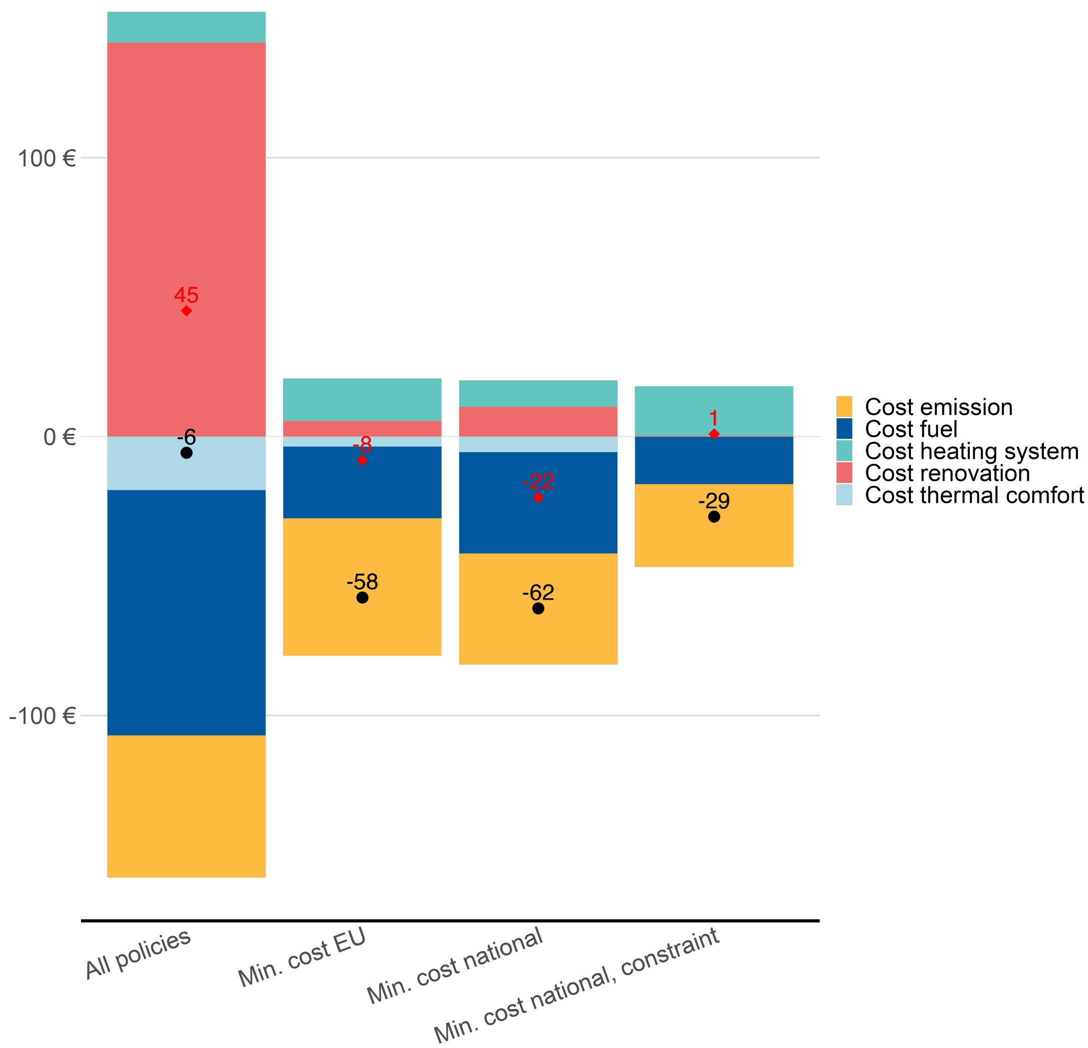
Figure 2.4 – Space heating emission (in $MtCO_2$) and energy use (in TWh) by heating system across policy scenarios.



8 Discussion

Despite progress in decarbonizing the energy supply and the increasing installation of heat pumps, current demand-side measures result in a 60% reduction in emissions compared to 2015 level, falling short of the 95% target by 2050. Our analysis shows that the implementation of ETS 2 alone is insufficient. Both cost reductions and subsidies for heat pumps are crucial to achieving climate targets. The investment gap is limited as the

Figure 2.5 – Social cost compared to the 'Baseline' scenario in euro per households and per year between 2025 and 2050. Black dots represent the social cost, while red diamonds indicate the private cost, excluding monetized benefits from avoided emissions.



cost of heat pumps largely substitutes the cost of other boilers, with prices expected to decrease, yet most countries will require additional subsidies, amounting to an additional €10 billion per year at the EU level.

In contrast, additional energy renovations have a modest impact on emissions reduction, indicating that a ‘Renovation Wave’ at the EU level is not justified by a cost-benefit analysis. Such a ‘Renovation Wave’ would require an average annual investment of €81 billion (€2,034 billion in total), with 73% of this amount coming from subsidies. Our analysis, however, suggests that subsidies for energy renovations have a positive balance in specific countries while also alleviating energy poverty and reducing peak electricity demand in most cases. These findings support the introduction of fine-tuned subsidies based on country, household income, and dwelling energy performance. Our conservative estimate, which serves as a lower bound since it does not include health, electricity system, or energy security benefits, indicates that an additional €5 billion per year, covered 75% by public expenditures, is necessary to tap into profitable potential. In addition to subsidies, ex-post inspections to increase realization rates and a focus on deep renovations are essential to fully capture energy-saving potential.

Importantly for policy makers, our findings call into question the goal of complete renovation of the European dwelling stock and suggest that public spending should be better targeted to specific countries and households. Given the heterogeneous financing needs across EU Member States and the limited revenues from ETS 2, EU funds should be considered to support the lowest income countries finance their energy transition.

Further development could extend our analysis by including additional co-benefits, such as health improvements and electricity savings. First, inefficient homes expose occupants to risks of acute coronary syndrome, pneumonia, and severe respiratory infections (Gillingham et al., 2021; Symonds et al., 2021). A study in France estimates that homes with theoretical heating consumption above 378 kWh/m^2/year incur a social cost of €135,000 per case, averaging €7,500 per exposed home (Dervaux and Rochaix, 2022). The probability of these diseases is higher for low-income households. Including these health benefits would likely make energy renovations advantageous for households exposed to these risks, reinforcing the need to target energy renovation efforts towards low-income households living in the worst-performing dwellings. Second, assessments find that the optimal level of energy renovation is driven by strong seasonal heat peaks rather than overall energy consumption, highlighting the co-benefit of reducing the need for additional power plants (Zeyen et al., 2021; Boomhower and Davis, 2020). This impact heavily depends on the national electricity generation mix. For example, since wind generation aligns better with winter heat demand peaks than solar PV, countries with substantial wind generation, such as Germany, Denmark, and Portugal, would see modest benefits from energy renovations (Zeyen et al., 2021). Coupling our model with a high-resolution energy model would allow us to fully understand these dynamics (Escribe et al., 2024).

Code availability

Message-ix Buildings is open-source. EU Implementation of Message-ix Buildings code can be freely accessed on GitHub: https://github.com/lucas-vivier/message-ix-buildings-eu.

CRediT authorship contribution statement

Lucas Vivier: Conceptualization, Methodology, Data curation, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing.
Alessio Mastrucci: Conceptualization, Writing - review & editing.

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Appendix

2.A Extended Data

Table 2.A.1 – Summary of the main results of the policy mix scenarios.

	Initial	Baseline	All policies	Optimal EU	Optimal national	Technical constraint
Population (Million)	449	465	465	465	465	465
Stock building (Million)	194	201	201	201	201	201
Energy use (TWh)	1851	1111	608	818	854	961
Energy use (MWh/hh)	9.6	5.5	3.0	4.1	4.2	4.8
Energy use (MWh/capita)	4.1	2.4	1.3	1.8	1.8	2.1
Energy saving (%)	-	40%	67%	56%	54%	48%
Energy use fossil (TWh)	1109	619	166	160	260	338
Share fossil-fuels (%)	60%	56%	27%	20%	30%	35%
Energy use electricity (TWh)	99	176	177	280	249	244
Emission (MtCO2)	304	128	34	33	53	70
Emission saving (%)	-	58%	89%	89%	82%	77%
Emission cum. (GtCO2)	-	7.9	5.3	5.4	5.9	6.4
Emission (tCO2/capita)	0.68	0.28	0.07	0.07	0.12	0.15
Energy poverty (M)	18	15	4	13	11	14
Energy poverty (%)	9%	7%	2%	6%	5%	7%
Heat-pumps (M)	12	60	90	97	90	80
Low carbon buildings (M)	86	116	150	159	149	143
Low carbon buildings (%)	45%	58%	74%	79%	74%	71%
Renovated buildings (M)	-	67	146	69	80	67
- advanced (M)	-	8	135	8	19	8
Renovated buildings (%)	-	33%	73%	34%	40%	33%
Total cost (B€)	-	2722	4898	2986	2973	2964
Total subsidies (B €)	-	-	2525	322	337	256
Cost heater (B€)	-	1682	1825	1889	1815	1922
Subsidies heater (B€)	-	-	273	322	248	254
Share sub. heater (%)	-	-	15%	17%	14%	13%
Cost renovation (B€)	-	1040	3074	1096	1158	1042
Subsidies renovation (B€)	-	-	2252	0	89	1
Share sub. renovation (%)	-	-	73%	0%	8%	0%
Taxes revenues (B€)	-	-	117	116	151	184
Gov. expenditures (B€)	-	-	2408	206	186	72

Figure 2.A.1 – Ranking of most impactful policies on Emission, Energy use, and Social cost outcomes: Policies are ranked based on their impact when assessed in interaction. First Order and Total Order effects are calculated using Sobol global sensitivity analysis, which quantifies the contribution of each input variable to the output variability. First Order effects measuring individual contributions and Total Order effects capturing combined contributions including interactions.

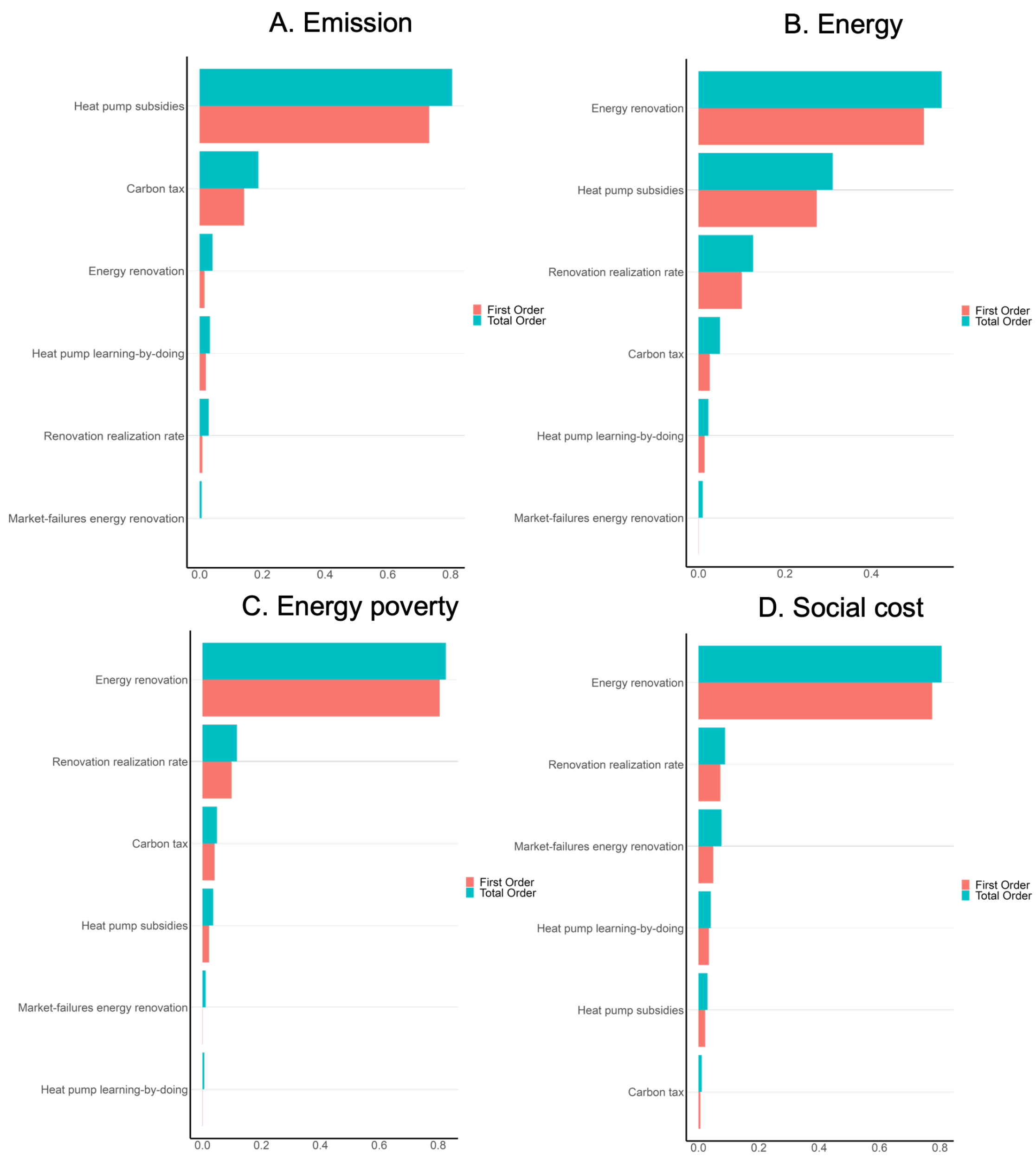


Figure 2.A.2 – Impact of policy mix on private cost, emission savings, and consumption savings: This figure excludes benefits from emissions avoided. Scenarios that include heat pumps with learning-by-doing and subsidies (medium level in blue, high level in green) are highlighted.

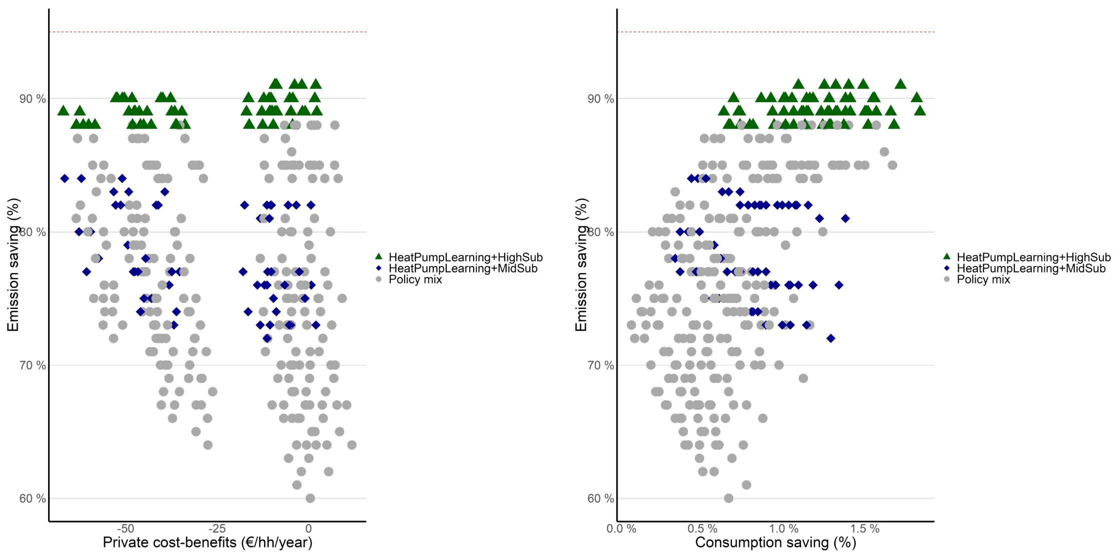


Figure 2.A.3 – Share of Fossil-Fuel Boilers in EU-27 Member States in 2015 (Initial) and in the Baseline Scenario: This figure explains why some countries do not rely on heat pump cost reductions or subsidies to meet climate targets. For example, Sweden, Finland, and the Baltic countries had a low share of fossil fuel boilers in 2015, while countries like the Czech Republic and Poland are projected to reach a similarly low share by 2050 due to current dynamics.

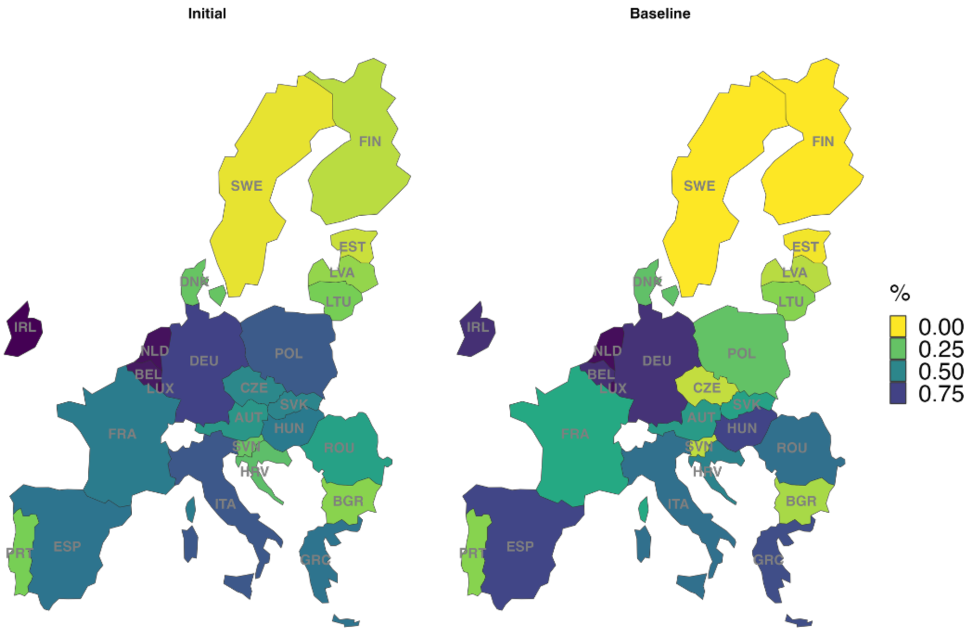
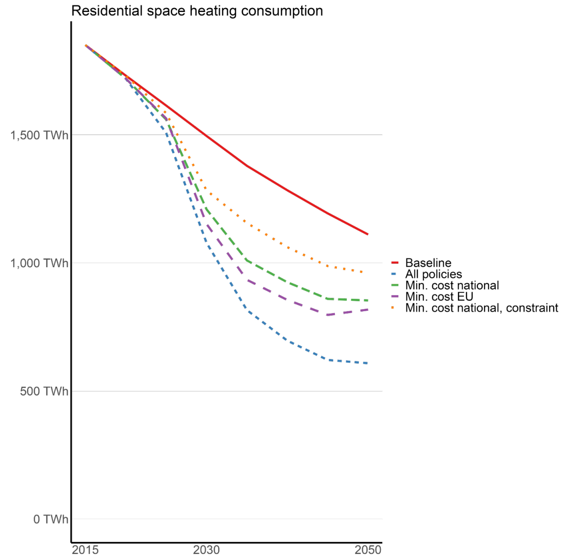


Figure 2.A.4 – Evolution of space heating consumption and electricity consumption in the EU across policy scenarios.



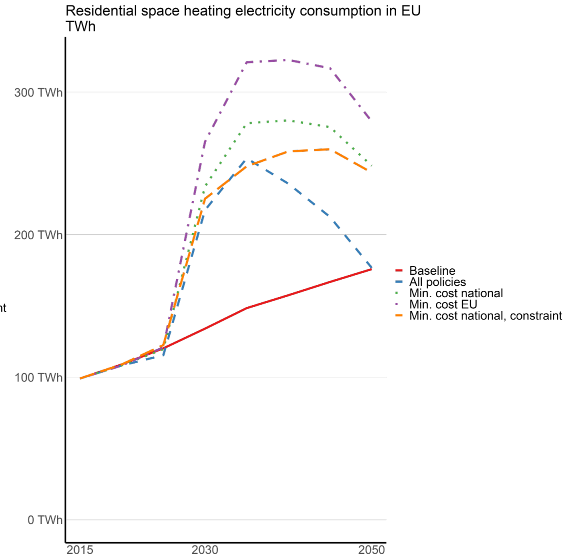
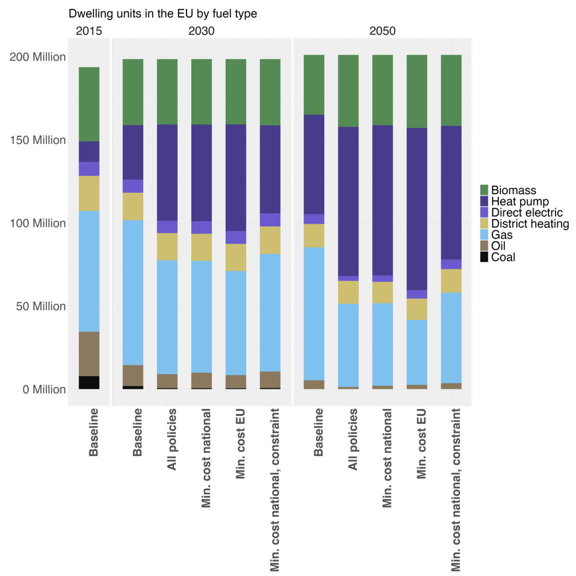
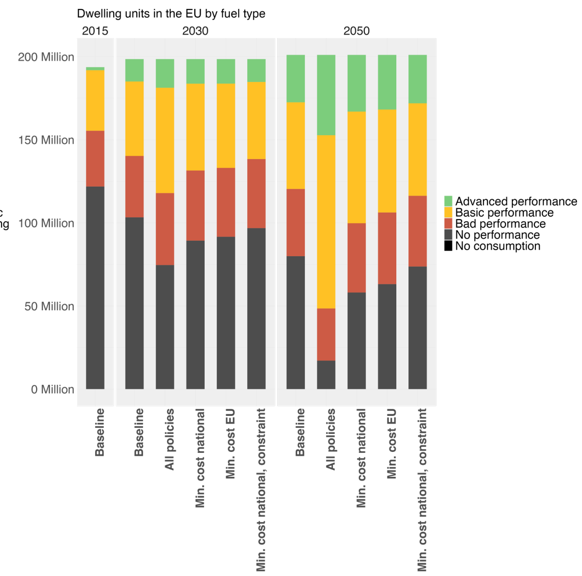


Figure 2.A.5 – Evolution of stock of heating system and energy performance of buildings in the EU. 'Advanced performance' stands for buildings using standard energy consumption lower than 50 kWh/m^2, 'Basic performance' between 50 kWh/m^2 and 100 kWh/m^2, 'Bad performance' between 100 kWh/m^2 and 150 kWh/m^2 and No performance more than 150 kWh/m^2.



A



B

2.B Supplementary information

2.B.1 Data

We draw from a variety of data sources to build a comprehensive representation of the builing stock and its dynamics. This section outlines the key data sources used in our study, with a Table 2.B.6 summarizing model parameters and sources. Macroeconomic projections, including population, urbanization, and income, follow the SSP2 scenario projections (Riahi et al., 2017), detailed by Mastrucci et al. (2021). Household sizes are derived from EUROSTAT data and are assumed to remain constant over time. An index factor from Knobloch et al. (2021) is used to extrapolate costs among EU member states. For the social cost of carbon, we utilize the latest estimates from the United States Environmental Protection Agency (EPA, 2022), converting the values to euros at an exchange rate of 0.9 €per USD to estimate the benefits of avoided emissions. We adopt the medium scenario with a 2% social discount rate.

Supply-side energy system

The supply side of the energy system is exogenously represented in our analysis but remains a critical input as it influences residential energy prices and carbon emission content. When energy prices rise, households typically reduce their heating energy consumption, which our model captures through the energy price elasticity of demand. Simultaneously, higher prices incentivize investments in energy renovations or heating system switches. These prices reflect the costs associated with the energy system and are influenced by mitigation pathways. Robust supply-side climate policies increase energy prices while reducing the emissions content of energy sources (Pietzcker et al., 2021). Therefore, it is crucial to rely on consistent trajectories for emission content and energy prices.

In this analysis, we begin with residential energy prices from 2015 (Knobloch et al., 2021) and project them to 2050 using the same growth pattern as the current policy scenario (Message NPi scenario). We consider carbon prices for the electricity and district heating sectors to account for the impact of the EU-27 cap-and-trade carbon price system, EU ETS. For the projection of the EU ETS price and emissions content of electricity, we rely on the results of Pietzcker et al. (2021). For district heating, we use the emissions content projection of the Message scenario, which aligns with a 1.5°C target, and apply the same ETS price.

Initial building stock

We developed an original database of the building stock in the EU-27 by integrating data from various sources. When data were unavailable at the same resolution, we assumed equal distribution across categories. Building numbers were determined using population and household size projections. We then classified buildings by archetypes and construction periods based on a 2017 snapshot from the Building Stock Observatory (BSO) (Commission, 2024). Each building segment was associated with a heating system

Figure 2.B.1 – Residential energy price in Germany for three different carbon tax scenarios.

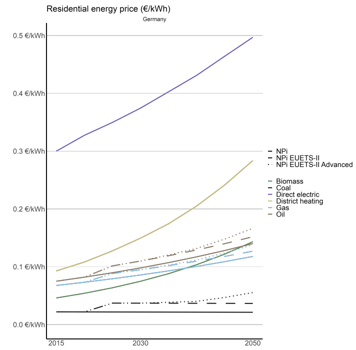


Table 2.B.1 – Social cost of carbon with a medium social discount rate of 2% (EPA, 2022), and EU ETS price projections from Pietzcker et al. (2021).

	Social cost of carbon	EU ETS price
2020	171	25
2025	189	25
2030	207	40
2035	225	50
2040	243	55
2045	261	75
2050	279	100

by country, using the updated JRC-IDEES database (Commission and Centre, 2024). Additionally, we incorporated occupation status and income levels from the EU-SILC survey. This synthesis provided a detailed representation of the building stock in 2015, as summarized in Table 2.1.

Space heating energy consumption

We extensively utilize the TABULA database (Loga et al., 2016), associating U-values and average sizes of walls, floors, roofs, and windows with each building's construction period and country. We assume a constant average heating degree-days by country over time (Loga et al., 2016). Based on multiple estimates, we use an average price elasticity of heating demand of -0.2. Additionally, we calibrate the energy model using final energy consumption for space heating from EUROSTAT data.

Stock turnover

We model the demolition of existing building stock using a Weibull function parameterized at the EU-level for each country. Additionally, we account for urbanization trends consistent with the SSP2 scenario.

Table 2.B.2 – Energy use for space heating in 2050 for all EU-27 member states.

Member states	Dwellings (M)	Floor size (Mm2)	Energy (kWh/dwelling)	Energy (kWh/m2)	Energy (TWh)
Bulgaria	2.9	192	4,662	71	14
Czech Republic	4.5	358	12,224	153	55
Estonia	0.6	35	12,480	214	8
Hungary	4.3	344	12,100	151	52
Lithuania	1.4	87	8,403	137	12
Latvia	0.9	58	9,608	150	9
Poland	13.7	1,163	10,911	129	150
Romania	7.8	571	6,996	96	55
Slovakia	2.0	173	8,079	92	16
Slovenia	0.8	57	10,452	153	9
Austria	3.9	453	13,710	118	53
Belgium	4.8	397	14,733	178	70
Cyprus	0.4	50	3,075	27	1
Germany	41.1	4,469	10,576	97	434
Denmark	2.8	368	11,390	88	32
Spain	19.1	2,004	3,826	37	73
Finland	2.7	327	14,209	119	39
France	29.4	2,859	10,750	111	316
Greece	4.4	492	6,722	60	30
Croatia	1.6	130	11,993	144	19
Ireland	1.8	264	11,810	79	21
Italy	25.6	2,780	9,931	92	254
Malta	0.2	16	747	7	0
Netherlands	7.7	987	9,029	70	70
Portugal	4.3	537	2,328	19	10
Sweden	4.9	528	10,089	93	49
EU-27	194	19,699	9,553	94	1,850

Replacement of heating systems

We rely on CITER studies for estimates of heating system costs in Denmark, extrapolating these to all countries using a cost index factor. In some scenarios, we consider a learning rate of 32% for heat pumps (Weiss et al., 2010), while assuming constant prices for other heating systems. We use the same assumptions for system efficiency and equipment lifetime as previous modeling assessments (Knobloch et al., 2021), uniformly setting the lifetime at 20 years for all technologies. To estimate current heating system replacement dynamics by EU member state, we utilize the latest update of the JRC-IDEES database.

Present discount rates are sourced from the BRISKEE project (Hartner et al., 2017), varying by country and owner income, derived from discrete choice experiments. We apply the lowest discount rates to landlords, who are generally wealthier. Additionally, we incorporate a status quo bias in the household utility function to account for the preference to retain existing heating systems, partly explaining the inertia to switch to low-carbon technologies. This bias is informed by a discrete choice experiment in France (Stolyarova, 2016) and used in Vivier and Giraudet (2024). The study's willingness-to-pay value of €4,300 for keeping the same system was included as a bonus in our model's utility function and extrapolated to other EU member states using the cost index factor.

Table 2.B.3 – Share of the population suffering from energy poverty in 2015 (EUROSTAT, EU-SILV survey)

Member states	Energy poverty (%)
Belgium	5%
Bulgaria	39%
Czechia	5%
Denmark	4%
Germany	4%
Estonia	2%
Ireland	9%
Greece	29%
Spain	11%
France	6%
Croatia	10%
Italy	17%
Cyprus	28%
Latvia	15%
Lithuania	31%
Luxembourg	1%
Hungary	10%
Malta	14%
Netherlands	3%
Austria	3%
Poland	8%
Portugal	24%
Romania	13%
Slovenia	6%
Slovakia	6%
Finland	2%
Sweden	1%

Table 2.B.4 – Cost of heating system in Denmark. We use cost index to extrapolate to other European countries. Source: JRC DataSet

Heating system	**Cost**
Oil boiler	€6,600
Gas boiler	€4,000
Coal boiler	€6,600
Biomass boiler	€11,000
Heat pumps	€11,000
Direct electric	€4,000
District heating	€3,500

Energy renovation decision

The data on renovations primarily come from a comprehensive survey of building renovations in Europe (European Commission et al., 2019). This survey provides detailed insights into renovation rates, costs, and expected final energy savings, broken down by member state and across four renovation levels.

Additionally, we use the Household Budget Survey to estimate barriers faced by landlords and owners of multi-family dwellings. First, we determine occupancy status and housing type using information on rents and maintenance costs in multi-family buildings. We then use data on dwelling maintenance and repair as indicators of energy renovations. By comparing the rate of maintenance and repair in multi-family dwellings to single-family ones, and in rental properties to owner-occupied ones, we extrapolate this ratio to energy renovation rates. This approach gives us a rough estimate of the barriers faced by landlords and owners of multi-family dwellings in the absence of more detailed data. From these differentiated renovation rates, we estimate reduced-form distortions in energy renovation decisions for landlords and owners of multi-family dwellings by EU member state during the calibration procedure.

Similar to heating system investment decisions, we use present discount rates from the BRISKEE project (Hartner et al., 2017). These rates, derived from discrete choice experiments, vary by country and owner income. We apply the lowest discount rates to landlords, who are generally wealthier.

There is no direct estimate of the price elasticity of demand for energy renovations in the literature. We rely on econometric assessments of the French tax credit initiative that offsets 30% of the cost of energy renovation. Nauleau (2014); Risch (2020) find that about 70% of tax credit beneficiaries would have renovated even without the incentive. Based on these findings, we estimate the price elasticity of demand for renovations to be approximately -1. We generalize this value for all countries and adjust the utility function in our model to reproduce this price elasticity in the base year.

Table 2.B.5 – Energy renovation rate and cost for medium energy renovation from European Commission et al. (2019)

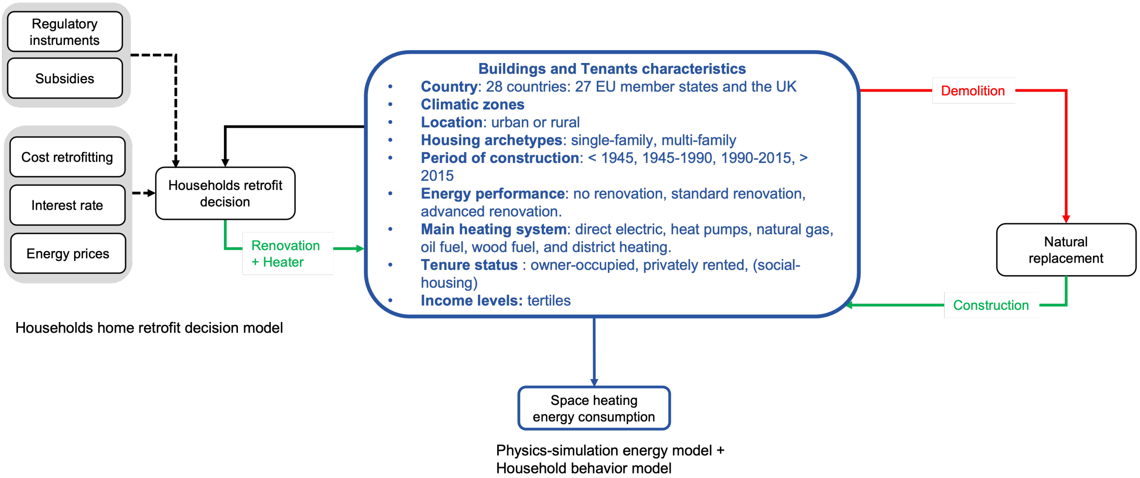
Member states	Annual renovation rate	Cost (€/m^2)
Austria	1.9%	230
Belgium	1.2%	174
Bulgaria	1.4%	86
Croatia	1.6%	93
Cyprus	2.4%	130
Czech Republic	1.7%	115
Denmark	0.6%	313
Estonia	0.8%	117
Finland	0.3%	389
France	1.2%	193
Germany	1.0%	285
Greece	1.3%	144
Hungary	1.0%	113
Ireland	0.7%	266
Italy	1.8%	121
Latvia	0.9%	86
Lithuania	0.9%	138
Luxembourg	0.5%	241
Malta	0.7%	190
Netherlands	0.9%	181
Poland	1.5%	78
Portugal	1.4%	54
Romania	1.4%	84
Slovakia	1.1%	118
Slovenia	1.4%	129
Spain	2.0%	38
Sweden	0.8%	388

Table 2.B.6 – Overview of data source used in the EU implementation. 'hh' stands for household.

Variable	Unit	Data sources
Macro		
Population		Riahi et al. (2017)
Households size	hh per dwelling	EUROSTAT, EU-SICL Survey
Floor per capita	m^2 per capita	Riahi et al. (2017)
Income per quintiles	€/(hh.year)	Riahi et al. (2017)
Countries cost factor	%	Knobloch et al. (2021)
Social cost of CO2	€/tCO2	EPA (2022)
Social discount rate	%	EPA (2022)
Energy poverty households	-	CITER
Supply-side Energy system		
Energy prices initial	€/kWh	Knobloch et al. (2021)
Energy prices trends	%/year	Message-ix | NPi scenario
Emission factor initial electricitity	kgCO2/kWh	Unnewehr et al. (2022)
EU ETS prices	€/tCO2	Pietzcker et al. (2021)
Emission factor trend	%/year	Pietzcker et al. (2021)
Initial building stock		
Share of archetypes and construction period	%	Building stock observatory, Commission (2024)
Share of a heating system	%	JRC-IDEES 2024
Share of occupancy status and income level	%	EU-SICL Survey
Space heating energy consumption		
U-values for existing buildings	W/(m^2.K)	Building stock observatory, Commission (2024)
U-values for new buildings	W/(m^2.K)	Building stock observatory, Commission (2024)
Surface area of envelope components	m^2	Loga et al. (2016)
Heating degree days	# days	Loga (2013)
Parameters TABULA Calculation method		Loga (2013)
Short-term price elasticity of heating demand		-0.2
Final space heating consumption	toe	EUROSTAT
Stock turnover		
Urbanization / Share of archetypes	%	Riahi et al. (2017)
Probability of demolition (shape, scale)		
Heating system investment decision		
Cost heating system	€	
Learning rate heat pumps	%	Knobloch et al. (2021)
Lifetime heating system	# years	Knobloch et al. (2021)
Efficiency	%	Knobloch et al. (2021)
Share heating system installation in base year	%	JRC-IDEES 2024
Household present discount rate	%	Hartner et al. (2017)
Inertia preferences	€	Stolyarova (2016)
Technical constraint		Own assumption
Envelope energy renovation decision		
Cost energy renovation	€/m^2	Renovation Survey, European Commission et al. (2019)
Lifetime renovation	# years	Own assumption (30)
Energy saving by energy renovation	%	Renovation Survey, European Commission et al. (2019)
Energy renovation rate	%/year	Renovation Survey, European Commission et al. (2019)
Market-share energy renovation	% per year	Renovation Survey, European Commission et al. (2019)
Price elasticity of demand for energy renovation	-	Own assumption (-1)
Household present discount rate	%	Hartner et al. (2017)
Renovation rate in multi-family	%	Own calculation from Household Budget Survey
Renovation rate in rented dwellings	%	Own calculation from Household Budget Survey

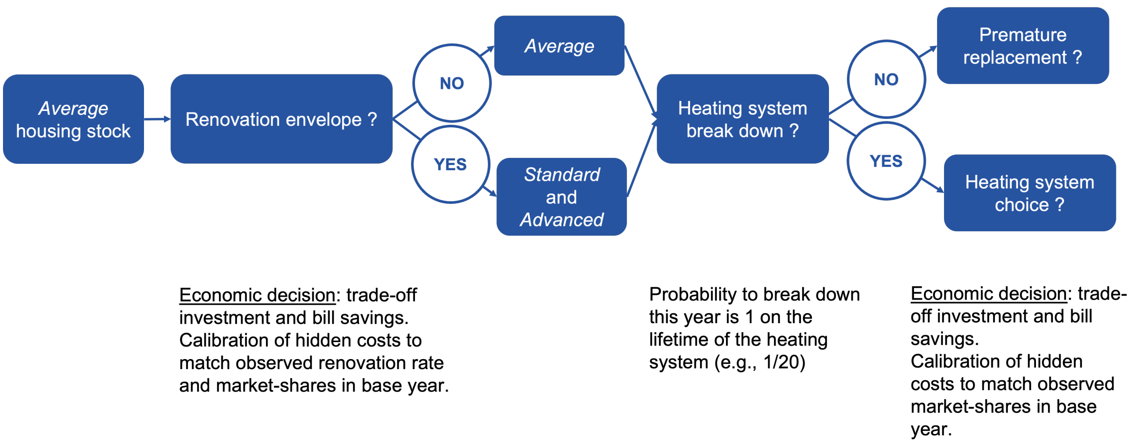
2.B.2 Model

Figure 2.B.2 – Framework of Message-ix Buildings: a bottom-up model of the evolution of the energy performance of the building stock.



The model is built on Vivier and Giraudet (2024). Here, we briefly summarize the specification of the standard investment decision model, without market frictions or behavioral anomalies. The model is applied successively to energy renovation and heating system investment decision (see Fig.2.B.3).

Figure 2.B.3 – Household energy efficiency investment framework. The model endogenously determines the decision to renovate the building and replace the heating system.



CHAPTER 3

How to allocate mitigation efforts between home insulation, fuel switch and fuel decarbonization? Insights from the French residential sector

Published in Environmental Research Letters (DOI: 10.1088/1748-9326/ad3a7f)
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Joint work with Célia Escribe, Louis-Gaëtan Giraudet and Philippe Quirion

Abstract

Reducing greenhouse gas (GHG) emissions in residential buildings relies on three channels that are rarely assessed together – insulating homes, switching to low-carbon heating systems and decarbonizing heating fuels. Their combination results from an interplay between top-down planning of the energy system and decentralized policies for the residential sector – insulation subsidies in particular. In this paper, we examine how the design of insulation subsidies influences the allocation of efforts between these three channels. To do so, we use an innovative framework coupling a highly detailed model of residential energy demand with a highly detailed model of the energy system, both focused on France. We find that the most cost-effective effort allocation to reach carbon neutrality implies 19% emission reductions from home insulation, 36% from fuel switch and 45% from fuel decarbonization. This however requires perfectly targeted subsidies. In three alternative, arguably more realistic subsidy scenarios, we find that total system cost is increased by 11 to 16%. Our results highlight the key role played by subsidy specifications in determining the trade-off between insulation and fuel switch, e.g., insulation investments doubles, and heat pump adoption is 19%

lower, when subsidies are restricted to the most comprehensive measures. Finally, alternative assumptions regarding the availability of renewable energy sources – biogas in particular – imply stronger energy efficiency efforts.

Keywords: climate change mitigation, energy efficiency, residential buildings, integrated assessment, energy modeling, second-best policy.

1 Introduction

The building sector contributes significantly to energy consumption and greenhouse gas (GHG) emissions in temperate and high-income countries (Cabeza et al., 2022; IEA, 2023). Most of these contributions stem from residential space heating. To mitigate the associated GHG externality, three main actions can be pursued: (i) improving the energy performance of the building envelope, e.g., through home insulation; (ii) switching to low-carbon heating systems, e.g., through the adoption of heat pumps and wood boilers; and (iii) decarbonizing heating fuels, e.g., by investing in wind power, solar power or renewable gas production (e.g. through methanation or biogas). Mitigation strategies therefore result in a trade-off between demand- and supply-side investments to abate GHG emissions while maintaining energy balance at the hourly scale. In particular, the strong seasonality in space heating demand drives peak energy load, thus impacting the investments needed in the energy sector (Maxim and Grubert, 2023). These strategies also result from an interplay between centralized decisions about the energy system and decentralized decisions from households in the residential sector, which makes them challenging to assess together.

From a policy perspective, the optimal effort allocation between the three mitigation channels would theoretically be guided by a carefully designed carbon price – the textbook economic solution to the GHG externality. In the residential sector, however, investment barriers are at the source of the ‘energy efficiency gap’ – i.e., suboptimal investment in energy efficiency (Gerarden et al., 2017). Chief among these barriers are credit constraints keeping low-income households in poorly insulated dwellings, where significant adverse health effects have recently been identified (Dervaux and Rochaix, 2022). In this context, a first-best policy aimed at maximizing social welfare would combine a common carbon price with individually tailored energy efficiency subsidies in the residential sector (Allcott et al., 2014; Chan and Globus-Harris, 2023). In practice, however, carbon prices are rarely set at their socially optimal level, nor do they cover all relevant sectors – if they are implemented at all[1] –, and subsidies cannot realistically be individually tailored.

While using realistic energy efficiency subsidies in the residential sector to jointly address the GHG externality and the energy efficiency gap is considered a second-best approach, there is significant flexibility in the way they can be designed. The subsidy amount can be proportional to the insulation performance, or determined *ad valorem*, i.e., as a fixed proportion of the product price. In addition, subsidies may be uniform or targeted to more comprehensive measures. The combination of these features in turn affects the allocation of efforts between home insulation, fuel switch and fuel decarbonization in ‘second-best’ approaches.

Most related analyses, however, keep at least one channel exogenous – e.g., home insulation and fuel switch in energy system models (Brown et al., 2018; Shirizadeh and Quirion, 2022), fuel decarbonization in building stock models (Mastrucci et al., 2021; Giraudet et al., 2021; Cabeza et al., 2022; Berrill et al., 2022). This limitation may result in inconsistencies between energy demand projections and the transformations they

[1] For instance, in France, the government froze the "household" carbon tax rate in response to the Yellow Vest protest movement (Douenne and Fabre, 2022).

imply in the supply system. A few recent studies have made significant progress towards endogenizing all three channels (Zeyen et al., 2021; Mandel et al., 2023) for all EU. They however focus on optimal investment and ignore distortions in household decision-making. Finally, mitigation strategies have recently been investigated in the building sector using REMIND, a global integrated assessment model (Levesque et al., 2021), but its processes are too coarse to capture the heterogeneity inherent in the building sector and the detailed impact of demand-side policies on the energy mix.

In this paper, we contribute to the integrated assessment of mitigation strategies in the residential sector by assessing different effort allocations under various subsidy designs. To do so, we develop an integrated framework combining a detailed representation of technology with advanced decision-making processes. Specifically, we link Res-IRF, a model of household energy demand (Vivier and Giraudet, 2024) and EOLES, a model of energy supply (Shirizadeh and Quirion, 2021), both focusing on France. The linkage is realized through joint optimization in a dynamic recursive perspective. The different policy options are assessed by a social planner seeking to minimize total system costs – including investment, energy operation and health costs – while achieving carbon neutrality by 2050. The added value of our framework lies in providing a detailed, endogenous description of all three mitigation channels while relying on an optimization framework fit for discussing first- and second-best approaches. Specifically, we introduce four policy scenarios, each including a shadow price of carbon in the energy system alongside ad-valorem subsidies for heat pumps. The differences among scenarios arise from the specification of home insulation subsidies. The first scenario adopts a first-best approach, offering perfectly targeted subsidies for home insulation. In contrast, the subsequent three scenarios correspond to a second-best approach, offering more realistic, albeit coarser, subsidy specifications (see Table 3.1).

In the 'first-best' approach where homeowners are induced to invest in the insulation level that is the most socially profitable for their dwelling, we find that home insulation contributes 19% of emission reductions, fuel switch 36% and fuel decarbonization 45%. Turning to alternative, arguably more realistic subsidy designs in 'second-best' approaches, we find that total system cost increases by 11% under proportional subsidies, 14% under *ad valorem* subsidies targeted at comprehensive actions and 16% under uniform *ad valorem* subsidies. The increase in total cost is paralleled by a greater role of fuel switch and lesser role for insulation. As for the energy system, we find that second-best scenarios imply a greater reliance on peaking plants and solar PV than in first best. Lastly, we assess the robustness of our results to fuel decarbonization specifications and find the potential of biogas to be the most sensitive assumption. Our main policy conclusions are as follows: first, it is crucial to engage all available channels for mitigation; second, the specification of subsidy programs significantly influences both the strategic approach and its cost-effectiveness.

The remaining of the paper is organized as follows. Section 2 describes the method. Section 3 presents the results. Section 4 discusses them and Section 5 concludes.

Table 3.1 – Summary of the interaction between decarbonization channels and policies.

	Supply-side: Energy sector	**Demand-side: Residential sector**	
Channels	**Fuel decarbonization**	**Home insulation**	**Fuel switch**
First-best approach policies	Shadow price of carbon associated with the carbon neutrality constraint	Residential carbon tax	
		Perfectly targeted subsidies	Ad valorem subsidies for heat-pumps
Second-best approach policies	Shadow price of carbon associated with the carbon neutrality constraint	Residential carbon tax	
		Coarsely targeted subsidies	Ad valorem subsidies for heat-pumps

2 Methods

We take a whole-system approach coupling a demand-side model, Res-IRF, with a supply-side energy model, EOLES, both focusing on France.

2.1 Modelling parts

Res-IRF is a dynamic microsimulation model of energy demand for space heating in the French building stock (Vivier and Giraudet, 2024). Developed with the goal of improving behavioral realism (Mundaca et al., 2010), the model provides a rich description of insulation levels (for walls, roofs, floors and windows) and heating systems (heat pumps, electric heating, gas-, oil- and wood-fired boilers). It simulates the evolution of energy consumption through three endogenous processes – the construction and demolition of buildings, the renovation of existing dwellings through insulation and fuel switch, and adjustments in heating behaviour. Energy efficiency investments are made by households and influenced by key economic costs and benefits, namely investment and financing costs, energy bill savings, and subsidy amounts. When making these investments, households face various barriers, such as credit constraints (decreasing with income), landlords' inability to pass energy efficiency investment onto rents, decision frictions in collective housing, and hidden costs (e.g., the inconvenience of insulation works). The model also takes into account a wedge between predicted and realized energy consumption in order to capture the much-discussed energy performance gap (Christensen et al., 2021). This wedge varies endogenously in response to energy efficiency improvements, energy prices and household income and captures the rebound effect in particular. The exercise presented here uses Version 4.0 of the model.

The EOLES model suite optimizes investment in and operation of the French energy system in order to meet a given energy demand (Shirizadeh and Quirion, 2022). Total cost include annualized capital costs, maintenance costs and operating costs. The model relies on a detailed description of various technologies. Electricity can be generated by solar PV, onshore and offshore wind, hydroelectricity, gas used in open cycle (OCGT) or combined cycle gas turbines (CCGT), and nuclear reactors. Hydrogen can be produced by water electrolysis. Gas can be fossil gas, biogas produced by methanization or pyrogazeification, or synthetic methane produced by methanation. Energy can be stored in batteries and pumped-hydro storage stations, in the form of hydrogen in salt caverns or in the form of methane in gas reservoirs. Technology dispatch is specified with an hourly temporal resolution, capturing the weather dependence of supply and demand and the specific challenges related to flexibility options. Given the strong reliance on gas in the residential sector currently, the interaction between gas and electricity becomes critical. While Res-IRF focuses on residential energy demand, EOLES spans all end-use sectors electricity demand. We therefore need to feed the latter with exogenous assumptions regarding non-residential uses (i.e., commercial buildings, industry, transport and agriculture), which we borrow from the French Transmission System Operator (TSO)'s latest projections ((RTE, 2022), central scenario). In particular, this exogenous demand includes space cooling demand, which is therefore not subject to endogenous rebound effects.[2]. We consider France independently, excluding interaction with neighboring countries. Additional details can be found in the Supplementary material 4.C.1, and an exhaustive description of the model is available in Shirizadeh and Quirion (2021).

2.2 Coupling

Our approach to coupling Res-IRF and EOLES relies on a dynamic recursive optimization framework in which a social planner makes investments in the energy system while funding energy efficiency subsidy programs in the residential sector. Specifically, the social planner seeks to minimize the total system cost under a national carbon budget constraint. Two subsidy programs are considered, together supporting the most strongly encouraged energy efficiency measures in France – insulation of the building envelope and adoption of heat pumps. These programs add up to the carbon tax that is already in place in the French residential sector.[3] On top of this policy portfolio, a residual carbon price is endogenously determined as the shadow price of the carbon constraint.

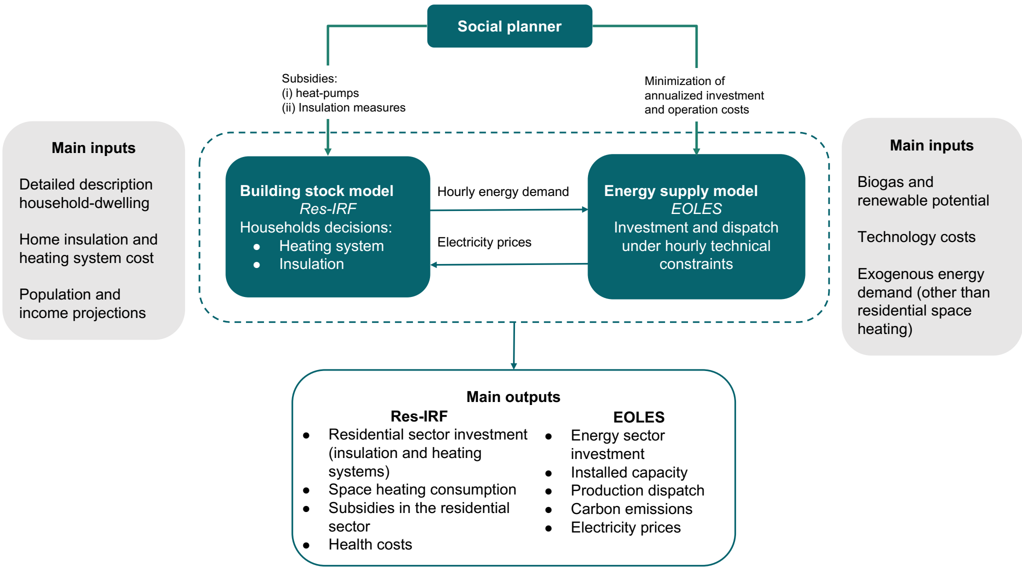
The coupled modelling framework is illustrated in Figure 3.1. The social planner's objective function is the annualized system cost, i.e., the sum of the annualized costs of the energy supply system, the annualized costs of heating and insulation investment, and the annualized health costs from poor insulation. Our inclusion of health costs in the social planner's objective function is motivated by recent evidence of high morbidity and mortality rates among low-income households living in the least energy efficient dwellings (Dervaux and Rochaix, 2022).[4] Within a given time step, a given set of subsidy parameters determines final energy demand for residential heating in the Res-IRF model. At the

[2]Reversible heat pumps are not included in the analysis.

[3]Initially scheduled to increase, the French carbon tax was frozen at €45/tCO_2 from 2020 to 2050 in response to the yellow vest movement.

[4]We thereby treat health costs as a pure externality, internalized by the social planner but not by households. One could argue that, since health is a private matter, failure to internalize it is rather akin to consumer irrationality. Notwithstanding, given the disproportionate prevalence of health costs among low-income households, we attribute them to credit constraints preventing their elimination through energy renovation – a legitimate market failure to correct.

Figure 3.1 – Joint optimization of demand and supply investments for a single time step. Control variables for the social planner include subsidies in the building sector and investment and dispatch in the energy sector.



same time, the EOLES model is run to optimize capacity investment and dispatch while meeting total energy demand. The social planner therefore effectively sets the subsidy parameters so as to minimize total system cost under the carbon budget constraint. This optimization is particularly challenging from a computational perspective, since the objective function depends on the subsidy parameters in a nonlinear way. To cope with this difficulty, we use a bayesian optimization framework relying on the Expected Improvement algorithm (Vazquez and Bect, 2010). Further details can be found in Section 3.E.2 in the Supplementary material.

The one-step optimization is then iterated over the entire time horizon, assuming a 5-year time step, from 2020 to 2050.[5] Note that our framework is myopic in that the social planner only considers one time step at a time. We argue this is fit for capturing short-sightedness in both the politicians' and stakeholders' behavior (Victoria et al., 2020), resulting in slow capital accumulation in both the building stock and the energy mix. Electricity prices are endogenously determined through demand-supply equilibrium. Technically, electricity prices for a given period are computed as the levelized cost to meet endogenous demand from the previous period. The resulting prices are topped with exogenous taxes. The prices of other fuels (gas, oil, wood) are exogenous.

Building on ADEME (2022), we consider an emission target of 4 $MtCO_2$ in 2050 for the electricity and residential sectors, representing a 93% reduction compared to 2018 emissions, and we assume a convex decrease in emissions along the trajectory (as displayed

[5]Res-IRF is run with the current policy scenario until 2025 and the first optimization period concerns the period 2025-2030.

in Table 3.B.1 in the Supplementary material). All investments costs are annualized with a 3.2% discount rate, which is the value recommended for public investment in France (Ni and Maurice, 2021). We then compare all scenarios in terms of total system cost, defined as the sum of annualized costs over the 2025-2050 period.[6] The health benefits from upgrading the least efficient dwellings are valued using newly published data for France (Dervaux and Rochaix, 2022).[7] We use the representative weather year 2006 as the basis for calculating renewable energy production and space heating demand (Pfenninger and Staffell, 2016). It has been shown that 2006 is the best representative year for weather conditions (Shirizadeh et al., 2022).[8]

2.3 Scenarios

Subsidy specifications are the key control variables in the social planner's optimization problem alongside investment and dispatch in the energy system. We consider two types of subsidies – one for the adoption of heat pumps and one for insulation of the building envelope. As heat pumps emerge as the primary choice for transitioning to low-carbon heating fuels in the building sector (Fallahnejad et al., 2024), we focus on a single *ad valorem* subsidy design, the rate of which is to be optimized.

In contrast, insulation investments offer a multitude of options. Hence, we explore diverse specifications for this subsidy design, presenting different scenarios that reflect different paradigms (refer to Table 3.2). In a first-best, 'optimal' scenario, households behave as if they were facing no investment barrier and thus invest in the most socially profitable option. In second-best scenarios, the barriers are taken into account and subsidies are implemented to overcome them, with a rate to be determined. In an effort to mimic the key programs implemented in France, we consider three subsidy regimes: a 'uniform' one, similar to the tax credit program that ran from 2005 to 2020; a 'comprehensive' one, similar to a scheme called 'Habiter mieux sérénité'; and a 'proportional' one, similar to white certificate obligations (Giraudet et al., 2021). By design, the 'uniform' subsidy is less targeted than the 'comprehensive' and the 'proportional' subsidies.

The endogenously-determined subsidy levels and the effort allocation they implement are sensitive to underlying assumptions regarding the potential for low-carbon energy sources – biogas (including methanization and pyrogazeification), solar, onshore and offshore wind and nuclear. As pointed out by public authorities, the magnitude of these potentials is highly uncertain (ADEME, 2022; RTE, 2022). To assess the robustness of our results to such uncertainty, we re-run our scenarios with more conservative assumptions regarding the potentials for biogas, renewables and nuclear power (Table 3.2). The

[6] Building on Hirth et al. (2021)'s work with the EMMA model, we use a 0% rate of pure time preference to give equal weight to all years when adding up annualized costs over the whole time horizon.

[7] €7,500 for each upgraded dewlling occupied by a low-income household, which can be decomposed into €400 reduction in care costs, €1,400 avoided morbidity cost and €5,700 avoided mortality cost.

[8] Our study does not take into account the effects of climate change, as we assume a static climate throughout the study period. Climate change is expected to only slightly reduce space heating demand in France by 2050 (Elnagar et al., 2023); this factor is outside the scope of our current study.

Table 3.2 – Description of insulation policy scenarios and supply-side assumptions. All scenarios include *ad valorem* subsidies for heat pumps. Variants for supply-side assumptions are based on scenarios from ADEME (2022) (scenario S2) and RTE (2022).

Scenario	Description
Insulation policy	
Optimal	The social planner designs an optimal subsidy for each household inducing them to invest in their more cost-effective option from a system perspective.
Uniform	All insulation measures are supported with the same *ad valorem* rate, to be determined.
Comprehensive	The *ad valorem* subsidy is restricted to the most comprehensive insulation measures—i.e., those permitting an upgrade by at least two energy performance certificate (EPC) ratings.
Proportional	All insulation measures are supported by a subsidy, the amount of which is proportional to the expected energy savings. The policy variable to be determined is the euro amount per unit of saved energy.
Variants with supply-side restrictions	
Biogas-	Biogas potential reduced by 28% compared to reference.
Renewables-	Potential for solar PV, onshore wind and offshore wind is reduced by 40%, 12% and 20% respectively compared to reference.
Nuclear-	Potential for newly built nuclear capacity is reduced by 50% compared to reference.

potentials for renewable energies (photovoltaics, onshore wind power, offshore wind power) and nuclear power in the reference scenario are given in the supplementary material.

2.4 Effect decomposition

In order to decompose the various channels of GHG emission reductions, we use an additive log mean division index (LMDI) model (Ang and Zhang, 2000) specified as follows:

$$\text{GHG} = \text{Surface} \times \sum_i sh_i \times I_i \times HI_i \times C_i$$

where sh_i is the share of heating system i in the the building stock (%), I_i is the specific energy consumption (kWh/m^2) determined by the insulation level and C_i is the carbon content of the fuels used (gCO$_2$/kWh). Next to these three channels of interest, we consider the contributions of total housing surface (m^2) and the varying intensity with which households heat their dwelling (HI_i, dimensionless).[9] Additional details about the methodology can be found in Section 3.C in the Supplementary material.

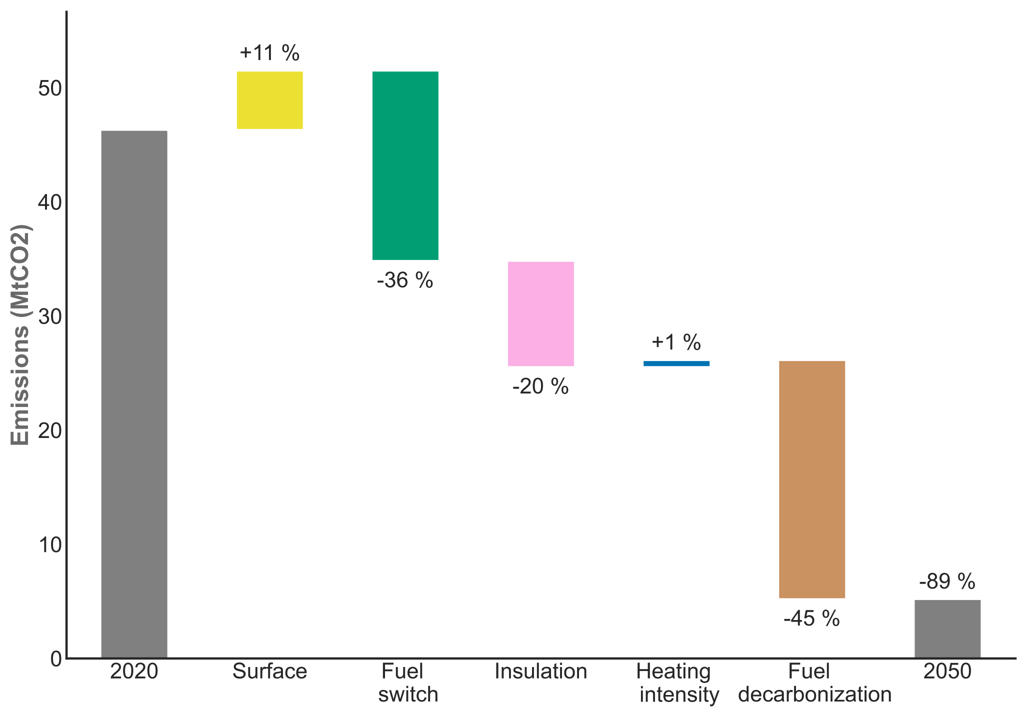
[9]This heating intensity varies with energy efficiency improvements and energy prices in Res-IRF to reflect adaptation of households heating behavior.

3 Results

3.1 First-best scenario

In the 'optimal' scenario, home insulation (net of rebound effect) accounts for 19% of total GHG emission reduction in 2050 compared to 2020, fuel switch for 36%, and fuel decarbonization for 45% (Figure 3.2). In addition, energy consumption is reduced by 37% in 2050 compared to 2020, mainly through insulation (column 'Optimal' in Table 3.3). This order of magnitude is consistent with that found in related assessments of the building sector, e.g., 21-35% energy consumption reduction in Mandel et al. (2023), 44-51% in Zeyen et al. (2021) and 32% in Palzer and Henning (2014).[10]

Figure 3.2 – Decomposition analysis of the main decarbonization channels for the first-best scenario ('optimal scenario') using LDMI method (Section 2). The increase in heating intensity is due to the rebound effect. Home insulation accounts for 19% of total GHG emission reduction when accounting for rebound effects that stem from heating intensity.



Unconstrained by investment barriers in energy efficiency markets, the social planner targets insulation efforts towards upgrading the least efficient dwellings, i.e., those with EPC ratings G and F. This approach significantly reduces energy bills, operational costs in

[10]The latter two studies rely on coarser representations of the building stock, thus potentially overestimating the potential for cost-efficient insulation. They moreover have a broader regional scope, not limited to France.

the electricity sector and health costs. As a result, the count of F- and G-rated dwellings sharply decreases and 80% of dwellings are rated C or better in 2050 (Figure 3.E.3 in the Supplementary material).

By then, 25% of energy demand for space heating is met by electricity (Table 3.3) and 15 million heat pumps have been installed, providing heating service to about 17% of dwellings. Annual electricity consumption remains relatively stable over time under the countervailing effects of insulation efforts and increased heat pump adoption. Overall, this first-best strategy requires approximately €150 billion investment in insulation (or €6 billion per year on average) and €77 billion investment in heat pumps (or €3 billion per year on average) (Table 3.3).

In 2050, 77% of electricity generation is met by solar, wind, and hydro power. This order of magnitude is consistent with that found in related works, e.g., 92-97% in Zeyen et al. (2021) and 90% in Mandel et al. (2023). Our somewhat lower figure can be attributed to the significant role played by nuclear in France, accounting for 20% of electricity generation in our assessment. As in Zeyen et al. (2021), the available potential for biogas is fully utilized, providing 46 TWh through methanization and 19 TWh through pyrogasification. Synthetic methane (obtained from methanation) is employed to fulfill the remaining gas demand for space heating and peak-load power plants, while hydrogen (obtained from electrolysis) is exclusively used for peak-load plants. Overall, peak-load power plants (gas turbines, such as OCGT and CCGT, and hydrogen turbines H2-CCGT), contribute 2.4% of total electricity production. In 2050, 17 TWh of fossil gas are still used to meet total methane demand – including final gas demand from the residential sector and intermediary gas demand for peaking plants, which is low enough to stay within the 4 $MtCO_2$ carbon budget of that year.

Figure 15 in the Supplementary material displays the comprehensive breakdown of total system costs including the energy supply system cost.

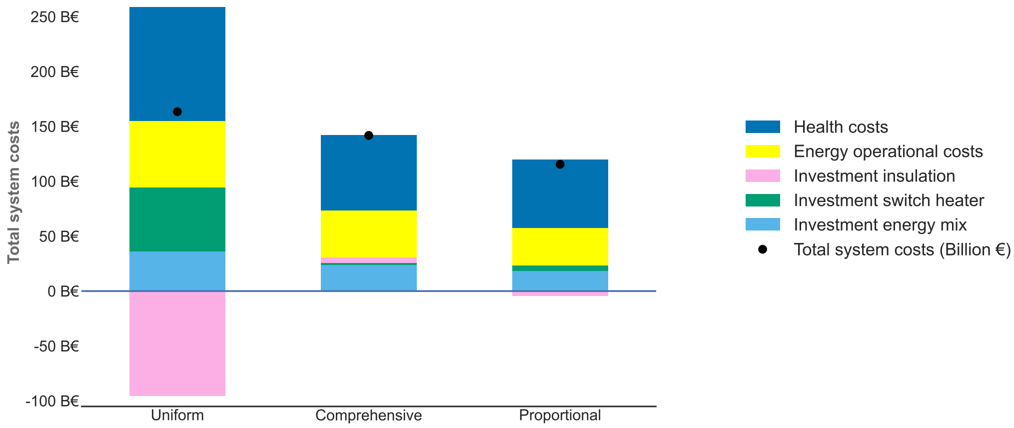
3.2 Second-best alternatives

By design, the second-best scenarios entail a higher total system cost – 11 to 16% higher than in first best, depending on the variants (Figure 3.3 and Table 3.3).[11] This is due to the fact that, unlike second-best alternatives, the first-best scenario ignores energy efficiency barriers that differently affect heterogeneous households. For instance, while the first-best scenario will optimally select the most cost-effective insulation measure in a given dwelling, investment in that measure will be hindered in practice by credit constraints if the occupant is from the low-income group. This barrier could not be fully overcome by alternative subsidy designs. This results in a different effort allocation between first-best and second-best scenarios, with a larger role played by insulation in the first-best scenario (Figure 3.4). In the first-best scenario, insulation alone achieves a 30% reduction in energy consumption, compared to the 6-20% range observed in second-best designs. Consequently, in the first-best scenario, there is a lesser need for additional capacities like

[11] Preliminary tests established that the carbon budget could not be met without subsidies. All second-best scenarios therefore fare better than a ‘laissez-faire’ scenario.

peaking plants and batteries (-3 GW), as well as solar capacity (-30 GW) (Figure 3.5). This adjustment substantially lowers the energy system's annual costs by 0.7-1.5 billion euros per year.

Figure 3.3 – Difference in total annualized system costs over period 2025-2050 (Billion EUR) compared to the 'optimal' subsidy insulation scenario. Energy operational costs include all costs related to system operation (e.g., methanization variable cost, wood energy expenditures).

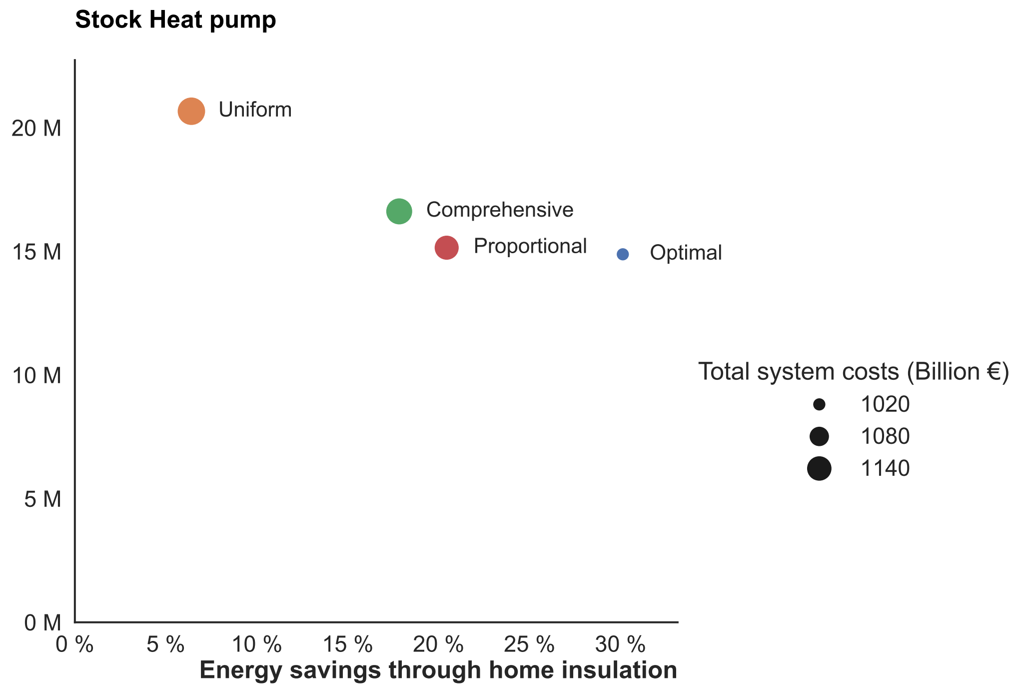


The effort allocation between insulation, fuel switch and fuel decarbonization varies greatly across subsidy designs. Compared to 'uniform' subsidies, 'comprehensive' subsidies entail a €23 billion lower total system cost (or €0.9 billion per year on average), as illustrated in Figure 3.3. Specifically, they involve twice as much investment in insulation (hence an extra €4.5 billion per year), less investment in both heat pump adoption (5 million fewer, hence a €3.7 billion less per year) and energy system (€0.5 billion less per year). This is achieved through endogenously-determined *ad valorem* subsidy rates of 50 to 75% for insulation and 0 to 60% for heat pumps over time horizon (Figure 3.E.1 in the Supplementary material). The 'comprehensive' and 'proportional' scenarios produce very similar results, save for more investment in insulation, and a slightly lower total system cost, in the former. Such a similarity by contrast highlights the poorer performance of the less well-targeted 'uniform' subsidy design, thereby revealing that energy performance is only poorly reflected in technology cost.[12]

Overall, our results highlight the key role played by subsidy specifications in determining the trade-off between insulation and fuel switch (Figure 3.4). Subsidy specifications are more marginal in the energy system (which again supplies all end-use sectors), and concentrated on peak-load and solar capacity and production. The main result is a 6 GW lower peak-load capacity in the 'comprehensive' scenario than in the 'uniform' one (Table 3.3).

[12]One can think of window replacement, for which households have a high willingness to pay, despite its ranking low in the energy performance merit order.

Figure 3.4 – Trade-offs between energy savings from home insulation and switch to heat pumps in 2050 across scenarios. Home insulation is reflected through energy demand savings compared to 2020, while heat pumps is reflected through stock evolution (in reference to 39 millions dwellings in 2050).



The residual carbon values associated with the carbon constraint vary mildly across scenarios, within a range that is consistent with the value recommended by French authorities for public assessment (Table 3.E.1 in Supplementary material 3.E.1).

Interestingly, our results continue to hold qualitatively when health costs are not included in the social planner's objective function, which establishes their robustness (Figures 3.D.1 and 3.D.2 in Supplementary material 3.D).

Figure 3.5 – Comparison of electricity mix across different scenarios. All scenarios install maximal capacity of onshore and offshore capacity. First-best ('optimal') scenario needs less peaking plants and batteries (-3 GW), as well as solar capacity (-30 GW).

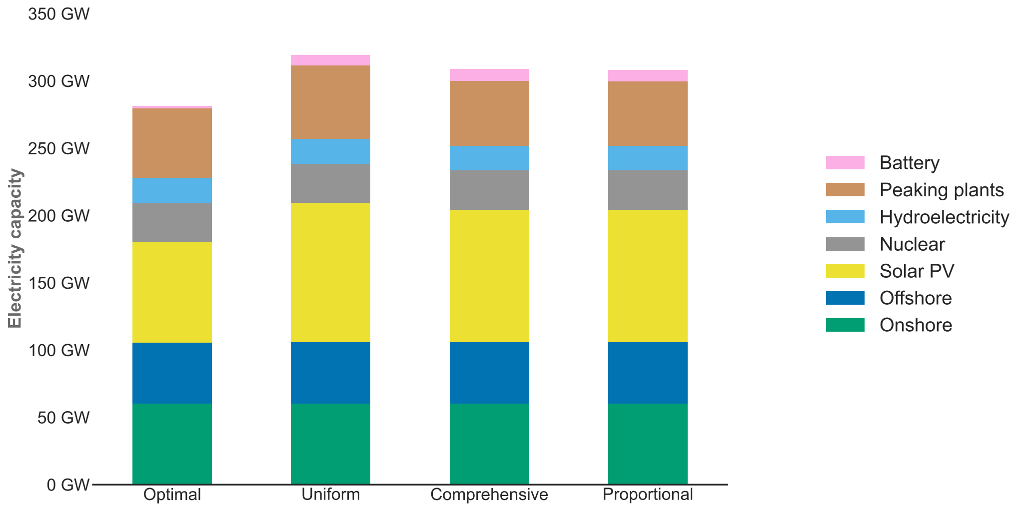


Table 3.3 – Summary of results. In the table, energy consumption refers to 2050. Values in billion euros are the sum of actual invested values between 2025 and 2050. In contrast, the metric Total system costs, used to compare scenarios (e.g in Figure 3.3), refers to the average of annualized costs over time period 2025-2050. Comparison is done with the 'optimal' scenario.

	Unit	**Uniform**	**Comprehensive**	**Proportional**	**Optimal**
Number of heat pumps	Million	21	17	15	15
Investments heat pumps	€Billion	181	88	84	77
Subsidies heat pumps	€Billion	141	29	12	NA
Investments insulation	€Billion	98	210	198	150
Subsidies insulation	€Billion	23	112	125	NA
Savings fuel switch	%	14	7	4	4
Savings insulation	%	6	17	20	30
Consumption Electricity	TWh	63	53	52	47
inc. heat pumps	TWh	48	33	30	28
inc. direct electric	TWh	16	20	22	19
Consumption Wood	TWh	60	56	57	55
Consumption District heating	TWh	24	22	21	18
Consumption Oil	TWh	0	0	0	0
Consumption Gas	TWh	52	63	66	65
Renewable capacity	GW	228	222	222	198
Peaking plants capacity	GW	54	48	48	51
Battery capacity	GW	8	8	8	2
Onshore/offshore production	TWh (%)	382 (52)	382 (53)	382 (53)	382 (54)
PV production	TWh (%)	147 (20)	140 (19)	140 (20)	106 (15)
Hydroelectricity production	TWh (%)	52 (7)	52 (7)	52 (7)	52 (7)
Peaking plants production	TWh (%)	22 (2.3)	17 (2.3)	15 (2.1)	17 (2.4)
Nuclear production	TWh (%)	124 (17)	122 (17)	121 (17)	140 (20)
Total system costs	€B/year (%)	47.3 (+16%)	46.4 (+14%)	45.4 (+11%)	40.7

3.3 Variants with restricted supply-side assumptions

As discussed in Section 2.3, we assessed the robustness of our results to more conservative (yet plausible) assumptions regarding the potential for biogas, nuclear and renewables.

By design, all alternatives result in a higher total system cost compared to the reference assumptions. In general, more limited potentials for fuel decarbonization imply stronger energy efficiency efforts through home insulation or heat pump adoption. Figure 3.6 more specifically illustrates the trade-offs between insulation and heat pump in all four scenarios, under alternative assumptions regarding fuel decarbonization potentials.

Clearly, the results are most sensitive to restrictions in the potential for biogas, which systematically and significantly increase heat pump adoption compared to the reference scenario. Their effect is more mixed on insulation – slightly positive in the 'optimal' and 'uniform' scenarios and slightly negative in the 'comprehensive and proportional' scenarios. In contrast, the impact of more conservative assumptions regarding nuclear and renewables is limited. Overall, in the 'uniform' scenario, restrictions on the energy system systematically imply more effort dedicated to home insulation, which was relatively little exploited under the reference supply-side assumptions due to a lack of targeting through the design.

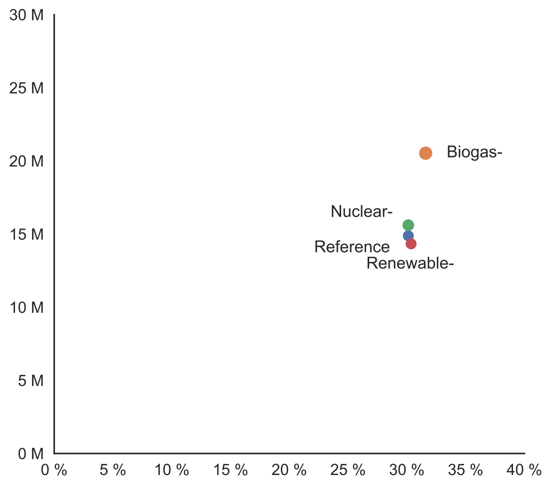
4 Discussion

Our findings are consistent with those of a recent study by the French National Environmental and Energy Management Agency (ADEME, 2022), which is the only integrated assessment of decarbonization in the French residential sector we are aware of. Specifically, our results align with their middle-of-the-road scenarios (S2 and S3), which anticipate a 48-55% reduction in heating energy demand compared to 2020 and a 26% share of heating provided by electricity. Our results however differ from those established at the global level, e.g., Levesque et al. (2021) finding 81% of emissions reductions achieved through fuel decarbonization, against 45% in our assessment. This discrepancy is arguably due to the France's already low-carbon electricity supply,[13] which leaves little room for more of this mitigation option. However, investments in the energy mix are still required to maintain such a low electricity carbon content, as many historic nuclear power plants will be decommissioned before 2050. It should be noted that our myopic approach may result in lower investment in long-lasting abatement technologies leading to some lock-in effects in the investment decision for home insulation, heating systems, and energy technologies. This may potentially lead to a lower role of insulation and fuel switching compared to a perfect foresight mitigation strategy.

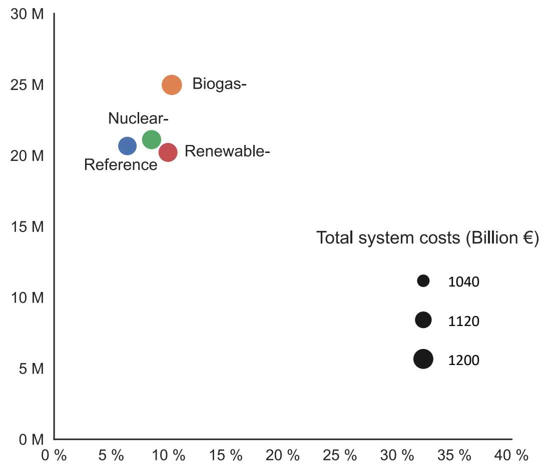
One important added value of our framework is to compare first-best and second-best strategies in a detailed bottom-up modeling framework. This allows us to identify a 11% to 16% higher total-system cost under second-best policy, as illustrated in Figure 3.3 and Table 3.3. In contrast, related works tend to rely on a first-best approach, implicitly

[13] For instance, electricity carbon content is 56 gCO2/kWh in France compared to 435 gCO2/kWh in Germany (Unnewehr et al., 2022)

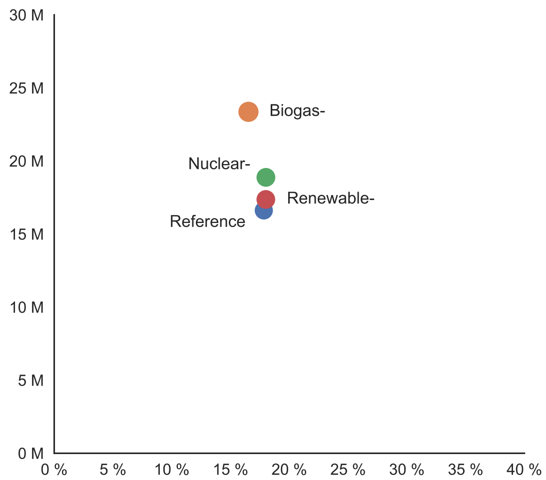
Figure 3.6 – Evolution of demand-side mitigation strategy depending on supply-side assumptions. x-axis corresponds to energy savings through home insulation in percentage of 2020 consumption, and y-axis corresponds to stock of heat pumps in million (in reference to 39 millions dwellings in 2050). Size of points on the figure corresponds to the total system costs.



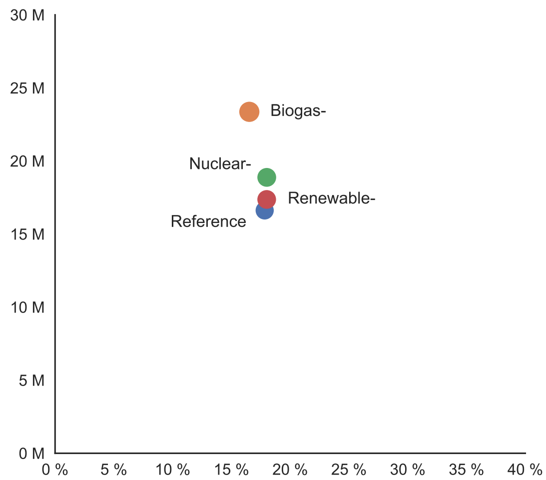
(a) 'Optimal' scenario



(b) 'Uniform' scenario



(c) 'Comprehensive' scenario



(d) 'Proportional' scenario

assuming the policy considered to be optimal (e.g., Zeyen et al. (2021); Mandel et al. (2023)). Our more comprehensive approach delivers a more cautionary message: granted, significant demand reductions can in theory be achieved in the residential sector, but only two thirds of it is attainable with realistic subsidy programs.

Our results point to the importance of targeting the most comprehensive insulation measures for increasing the cost-effectiveness of subsidy programs. In particular, we show that ambitious but non-targeted insulation subsidies lead to more expensive mitigation strategy. It should be added here that targeting is also crucial for fairness. Indeed, the least energy-efficient housing segments, where comprehensive measures make the most sense, are disproportionately occupied by low-income households, particularly exposed to health costs (Bourgeois et al., 2021). Incidentally, our analysis illustrates the benefits from factoring in health costs in building sector assessments. Another step towards incorporating more co-benefits from energy efficiency would be to include reference values for enhanced energy security and reduced air pollution (Ürge Vorsatz et al., 2014). This is however contingent upon the availability of empirical estimates.

Lastly, our analysis emphasizes that uncertainty about supply-side assumptions matters tremendously for demand-side strategies, especially in relation to subsidy design. This is important to bear in mind, considering that the available potential for low-carbon energy sources is known to be highly uncertain (Krey et al., 2019), in particular biogas potential (Pye et al., 2015; Panos et al., 2023). Similarly, the current installation rates of renewables like solar and onshore wind in Europe raise concerns about the ability to sustain the necessary installation pace.

5 Conclusion

Taking a whole-system demand-supply approach to the decarbonization of residential space heating, we show how a politically-constrained social planner can implement energy efficiency subsidies so as to mitigate the GHG externality while overcoming energy efficiency barriers in the most cost-effective way. We found that carbon neutrality can be achieved in residential heating with fuel switch contributing 36% of emission reductions, home insulation 19% and fuel decarbonization 45%. These efforts involve the installation of 15 million heat pumps and 34% energy demand reduction by 2050. Compared to this first-best benchmark, the total-system cost is 11 to 16% higher under second-best subsidy scenarios. Targeted subsidy designs place a greater emphasis on insulation. Finally, our results are very sensitive to supply-side assumptions, specifically a lower biogas potential significantly increase heat pump adoption. Overall, our findings show that it is crucial to engage all available channels for mitigation of the residential sector, and that the specification of subsidy programs significantly influences both the strategic approach and its cost-effectiveness.

Code availability

Both models EOLES and Res-IRF 4.0 are open-source. The code of the framework can be freely accessed at the following URL/DOI: https://doi.org/10.5281/zenodo.10409266. Res-IRF 4.0 code can be freely accessed at the following URL/DOI: 10.5281/zenodo.10405492.

Data availability statement

The data that support the findings of this study are openly available on the URL/DOI of the models. Simulation results are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.10409404.

CRediT authorship contribution statement

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

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Appendix

3.A Description of EOLES

3.A.1 Modeling hypotheses

The hourly capacity factors for variable renewable energy (VRE) (offshore and onshore wind and solar PV) are specified at the French departmental level, based on historical records for the 2000-2018 period.[14] Most of the technological cost parameters are taken from the French Transmission System Operator (TSO)'s latest long-term assessment (RTE, 2022), supplemented with inputs from ADEME (2018) and Zeyen et al. (2021) when nonavailable.

The central scenario considered for the energy mix partly relies on exogenous assumptions. First, the residual electricity demand that is not endogenously determined in Res-IRF – namely, all uses other than heating – is based on the TSO's central scenario, projecting a 595 TWh demand in 2050. This projection takes into account the increased penetration of electric vehicles. In addition, a 40 TWh hydrogen demand is considered in 2050. Second, maximal capacities are imposed on VRE and nuclear technologies, based on the TSO's central production scenario. Third, the potential for biogas production (through methanization and pyrogazification) is taken from ADEME,[15] adjusted to the scope of the energy sector and the residential sector.

The main simplification assumptions in the EOLES are similar to the other versions of the EOLES family of models:

- Power system of the studied country follows the copper plate assumption, which means that the electricity produced at each point of the country can be transmitted to the consumption point instantaneously. This assumption entails the representation of the studied country (here, continental France) in a single node.

- Electricity, methane and hydrogen demand are considered inelastic. Nevertheless, thanks to sector coupling between electricity, methane and hydrogen networks, electricity demand for hydrogen production and gas demand for electricity production are elastic and calculated endogenously.

[14] This is achieved using data from the renewables.ninja website (https://www.renewables.ninja/), following the methods proposed by Pfenninger and Staffell (2016).

[15] We specifically consider the S3 scenario.

- This model uses only linear optimization: while non-linear constraints such as studying unit commitment, they entail a large increase in computation time. According to Palmintier (2014), linear programming provides an interesting trade-off, which speeds up processing by up to 1500 times.

Table 3.A.1 – Evolution of CAPEX (€/kWe). New nuclear power can only be installed starting in 2035. Methanation is calculated as the sum of electrolysis CAPEX and Sabatier reaction CAPEX.

Technology	2025	2030	2035	2040	2045	2050	Reference
Offshore wind, Floating	3580	3280	3130	2980	2830	2680	RTE (2022)
Offshore wind, Fixed	2930	2480	2380	2280	2180	2080	RTE (2022)
Onshore wind, Fixed	1250	1210	1190	1170	1150	1130	RTE (2022)
Solar PV, ground	672	597	557	517	497	477	RTE (2022)
Solar PV, Mounted	967	867	812	757	717	677	RTE (2022)
Nuclear power	NA	NA	5391	5035	4505	4500	RTE (2022)
Methanation	1700	1341	1300	1274	1240	1207	RTE (2022)
Methanization	370	370	370	370	370	370	ADEME (2018)
Pyrogazeification	2500	2500	2500	2500	2500	2500	ADEME (2018)
OCGT	600	600	600	600	600	600	RTE (2022)
CCGT	900	900	900	900	900	900	RTE (2022)
CCGT for hydrogen	1100	1100	1100	1100	1100	1100	RTE (2022)

Table 3.A.2 – Evolution of fOM (€/kWe/yr).

Technology	2025	2030	2035	2040	2045	2050	Reference
Offshore wind, Floating	95	80	70	60	55	50.3	RTE (2022)
Offshore wind, Fixed	70	58	51	47	41	36	RTE (2022)
Onshore wind, Fixed	37.5	35	32.5	30	27.5	25	RTE (2022)
Solar PV, ground	10.5	10	9.5	9	8.5	8	RTE (2022)
Solar PV, Mounted	10.5	10	9.5	9	8.5	8	RTE (2022)
Nuclear power	100	100	100	100	100	100	RTE (2022)
Methanation	59	59	59	59	59	59	RTE (2022)
Methanization	37	37	37	37	37	37	ADEME (2018)
Pyrogazeification	225	225	225	225	225	225	ADEME (2018)
OCGT	20	20	20	20	20	20	RTE (2022)
CCGT	40	40	40	40	40	40	RTE (2022)
CCGT for hydrogen	40	40	40	40	40	40	RTE (2022)

3.A.2 Data

We display cost projections of the main electricity supply technologies used in our simulations, which are mainly from RTE (2022). When RTE only provides some but not all intermediate values between 2025 and 2050, we rely on linear extrapolation to estimate missing values. The annuities calculated, taking into account the interest incurred during construction, assuming a single discount rate of 3.2% per year. Evolution of CAPEX is displayed in Table 4.C.3, evolution of fixed operation costs is displayed in Table 4.C.2.

The energy system strongly relies on available potential for different technologies, namely biogas (Table 4.C.5 and low-carbon technologies (Table 4.C.4).

Table 3.A.3 – Other constant electricity generation technology parameters.

Technology	Lifetime (yr)	Variable O&M (€/MWh)	Efficiency (%)	Reference
Offshore wind, Floating	40	0	-	RTE (2022)
Offshore wind, Fixed	40	0	-	RTE (2022)
Onshore wind, Fixed	30	0	-	RTE (2022)
Solar PV, ground	30	0	-	RTE (2022)
Solar PV, Mounted	30	0	-	RTE (2022)
Nuclear power	60	6	-	RTE (2022)
Methanation	20	5	60	RTE (2022)
Methanization	20	50	-	ADEME (2018)
Pyrogazeification	20	32	-	ADEME (2018)
OCGT	30	-	40	RTE (2022)
CCGT	40	-	57	RTE (2022)
CCGT for hydrogen	40	-	57	RTE (2022)

Table 3.A.4 – Low-carbon technologies potential in 2050 (GW).

Technology	2050 (GW)	Reference
Offshore wind, Floating	30	RTE (2022)
Offshore wind, Fixed	15	RTE (2022)
Onshore wind, Fixed	58	RTE (2022)
Solar pv, Ground	96	RTE (2022)
Solar pv, Mounted	66	RTE (2022)
New nuclear power	13.5	RTE (2022)

Table 3.A.5 – Evolution of biogas potential (TWh).

Potential	Scenario	2025	2030	2035	2040	2045	2050	Reference
Methanization	S2	0	14	19	24	29	35	ADEME (2018)
	S3	0	19	25	32	39	46	ADEME (2018)
Pyrogazeification	S2	0	0	0	0	0	0	ADEME (2018)
	S3	0	0	5	9	14	19	ADEME (2018)

Table 3.A.6 – Evolution of storage CAPEX (€/kWh).

Technology	2025	2030	2035	2040	2045	2050	Reference
PHS	20	20	20	20	20	20	RTE (2022)
1h Battery storage	537	439	340	332	324	315	RTE (2022)
4h Battery storage	370	299	228	214	200	185	RTE (2022)
Salt cavern	350	350	350	350	350	350	RTE (2022)

3.B Additional data

Table 3.B.1 – Evolution of carbon budget.

Year	Carbon budget
2025	53
2030	26
2035	18
2040	11
2045	7
2050	4

3.C Decomposition analysis

We can write CO_2 emissions as follows:

$$CO2 = \sum_i \text{Surface} \times \frac{\text{Surface}_i}{\text{Surface}} \times \frac{FE_{conv,i}}{\text{Surface}_i} \times \frac{FE_i}{FE_{conv,i}} \times \frac{C_i}{FE_i} \quad (3.1)$$

$$= \text{Surface} \times \sum_i sh_i \times I_i \times HI_i \times C_i, \quad (3.2)$$

where i represents a given type of heating systems (e.g. gas boiler, heat pump, etc...), sh_i denotes the share of heating systems in the total stock, I_i denotes insulation, HI_i denotes heating intensity (ratio between conventional consumption and actual consumption) and C_i denotes carbon intensity. Following (Ang and Zhang, 2000), we know that if emissions can be decomposed as $CO2_t = X_1 \times X_2 \times \ldots \times X_n$, then the variation of emissions $\Delta CO2 = CO2^F - CO2^0$ can be decomposed as $\Delta CO2 = \Delta^1 + \Delta^2 + \ldots + \Delta^n$ where :

$$\Delta^i = \frac{\Delta CO2}{\Delta \ln CO2} \ln(\frac{X_i^F}{X_i^0}) \quad (3.3)$$

Therefore, we can decompose variations in CO_2 emissions as follows:

$$\Delta CO2 = \sum_i \frac{\Delta CO2_i}{\Delta \ln CO2_i} \left(\ln(\frac{m_2^F}{m_2^0}) + \ln(\frac{sh_i^F}{sh_i^0}) + \ln(\frac{I_i^F}{I_i^0}) + \ln(\frac{HI_i^F}{HI_i^0}) + \ln(\frac{C_i^F}{C_i^0}) \right) \quad (3.4)$$

We can finally propose the following groupings, to derive the respective effect of evolution of square meters, insulation, fuel switch and carbon content:

$$\Delta CO2 = \Delta \text{Surface} + \Delta SH + \Delta I + \Delta HI + \Delta C \quad (3.5)$$

where:

$$\Delta \text{Surface} = \ln(\frac{\text{Surface}^F}{\text{Surface}^0}) \sum_i \frac{\Delta CO2_i}{\Delta \ln CO2_i}, \quad (3.6)$$

$$\Delta SH = \sum_i \frac{\Delta CO2_i}{\Delta \ln CO2_i} \ln(\frac{sh_i^F}{sh_i^0}), \quad (3.7)$$

$$\Delta I = \sum_i \frac{\Delta CO2_i}{\Delta \ln CO2_i} \ln(\frac{I_i^F}{I_i^0}), \quad (3.8)$$

$$\Delta HI = \sum_i \frac{\Delta CO2_i}{\Delta \ln CO2_i} \ln(\frac{HI_i^F}{HI_i^0}), \quad (3.9)$$

$$\Delta C = \sum_i \frac{\Delta CO2_i}{\Delta \ln CO2_i} \ln(\frac{C_i^F}{C_i^0}) \quad (3.10)$$

3.D Simulations without health costs

We ran the same simulations as in Section 3 without the health costs (Figures 3.D.1 and 3.D.2). We observed the same ranking of the scenarios, and the same variation in terms of optimal strategy, as displayed in the following figures.

Figure 3.D.1 – Difference of total system costs.

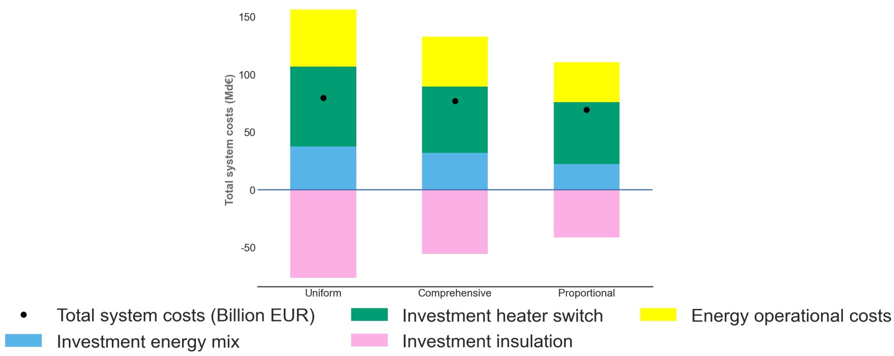
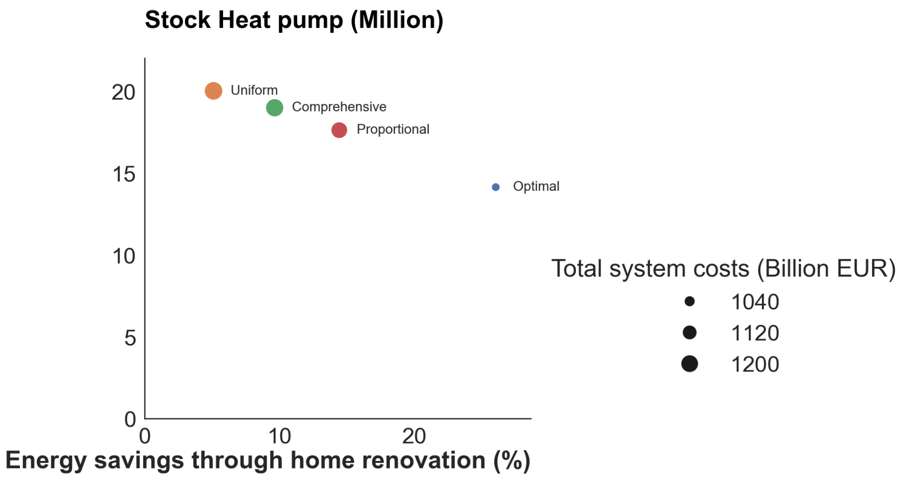


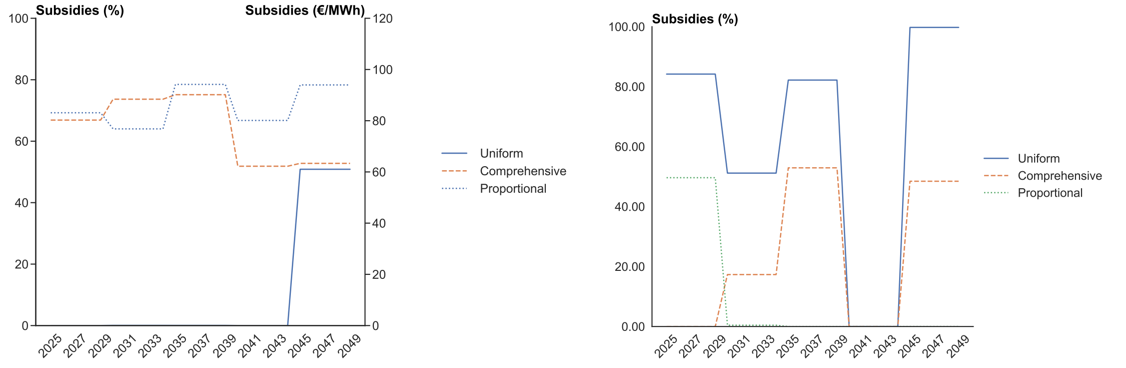
Figure 3.D.2 – Evolution of demand-side strategy.



3.E Additional figures

We display additional figures corresponding to simulations in Section 3, including evolution of subsidies (Figure 3.E.1), evolution of heat pumps stock (Figure 3.E.2), evolution of buildings stock by performance (Figure 3.E.3). We also display electricity dispatch for two representative weeks, for the 'optimal' scenario (Figure 3.E.4).

Figure 3.E.1 – Evolution of subsidies for the scenarios ‘uniform’, ‘comprehensive’ and ‘proportional’. For ad valorem subsidy, the left y-axis depicts the level of the percentage of capex that is eligible for the rebate. For the ‘proportional’ insulation subsidy design, the right y-axis depicts the optimal price in €/MWh for the insulation subsidy. Similarly, heat pumps subsidies increase across all the time horizon (except for time period 2030-2035, since required investments were made during preceding time step).



(a) Evolution of insulation subsidies.

(b) Evolution of ad valorem heater subsidies.

Figure 3.E.2 – Development of the stock of heat pumps in all scenarios. The more the scenario relies on insulation, the fewer heat pumps are needed to meet the carbon budget. In 2050, there are between 15 and 20 billion homes equipped with heat pumps.

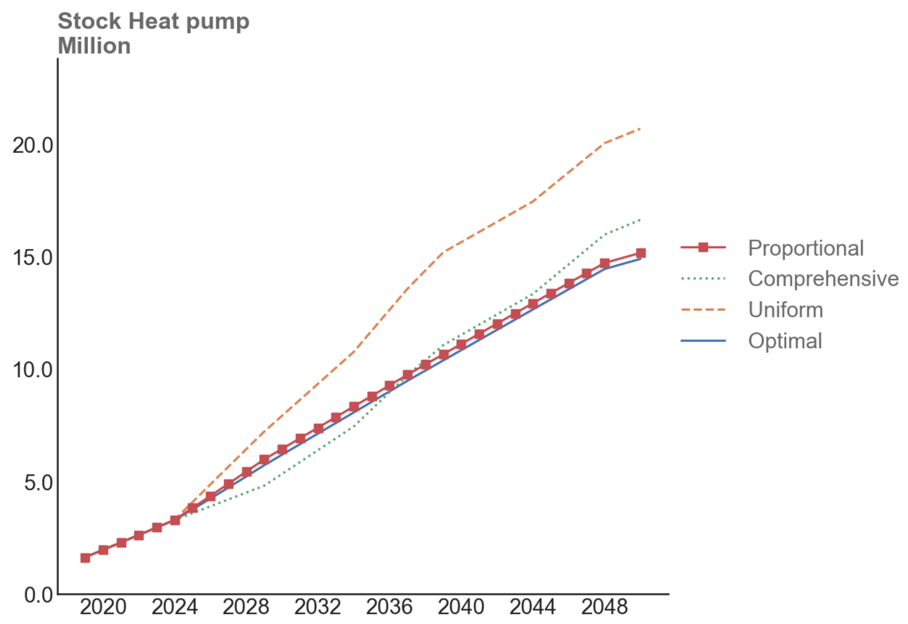


Figure 3.E.3 – Development of the housing stock (millions of dwellings) according to energy performance certificates (G to A). ‘Optimal’ scenario eliminates the least efficient dwellings (G and F) by 2030, while they still exist in a ‘uniform’ scenario.

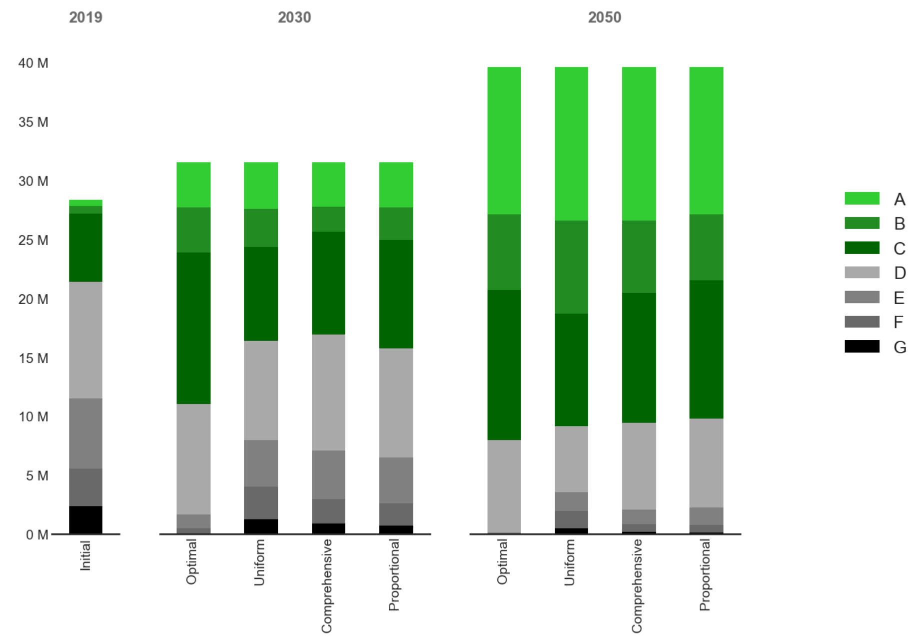
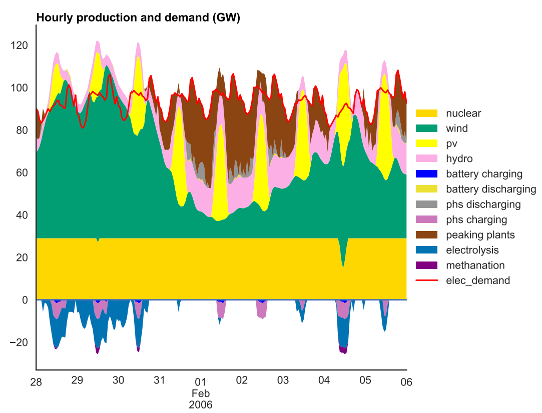
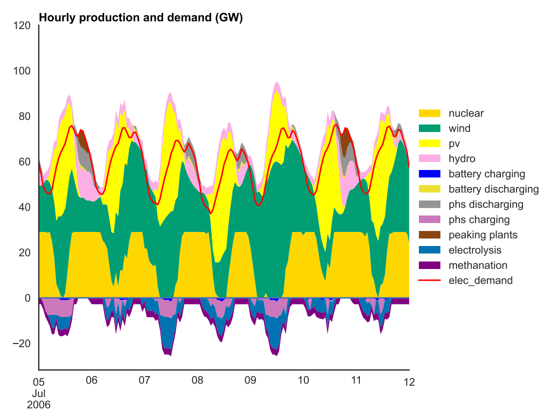


Figure 3.E.4 – Hourly generation for two representative weeks in winter and summer, for the ‘optimal’ scenario. The hourly demand profile is different in February and July due to the strong seasonality of heating demand.

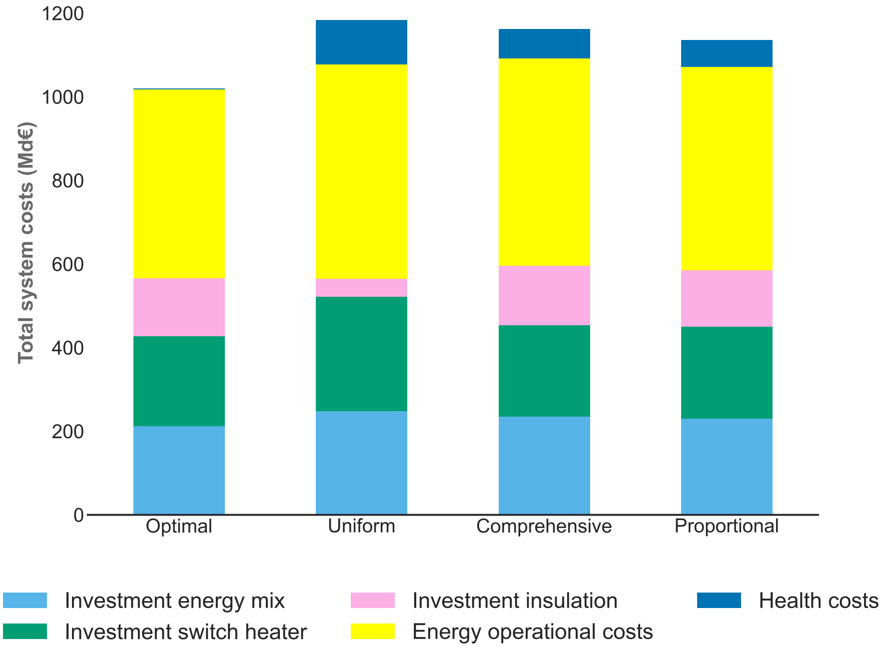


(a) Representative week of February



(b) Representative week of July

Figure 3.E.5 – Breakdown of total system costs.



3.E.1 Implicit carbon value for scenarios in Section 3.2

Table 3.E.1 displays the implicit carbon value obtained for the different subsidy design scenarios in Section 3.2. This carbon value corresponds to the dual multiplier associated with the carbon budget constraint.

Table 3.E.1 – Evolution of implicit carbon values in €/tCO_2 for each subsidy scenario.

Year	Uniform	Comprehensive	Proportional	Optimal
2030	283	282	184	0
2035	750	252	233	136
2040	500	574	489	239
2045	440	490	419	311
2050	850	873	655	422

3.E.2 Bayesian Optimization

As was emphasized in the Section 2, we use a bayesian optimization framework to find the optimal strategy of the social planner. This framework allows to find the minimum of a function without any assumptions on the function. Indeed, classical optimization algorithms rely on an analytical expression for the objective function f, and often some information on its first or second derivative. In a setting where it is only possible to evaluate the function on a given point - which is our case, due to the Res-IRF model which is a simulation model without an analytical expression - such classical optimization algorithms can no longer be used. In the case where it is cheap to evaluate the function f, one could just sample many points via grid search for example, or perform numeric gradient estimation. However, in our case, function evaluation is expensive (it takes several minutes for each time step of 5 years). In that case, it is important to minimize the number of samples drawn in order to perform the optimization. The bayesian optimization framework combines a surrogate model of the objective function (relying on gaussian processes in our case) and an acquisition function that directs sampling to areas where an improvement over the current best observation is likely. The acquisition function used in our setting is the Expected Improvement acquisition function which finds a trade-off between exploration (sampling in areas where the surrogate model is more uncertain) and exploitation (refining the value of the optimum). The problem is solved with the GpyOPT package.[16]

[16] https://pypi.org/project/GPyOpt/

CHAPTER 4

Banning new gas boilers as a no-regret mitigation option

Review & Resubmit in Nature Communications
Co-first author with Célia Escribe

Abstract

The low uptake of low-carbon heating systems across Europe has prompted authorities to consider more ambitious measures, including a complete ban on the installation of new fossil fuel boilers. In this analysis, we simulate the impacts of introducing this ban in France under 11,664 scenarios covering major uncertainties. We find that the ban induces major changes in the energy system, leading to efficiency gains. Additionally, we find that the ban increases the likelihood of reaching carbon neutrality while reducing total system cost in over 75% of scenarios. Finally, we show that the implementation of the ban, when coupled with the existing subsidy framework, mitigates inequalities among owner-occupied households but generates adverse effects for those in privately rented homes.

Keywords: climate change mitigation, fossil fuel ban, residential sector, energy mix, policy assessment.

1 Introduction

Achieving carbon neutrality in the European residential sector requires a major switch from fossil fuel boilers to low-carbon energy sources such as electricity, solid biomass or district heating (Cabeza et al., 2022). In Europe, residential space heating represents 17% of total final energy consumption, with approximately 75% still relying on fossil fuels (Eurostat, 2023). A major obstacle to the transition to low-carbon heating systems is that the social cost of carbon is typically not included in residential energy prices, so homeowners' investments are not aligned with environmental goals. In addition, homeowner behavior may deviate from the perfectly rational consumer assumed in standard microeconomic models, leading to suboptimal levels of investment. In particular, homeowners tend to undervalue future energy benefits (Schleich et al., 2019) or express a bias for the existing technology (Lang et al., 2021) when making heating system investment decisions. Without proper policy instruments, these behaviors could drive excessive gas demand in the residential sector, hindering the achievement of climate targets. Environmental externalities and heterogeneous behavioral anomalies in the residential sector imply that the first-best policy mix should be a two-part instrument including perfectly targeted subsidies and a carbon tax (Allcott et al., 2014). It is, however, challenging to implement a policy mix that comes close to this optimum : carbon taxes at the socially optimal level are often politically unfeasible (Douenne and Fabre, 2022), and realistic subsidy designs cannot be individually targeted. Consequently, and despite efforts to implement market-based instruments (Alberini and Bigano, 2015), uptake rates of low-carbon heating systems across Europe remain low (Camarasa et al., 2022), leading authorities to consider more ambitious measures. The uncertain nature of most of the parameters driving investment decisions in the residential and the energy sectors increases the risk of misaligned price incentives. Such misalignment may result in unmet climate targets if subsidies are insufficiently ambitious, or distributional issues among households— between those receiving subsidies and those bearing the costs—if subsidies are high. In addition, the long heating systems lifetimes require a complex intertemporal approach to instrument design to avoid lock-in effects. Given these difficulties, a ban on fossil fuel boilers emerges as a pragmatic policy choice that makes it easier to achieve climate targets without having to rely on excessive subsidies.

Although several EU Member States have already introduced ban measures to phase out fossil fuel boilers, these regulations affect only a minor share of the EU's heating energy consumption (Braungardt et al., 2023). They mostly target new buildings, specific fuels like oil, or include numerous exemptions. Therefore, the EU Commission has proposed to extend the ban to all standalone fossil fuel boilers across the EU from 2029, as per the EU Save Energy Plan (Comission, 2022). Furthermore, the recent adoption of the Energy Performance Building Directives mandates that Member States implement measures to completely phase out fossil fuel heating and cooling by 2040. In this context, EU Member States are currently considering implementing a complete ban on installing new fossil fuel boilers.

Economists often argue that regulatory instruments are less cost-effective than price-based policies. These policies fail to account for the heterogeneity of households by imposing uniform requirements that may not be consistent with individual cost-effectiveness (Hepburn, 2006). A major concern of the ban on gas boilers is the induced energy system externalities. Specifically, a rapid increase in space heating electricity demand concentrated during peak load could require further investments in the electricity sector, increasing overall costs and hampering the ability to achieve carbon neutrality. Little engineering research investigates how a large roll-out on heat pumps impacts the electricity system (Zeyen et al., 2021; Roth, 2023; Maxim and Grubert, 2023; RTE, 2023), but none considers the dynamics associated with a ban on gas boilers. In addition, these studies do not explore the cost-effectiveness and fairness of this ban. Despite the potentially massive impact and this controversial position, this measure has been little studied.

The objective of this paper is to assess the impact of implementing a ban of gas boilers in the residential sector. We address the following questions: To what extent does the ban contribute to achieving carbon neutrality, and what are its impacts on the energy system, total system costs, and distributional effects?

To answer these questions, we extend a modelling framework that integrates detailed bottom-up models for the energy and residential sectors (Escribe et al., 2023). The framework relies on two key features to assess the ban of fossil fuel boilers. First, the model simulates endogenous investments in home insulation and heating systems. Each homeowner upgrades their heating system or insulates their home based on a discrete choice model influenced by existing policies and market barriers such as credit constraints, behavioral anomalies, and hidden costs of energy efficient technologies. This model is therefore suitable for comparing the effects of a ban, which is represented as restriction of homeowners' choice set, with a current policy scenario that mimics implemented policies in France (Vivier and Giraudet, 2024). The policy mix includes subsidies for home insulation and low-carbon heating systems as well as a residential carbon tax of €45/tCO_2. Second, the model includes the main interactions between the residential sector and the energy system. The hourly resolution finely captures the impact of additional residential electricity demand on peak power load and the resulting investment needs in the electricity sector. In addition, the energy model allocates gas production to both residential gas boilers and the use of peaking power plants in the electricity sector. Low-carbon gas is produced either by biogas with its limited supply or by power-to-gas technologies, which in turn increase electricity demand. Consequently, our framework captures significant cross-sectoral interactions between residential and energy sectors, as well as between the two main energy vectors: gas and electricity. Finally, the model is open-source (Escribe and Vivier, 2023).

Taking France as a case study, we examine how the implementation of a ban on gas boilers - which is synonymous with a ban on all fossil fuels in France, as a ban on oil boilers has already been enacted - contributes to achieving carbon neutrality in the long term. To this end, we systematically compare two policy scenarios: the current policy scenario and an alternative scenario that adds a ban on gas boilers to the current policies. All simulations are done under a carbon budget constraint. We simulate 11,664 scenarios (half with the ban and just as many only with the current policy mix) capturing the main uncertainties driving investment dynamics in the energy and residential sectors (see Table

4.1). These include uncertain renewable and biomass potential capacities (Bosetti et al., 2015; Pye et al., 2015), volatile natural gas prices and uncertain electricity demand in other sectors. We also consider the level of policy ambition to be uncertain, as it has varied considerably over the last ten years (Vivier and Giraudet, 2024). The response of households to price changes, which is represented here by an average price elasticity parameter, is difficult to estimate and is also considered uncertain. Additionally, the future efficiency and cost of heat pumps span a wide range (Chaudry et al., 2015). Lastly, the 2050 carbon budget for the energy and residential sectors hinges on uncertain carbon sinks and abatement in other sectors. We evaluate the ban in terms of its robustness to achieving the carbon neutrality target under uncertainty, its cost-effectiveness, and its distributional effects among the large set of plausible future scenarios (Goulder and Parry, 2008).

This study makes four key contributions to understanding the impact of a gas boiler ban. First, we demonstrate that the additional electricity demand resulting from the implementation of the ban does not have any adverse effects on the electricity system. Instead, it leads to reduced primary energy requirements and improved capacity factors for power plants. Second, we demonstrate that the ban increases the likelihood of meeting climate targets, showing no adverse effect on the electricity system while hedging against the lower-than-expected biogas potential. Third, we find that while the cost implications of the ban are highly dependent on uncertainty factors, it reduces total system costs in 75% of the scenarios analyzed. Fourth, we show that the distributional impacts are highly sensitive to the subsidy design for heat pumps, requiring consideration of both income and occupation status.

2 Method

Our framework integrates two detailed bottom-up models: (i) Res-IRF, which simulates energy demand for space heating, and (ii) EOLES, a comprehensive energy system model. Within a given time step, the exogenous policy scenario determines final energy demand for residential space heating in the Res-IRF model. The EOLES model is subsequently run to optimize capacity investment and dispatch in the energy sector while meeting total energy demand and carbon budget. This process is then iterated in 5-year time steps, from 2020 to 2050. For a given period, wholesale electricity prices are endogenously computed as the levelized cost to meet demand from the previous period. The resulting prices are topped with exogenous energy taxes. The prices of other fuels (gas, oil, wood) are exogenous. Overall, the framework represents a high level of technological granularity both for the energy system (offshore, onshore, solar PV, nuclear, peaking plants, etc...) and residential sector (gas, oil and wood boilers, direct electric and heat pumps). We detail the framework and the data used to calibrate the model in (Escribe et al., 2023).

The framework relies on two key features to assess the ban of fossil fuel boilers. First, the model simulates endogenous investments in home insulation and heating systems. Each homeowner upgrades their heating system or insulates their home based on a discrete choice model influenced by existing policies and market barriers such as credit constraints,

Table 4.1 – Uncertainty scenarios for model parameters. Reference configuration is in bold letters.

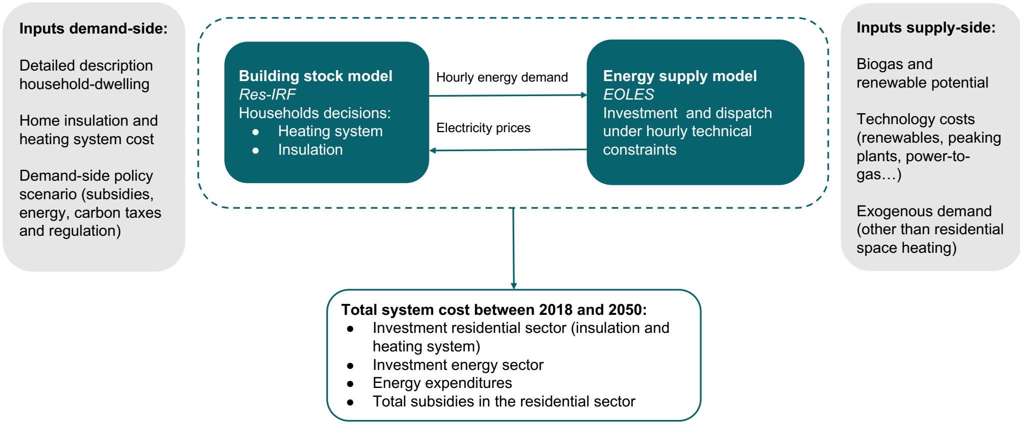
Parameter	Description	Values
Energy system		
Biogas potential	Available potential for methanization and pyrogazification	Low, **Ref**, High
Renewable potential	Available potential for solar pv, onshore and offshore wind	Low, **Ref**, High
Gas prices	Growth rate for wholesale natural gas prices	Low, **Ref**, High
Residential Demand		
Technical progress heat pumps	How much will cost decrease in 2035 compared to 2018 ?	Low, **Ref**, High
Insulation policy	Whether the policy package includes ambitious insulation policy	No, **Yes**
Heater policy	Whether the policy package includes ambitious heater policy	No, **Yes**
Heat pump price elasticity	Parameter driving households' heat pump price elasticity	Low, **Ref**, High
Global parameters		
Other electricity demand	Level of electricity demand for all sectors excluding residential space heating	Low, **Ref**, High
Carbon budget	Trajectory of available carbon budget for residential and electricity sector	Low, **Ref**

behavioral anomalies, and hidden costs of energy efficient technologies. The model is therefore suitable for comparing the effects of a ban, which is represented as restriction of homeowners' choice set, with a current policy scenario that mimics implemented policies in France (Vivier and Giraudet, 2024). The policy mix includes subsidies for home insulation and low-carbon heating systems as well as a residential carbon tax of €45/tCO_2.

Second, the model includes the main interactions between the residential sector and the energy system. The hourly resolution finely captures the impact of additional residential electricity demand on peak power load and the resulting investment needs in the electricity sector. In addition, the energy model allocates gas production to both residential gas boilers and the use of peaking power plants in the electricity sector. Low-carbon gas is produced either by biogas with its limited supply or by power-to-gas technologies, which in turn increase electricity demand. Consequently, our framework captures significant cross-sectoral interactions between residential and energy sectors, as well as between the two main energy vectors: gas and electricity. Finally, the model is open-source (Escribe and Vivier, 2023).

Our assessment is anchored within the carbon budget detailed in SNBC (Low Carbon National Strategy), France's national plan aiming for net zero emissions by 2050. Specifically, the allocated carbon budget for the residential sector, together with the power sector, is projected to be 26.5 MtCO2 annually by 2030, 20.5 MtCO2 by 2035, 14.5 MtCO2 by 2040, 9 MtCO2 by 2045, and 4 MtCO2 by 2050.

Figure 4.1 – Schema of the modeling framework.



2.1 Policy assessment

Our analytical framework is based on the comparison of scenarios that include the ban on gas boilers with counterfactual scenarios without the ban. Building on Vivier and Giraudet (2024), we outline counterfactual scenarios that closely mimic the current policy mix for low-carbon heating in France. The current policy mix includes various energy efficiency measures, in particular a direct subsidy for heat pumps and wood fuel boilers of €4,000 for low-income households and €2,500 for high-income households. It also includes mandatory insulation for private landlords, a carbon tax and an oil boiler ban. The ban of gas boilers is introduced in 2025 and applied indiscriminately to single and multi-family dwellings. Concretely, when their heating system reaches the end of its lifetime, homeowners pick one replacement option among non-fossil fuel options, such as wood-fuel boilers, direct-electric, and heat pumps. District heating projection are determined exogenously, as they rely not on individual homeowner investments but on broader infrastructural investment decisions. We assume that homeowners only consider replacing their heating system when it is no longer working and therefore do not consider premature replacement. We also assume that the lifetime of heating systems remains constant over time, which means that we do not take into account repairs to extend the lifetime of a system. This effect could reasonably be triggered by the implementation of the ban delaying the replacement of gas boilers.

Our analysis focuses on three key outcomes: the ability of a scenario to satisfy the carbon constraint, and, provided this constraint is met, the total system costs and a measure of distributional effects. Overall total system costs is defined as the sum of annualized costs over the 2025-2050 period. Building on Hirth et al. (2021)'s work with the EMMA model, we use a 0% rate of pure time preference to give equal weight to all years when adding up annualized costs over the whole time horizon. The annualized system costs comprise both the investment and operational costs of the energy supply system, along with the costs associated with heating and insulation investments. The distributional indicator is defined as the average additional cost (or benefit) paid by the household group due to the introduction of a ban on gas boilers. These costs include the additional costs of the heating system net of subsidies, the energy costs and a lump-sum tax meant to cover additional subsidy costs. We differentiate the costs according to income, occupation status (owner-occupied and private) and housing type (single-family and multi-family dwellings).

2.2 Uncertainty assessment

The model processes rely on a large set of parameters, many of which are deeply uncertain. Such key uncertainties impact the supply energy system, the residential sector and the other sectors (here only represented by the total electricity demand). Regarding the energy supply system this corresponds to the potential for renewable technologies and renewable gas, as well as fuel prices. In the residential sector, it encompasses technological parameters such as the evolution of the efficiency and the price of heat pumps and behavioral parameters such as the average heat pump price elasticity. Table 4.1 summarizes the uncertain parameters and values used in this study.

We perform a global sensitivity analysis (GSA) to identify the most influential vulnerabilities in the counterfactual scenario that are mitigated with the ban in place. We rely on variance decomposition methodology and we estimate Sobol indices based on our set of scenarios obtained by testing all combinations of uncertainty (Sobol, 2001). The variance decomposition is done to identify the uncertain determinants that increase the vulnerability of the counterfactual scenario (Additional details can be found in the Supplementary material 4.C).

On the one hand, the first-order Sobol index S_i measures the direct effect of varying the uncertain parameter X_i alone. This effect is averaged over the variations in all other uncertain parameters. A high S_i value indicates that X_i significantly influences the outcome by itself. On the other hand, the total effect Sobol index S_{T_i} measures the total contribution of X_i to the output variance, including through its interaction with all other input variables. A low S_{T_i} suggests that X_i has minimal overall impact. Therefore, if S_i is low but S_{T_i} is high, it suggests that X_i primarily affects the outcome through its interactions with other variables. Details of the method are can be found in SI 4.C.

2.3 Limitation

Here, we draw attention to four key limitations of our modelling approach.

First, our framework does not fully account for some costs associated with banning fossil fuel boilers. These include potential investments needed to expand the distribution network to enable increased heat pumps uptake, or the financial impact of stranded gas networks due to falling household demand for gas. We argue that these additional costs can be partially captured with high heat pump cost scenarios.

Second, the building models overlook certain behavioral options. Following a ban on gas boilers, agents might choose to forego heating systems altogether or delay replacing their existing systems. Similar behavior has been observed in the automotive sector, where delayed vehicle replacement led to a rebound effect of 11% in energy savings (Jacobsen and van Benthem, 2015).

Third, our analysis addresses the question of what would happen in France if we assess a ban on gas boilers. We take a positive approach, focusing on the outcomes rather than determining if the ban is superior to all other possible policy mixes. Further research could expand our analysis to compare different policy mixes with the implementation of the ban. Additionally, we focus on one specific design of the ban—starting in 2030 and targeting all dwellings—while other potential bans could, for example, target only standalone gas boilers.

Fourth, regulatory instruments, and ban in particular, can generate significant hidden costs, as they may conflict with consumers' preferences that are unobserved by the regulator. These hidden costs can be additional monetary costs, such as the laying of pipes or circuits, or non-monetary costs, such as the inconvenience of finding out about a new heating system, the cost of obtaining information or the inconvenience during the works (Fowlie et al., 2015). We do not include these hidden costs in our cost analysis primarily because they are difficult to identify without further empirical research. Moreover, these costs could fluctuate over time with changes in consumer preferences and may also be directly affected by the implementation of the ban. However, they would amount to additional costs for heat pumps and can again be partially captured by the high cost scenario for heat pumps. Such potential additional costs, though they could reduce the cost-effectiveness of banning gas boilers, would however not alter the conclusion that the ban is critical to meet climate targets. Overall, further research could move away from the 'accounting approach' used here to assess cost-effectiveness towards a 'welfare approach' that takes into account the unobserved utility (i.e including hidden cost) of households in adopting a particular technology (Allcott and Greenstone, 2024).

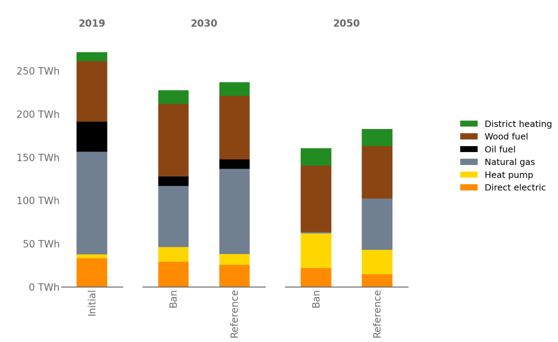
3 Results

3.1 A ban addresses energy service demands more efficiently

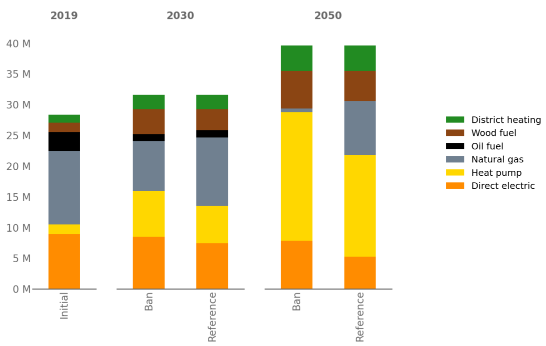
Figure 4.2a shows that the ban on gas boilers shifts residential energy demand primarily to electricity, due to the high efficiency of heat pumps and the limited availability of wood and district heating. Despite the increasing number of dwellings (see Figure 4.2b), home insulation policies decrease overall energy demand, leading to a modest increase in electricity demand in the counterfactual scenario (33%), compared to a 75% increase when the ban is enforced. This increase in electricity demand is particularly pronounced in the cold months, when the demand for space heating is at its highest and the technical efficiency of heat pumps is at its lowest due to the low outside temperatures. Supplementary Figure 4.B.3b illustrates that the ban could raise peak electricity demand by up to 10 GW in 2050 compared to the current policy scenario.

Banning gas boilers influences the strategy for allocating gas resources, which are limited due to carbon constraints and the limited biogas potential. While low-carbon gas is used in gas boilers under the current policy scenario, it can instead by used in peaking power plants that supply electric heating systems if the ban is implemented. This new allocation of gas resource provides more flexibility to the energy system that leads to

Figure 4.2 – Evolution of heating system stock in the current policy scenario and when the ban is implemented. Notation "Natural gas" corresponds to households heating their dwelling with gas boilers. Such heating systems may rely on renewable gas in addition to fossil gas.



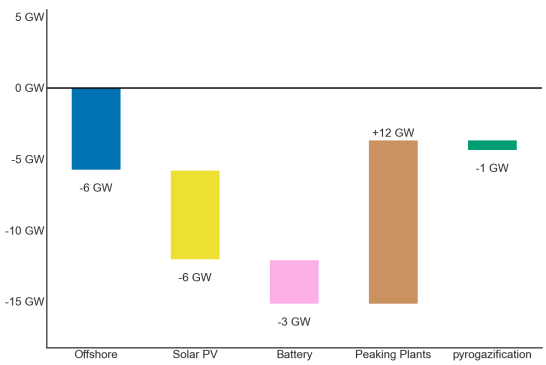
(a) Space heating consumption in the residential sector (TWh per year)



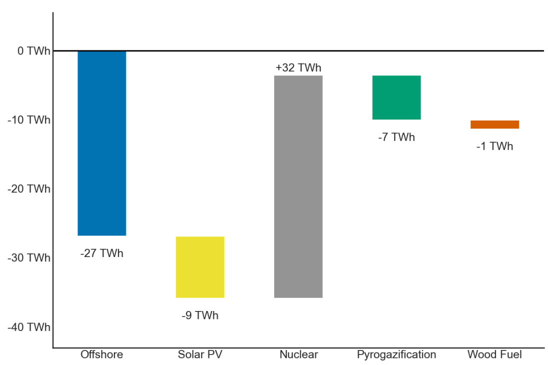
(b) Heating system stock (Million)

efficiency gains on two levels. First, using peaking power plants combined with heat pumps addresses energy service demands more effectively, as indicated in Supplementary Figure 4.B.2, thus reducing the need for primary energy generation (Figure 4.3b). Second, this approach optimizes the use of electricity capacities. The capacity factors of both nuclear power plants and peak-load power plants are higher (Table 4.A.1) and lead to a lower total installed capacity. Specifically, Figure 4.3a illustrates that the ban saves the installation of 12 GW in renewable capacities (offshore wind and solar PV) combined with 3 GW in batteries, by opting instead for an additional 12 GW in peaking plants.

Figure 4.3 – Additional installed capacity and generation in 2050 when the ban on gas boilers is implemented.



(a) Additional installed capacity (GW)



(b) Additional primary energy (TWh)

3.2 A ban is critical to meet carbon neutrality under uncertainty

We conduct simulations across 11,664 scenarios, and find that 99 % of these scenarios achieve carbon neutrality with the ban in place, compared to only 52 % in the current policy scenario. On the one hand, scenarios that achieve carbon neutrality without the ban also succeed under the ban, indicating no adverse effects from its implementation. This suggests that the electricity system can dynamically and effectively adapt to the additional peak load, responding quickly to the heat pump roll-out induced by the ban. On the other hand, we show that incentives in the current policy package are not well-aligned with climate targets when considering a wide range of plausible futures.

Figure 4.4 identifies the key uncertainties that undermine the climate objective in the absence of the ban. We show that the implementation of the ban significantly reduces reliance on biogas potential. Given that meeting residential gas demand is constrained by available biogas potential, the shift to heat pumps driven by the ban hedges against biogas supply shortages. This effect is exacerbated by the more efficient use of gas resources detailed in the precedent section. Furthermore, the regulatory nature of the ban ensures that the adoption of heat pumps is less dependent on uncertain demand-side factors, such as the ambition of subsidy policies or households' responsiveness. Conversely, without the ban, failure to meet climate targets may be prompted by an insufficient level of ambition in home insulation policies to reduce residual space heating demand, lower-than-expected household response to incentives (i.e., low price elasticity of heat pumps), or inadequate subsidies for low-carbon heating systems. Interactions among demand-side and supply-side uncertainties play a large role in the increased robustness of the ban, as evidenced by larger total order indices compared to first order indices. Overall, the ban appears as a more robust strategy to meet carbon neutrality against the uncertainty of various factors driving the decarbonization of the residential and energy sectors.

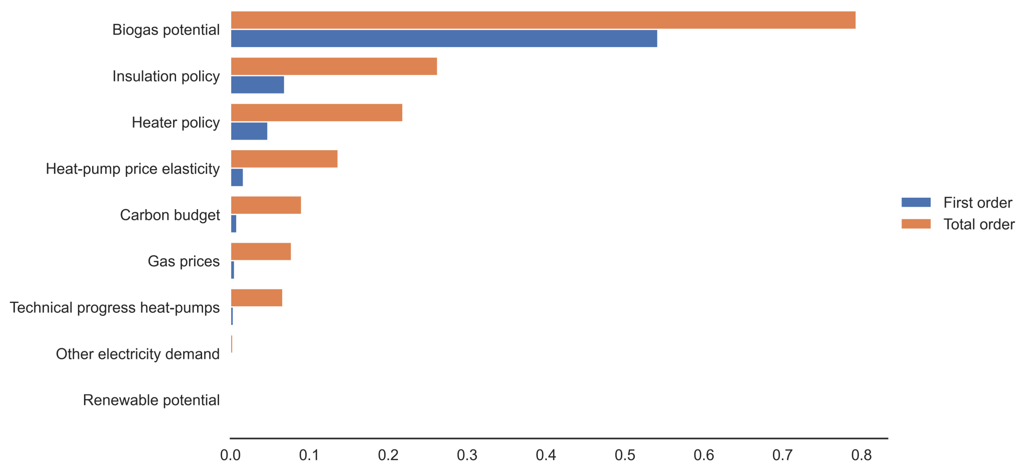
3.3 A nuanced impact on total system costs

Comparison of total system costs is done across scenarios where both the ban and the current policy scenario achieve carbon neutrality. Total system costs are defined as the sum of annualized costs over the 2025-2050 period. All investment costs are annualized using a 3.2% discount rate, as recommended for public investment in France (Ni and Maurice, 2021).

Figure 4.5a shows that in the reference configuration, the scenario with the ban is slightly more expensive than the current policy scenario. Implementing the ban implies additional cost in heating systems as heat pumps, the most widely adopted system when the ban is implemented, are more expensive than gas boilers. In contrast, energy system investment and operation costs decrease. This cost decrease arises from the reduced primary energy need and optimized use of electricity capacities, as discussed above. Specifically, the ban relies on additional peaking power plants capacity while reducing the need for the more costly combination of renewable and battery storage capacities.

The comparison of total system costs across all uncertain scenarios however draws a different picture. In 49% of scenarios where both policy scenarios satisfy the carbon

Figure 4.4 – Ranking of uncertainties undermining the achievement of climate targets in the current policy scenario compared to the ban. First-order Sobol indices illustrate the share of variance explained by each uncertainty independently, while total order Sobol indices represent the share of the variance explained by each uncertainty in interaction with other uncertainties. The latter can cumulatively exceed 1 (interaction terms are counted multiple times).

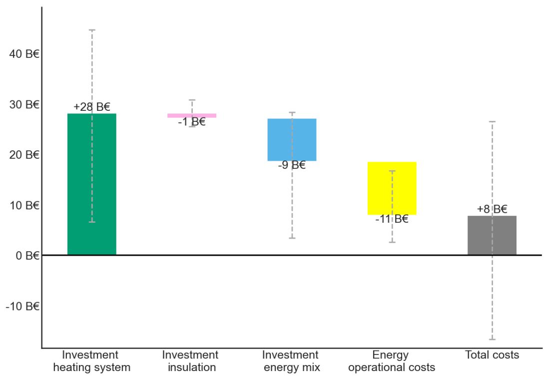


constraint, implementing the ban reduces total system costs. In particular, pessimistic assumptions on uncertain parameters require ambitious and expensive investments in energy system flexibility to accommodate the additional residual gas demand in the current policy scenario (Figure 4.5b). The same factors that contribute to the increased robustness of the ban in achieving carbon neutrality, also make the scenario less costly (see Supplementary Figure 4.B.5). This underlines that the current policy scenario only reduces total system costs compared to the ban scenario under specific conditions. Overall, in more than 75% of all scenarios - including those failing to meet carbon constraints and considered infinitely more costly -, implementing the ban results in lower total system costs. Our results highlight that relying solely on a reference configuration can be misleading, as it overlooks the nuanced cost-effectiveness of the ban amid existing uncertainties.

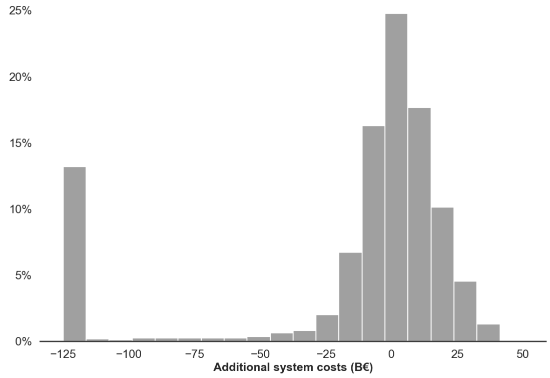
3.4 Distributional impacts of the ban

We investigate the distributional consequences of implementing a ban in the reference configuration by comparing the cost incurred by different income groups and housing categories (occupancy status and housing type) under the ban versus the current policy scenario. By doing so, we assess the marginal impact of the ban on households. Costs include heating system purchase costs and energy expenditure, supplemented by taxes meant to cover additional subsidy costs. We assume these taxes are evenly distributed among French households in a lump-sum manner, which is a standard approach in economic models (Allcott et al., 2014; Chan and Globus-Harris, 2023; Allcott and Greenstone, 2024).

Figure 4.5 – Breakdown and distribution of additional cost when implementing the ban of gas boilers compared to the current policy scenario. a. Breakdown of additional cost in the Ban scenario. Error bars represent the 25th and 75th percentiles of the data set, focusing solely on scenarios featuring plausible energy systems. b. Distribution of additional cost across uncertainties. There are approximately 20% of the scenarios that incur significantly higher costs in the absence of the ban, including for example an exceptionally large amount of batteries. We winsorize at -125B€ for readability.



(a)



(b)

Although these additional costs account for a small percentage of overall household energy costs, our analysis reveals significant disparities in the impact of the ban on households, with additional annual costs varying from -€18 to €40 across groups (see Figure 4.6). These disparities are shaped by the financial impact of replacing the gas boiler on the intensive margin and the proportion of households affected by the ban on the extensive margin.

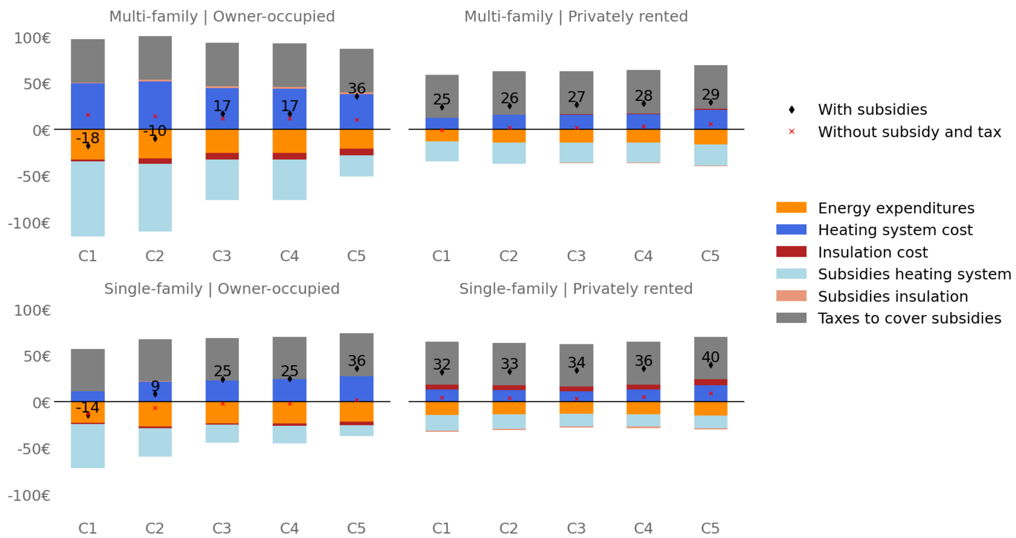
First, the financial impact of the ban depends on the profitability of adopting an alternative heating system, which varies widely among households. This variation primarily stems from differences in heating system choices and eligibility for subsidies. In short, adopting heat pumps is the only profitable choice, provided that subsidies are available to offset the purchase costs. Without substantial subsidies, or if households opt for wood fuel boilers or direct electric heating, the switch is not financially profitable for households. For owner-occupied households, the progressive nature of the French subsidy system, which adjusts the subsidy level to income, creates positive redistributive effects for low-income households, while high-income households face adverse outcomes. Importantly, market and behavioral failures such as credit constraints and a strong present bias are prevalent among low-income households, leading them to choose less profitable investments such as direct electric systems. The subsidy design is therefore also instrumental in encouraging low-income households to invest in heat pumps, their most profitable option. In contrast, for privately rented homes, investment decisions are made by landlords, who typically have higher incomes (see Supplementary Figure 4.B.7) and are eligible for smaller subsidies. As a result, tenants, who bear the investment cost of heating systems through increased rent, do not benefit from the subsidies that correspond to their level of income. This affects disproportionately low-income tenants, as shown in Supplementary Figure 4.B.6 through the relative impact on households' budget. Consequently, while the implementation of the ban in France leads to progressive financial outcomes for owner-occupiers, it adversely impacts tenants. We also observe significant differences between housing types. Households in single-family homes, typically with more space, benefit more from the energy savings of switching to heat pumps, enhancing the profitability of their investment compared to those in multi-family homes. Conversely, some households in single-family homes may opt for wood boilers despite lower profitability. Overall, these mixed effects lead to a smaller range of distribution effects in single-family homes compared to multi-family homes.

Second, the impact of the ban, measured by the number of households needing to change their boilers, varies significantly across different groups. The differences are primarily across housing types rather than income levels. While the ban triggers additional government subsidies, we assume that these extra costs are financed by a lump-sum tax across all households. Consequently, households not directly impacted by the ban contribute to this tax, funding the subsidies without benefiting from them. Notably, in the current policy scenario, the share of gas boilers in privately rented and single-family homes is lower than in other groups (see Supplementary Figure 4.B.11), implying that a smaller fraction of these households is affected by the ban and thus uses subsidies, despite bearing the cost of the lump-sum tax. This situation is particularly pronounced for low-income households in privately rented dwellings, who bear the tax burden without reaping the subsidy benefits aligned with their income level.

4 Discussion

In this study, we present the first evaluation of the highly debated ban on new fossil fuel boilers by assessing its robustness in achieving carbon neutrality under uncertainty, its cost-efficiency, and its distributional effects. First, the ban shifts the strategy for gas resource allocation from gas boilers to a combination of peaking power plants and heat pumps. This new allocation leads to an energy system that both reduces the need for primary energy generation and optimizes utilization of electricity capacities. Second, we demonstrate that achieving carbon neutrality in the residential sector is highly uncertain under the current policy regime. In contrast, we show that the ban is a more robust strategy for achieving climate neutrality, showing no adverse effect on the electricity system while hedging against the lower-than-expected biogas potential. Third, despite costly investments in heating system, the ban leads to lower total system costs over a large range of plausible futures. Fourth, we show that the distributional impacts are highly sensitive to the subsidy design for heat pumps and needs to account for both income and occupation status. When coupled with the French existing subsidy framework, it mitigates vertical inequalities among owner-occupied households but does not extend to those in privately rented homes.

Figure 4.6 – Average additional annual costs by household group under the reference configuration if the ban is implemented (euro per year). 'C1' refers to the first income quintile, i.e. very low income, and 'C5' refers to the last income quintile, i.e. very high income. A negative value means that the ban reduces household expenditure, while a positive value means that the ban increases household expenditure. Total cost is shown net of subsidies and taxes (black diamond) and without including these factors in order to measure the strict effect of the ban before redistribution (red cross).



From a modelling perspective, we address a gap in the existing literature, which typically relies on simplified policy, such as shadow carbon pricing, and thus offers limited insights into climate policy design (Pollitt et al., 2024). Specifically, we complement recent simulation studies that assess real-world policies in the residential sector (Knobloch et al., 2021; Giraudet et al., 2021; Müller et al., 2024), by also considering how these policies interact with the energy system. Our open-source modeling framework paves the way for investigating the impact of banning fossil fuel boilers in other economies like Germany or Netherlands, which have the largest share of fossil fuel boilers among EU countries (Braungardt et al., 2023).

Choosing appropriate policy instruments for the transition to low-carbon heating systems is inherently difficult because of competing evaluation criteria (Goulder and Parry, 2008). We show that the ban on gas boilers is justified when moving beyond mere cost-effectiveness to consider the robustness of policies under uncertainty. Focusing only on a reference configuration can be misleading as it overlooks the nuanced cost impact of the ban amid existing uncertainties. This measure also involves trade-offs with distributional impacts, which can be mitigated through further research on the design of subsidies. Finally, our approach focuses on physical costs rather than the welfare criteria often used in economics. Assessing the welfare impact of a ban in contexts with behavioral biases would however require more sophisticated models than those commonly used (Tsvetanov and Segerson, 2014), at the expense of technical details.

Code availability

Both models EOLES and Res-IRF 4.0 are open-source. The code of the framework can be freely accessed at the following URL/DOI: https://doi.org/10.5281/zenodo.10409266. Res-IRF 4.0 code can be freely accessed at the following URL/DOI: 10.5281/zenodo.10405492 or on GitHub: https://github.com/CIRED/Res-IRF4.

Data availability statement

The data that support the findings of this study are openly available on the URL/DOI of the models. Simulation results are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.10409266.

CRediT authorship contribution statement

Celia Escribe: Conceptualization, Methodology, Data curation, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Lucas Vivier**: Conceptualization, Methodology, Data curation, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing.

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Appendix

4.A Supplementary table

Table 4.A.1 – Summary of results. In the table, all values refer to 2050. Values in billion euros are the sum of actual invested values between 2025 and 2050.

	Unit	**Current policy scenario**	**Ban**
Number of heat pumps	Million	16	20
Number of direct electric	Million	5	7
Number of gas boilers	Million	8	0
Number of wood boilers	Million	4	6
Subsidies insulation	B€	60	59
Subsidies heater	B€	47	71
Investment heating system	B€	321	349
Investment insulation	B€	136	135
Consumption Electricity	TWh	42	61
Consumption Gas	TWh	59	1
Consumption Wood	TWh	60	76
Offshore capacity	GW	45	39
Onshore capacity	GW	60	60
Solar PV capacity	GW	75	69
Nuclear capacity	GW	29	29
Battery capacity	GW	3	0
Peaking plants capacity	GW	47	59
Methanization capacity	GW	5	5
Pyrogazification capacity	GW	2	1
Hydroelectricity capacity	GW	18	18
Offshore production	TWh	210	183
Onshore production	TWh	171	171
Solar PV production	TWh	107	98
Battery production	TWh	3	0
Hydroelectricity production	TWh	51	51
Peaking plants production	TWh	14	32
Nuclear production	TWh	137	170
Methanization production	TWh	46	46
Pyrogazification production	TWh	19	12

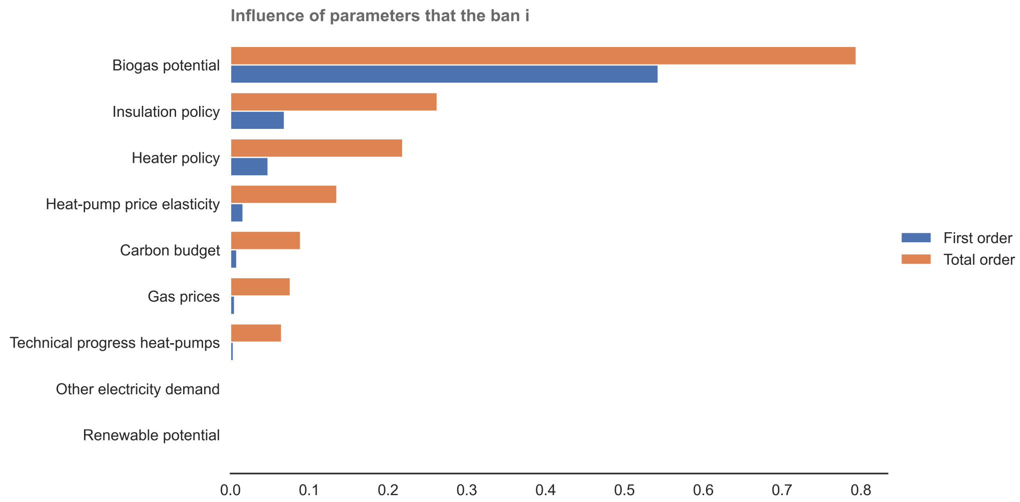
Table 4.A.2 – Summary of main results in the residential sector in the configuration setting by 2050.

	Ban	Current policy
Stock (Million)	31.57	31.57
Surface (Million m2)	2730.63	2730.61
Consumption (TWh)	227.25	236.59
Consumption (kWh/m2)	83.22	86.64
Consumption PE (TWh)	286.88	286.01
Consumption Electricity (TWh)	45.86	38.02
Consumption Natural gas (TWh)	70.93	98.36
Consumption Oil fuel (TWh)	10.83	10.83
Consumption Wood fuel (TWh)	84.00	73.69
Consumption Heating (TWh)	15.63	15.68
Energy poverty (Million)	2.59	2.62
Emission (MtCO2)	27.33	32.64
Stock G (Million)	1.41	1.24
Stock F (Million)	2.06	2.09
Stock E (Million)	4.04	4.18
Stock D (Million)	8.99	9.38
Stock C (Million)	8.28	8.58
Stock B (Million)	2.65	2.25
Stock A (Million)	4.14	3.85
Stock Heat pump (Million)	7.42	6.07
Stock Direct electric (Million)	8.51	7.41
Stock Gas boiler (Million)	8.12	11.17
Stock Oil fuel boiler (Million)	1.14	1.14
Stock Wood fuel boiler (Million)	4.05	3.45
Stock District heating (Million)	2.33	2.33
Energy expenditures (Billion €)	24.12	24.76
Cumulated Emission (MtCO2)	649.67	881.94
Cumulated Renovation (Thousand households)	17297.22	17735.69
Cumulated Investment insulation (Billion €)	208.83	212.04
Cumulated Subsidies insulation (Billion €)	60.92	61.33
Cumulated Investment heater (Billion €)	341.19	310.32
Cumulated Subsidies heater (Billion €)	73.86	49.40
Annual average Renovation (Thousand households)	1572.47	1612.34
Annual average Investment insulation (Billion €)	18.98	19.28
Annual average Subsidies insulation (Billion €)	5.54	5.58
Annual average Investment heater (Billion €)	31.02	28.21
Annual average Subsidies heater (Billion €)	6.71	4.49
Consumption saving (%)	0.16	0.13
Emission saving (%)	0.38	0.26
Energy poverty reduction (%)	0.29	0.28

4.B Supplementary figures

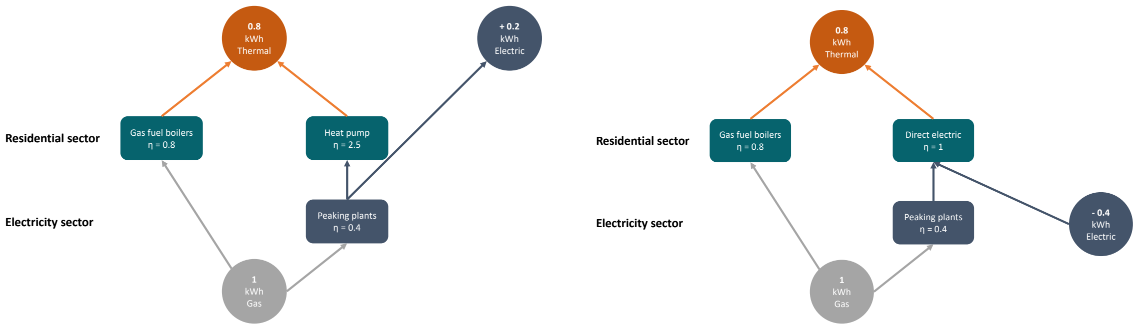
We assess the key uncertainties that undermine the climate objective under the current policy scenario in Figure 4.B.1.

Figure 4.B.1 – Ranking of most influential parameters driving the capacity of the counterfactual scenario to achieve carbon neutrality.



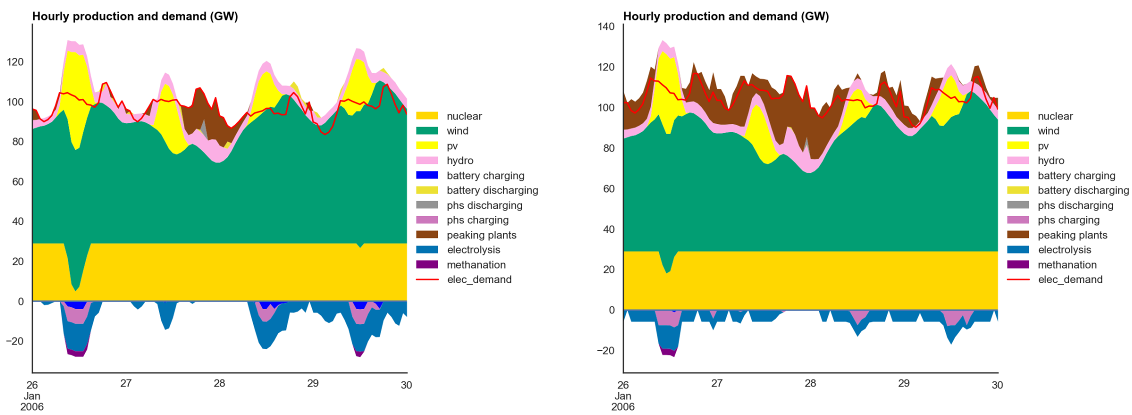
4.B.1 Supplementary figures to assess the consequences of implementing the ban on the energy system

Figure 4.B.2 – Simplified diagram showing the overall efficiency of replacing gas boilers with heat pumps and direct electricity.



(a) When heat pump is chosen   **(b)** When direct electric is chosen

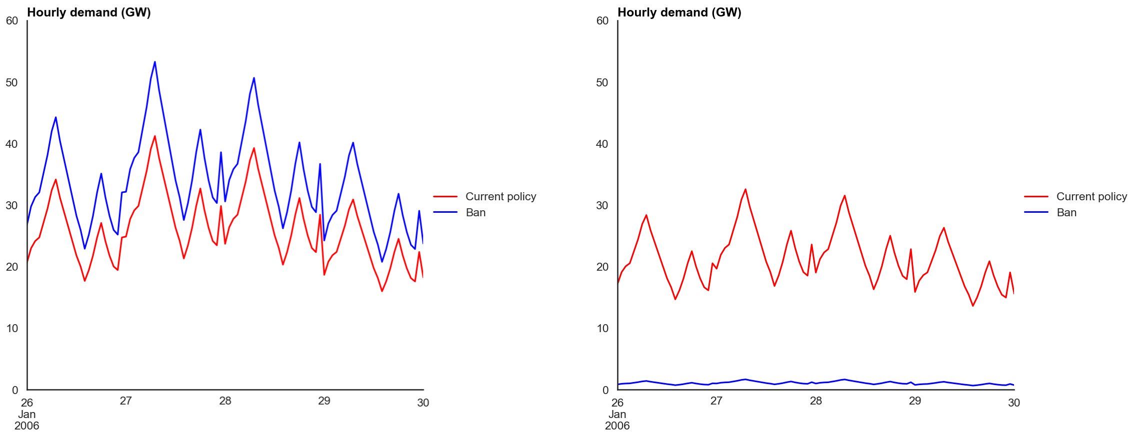
Figure 4.B.3 – Hourly dispatch to meet electricity demand in 2050 over a typical week in January.



(a) Current policy scenario.   **(b)** Ban scenario.

Supplementary Figure 4.B.5 identifies the determinants responsible for the higher cost-effectiveness of the counterfactual scenario compared to the ban. Scenarios exhibiting higher system costs under the ban typically feature high heat pump price elasticity—indicating a strong household investment response to reductions in heat pump prices—substantial biogas potential—suggesting favorable conditions for decarbonizing the residential gas supply—and ambitious insulation policies. This underscores that

Figure 4.B.4 – Load profile for electricity and gas heating demands in 2050 over a typical week in January.



(a) Electricity demand.

(b) Gas demand.

numerous conditions must be met for the ban to be less costly than the current policy scenario. Conversely, no specific condition is required for the ban to guarantee greater cost-effectiveness over the current policy scenario. It is important to note that the success of the current policy scenario in achieving carbon neutrality—and thus the basis for a cost-effectiveness comparison—is contingent upon the adoption of policies to promote ambitious low-carbon heating systems.

Figure 4.B.5 – Frequency of scenarios with total system cost lower with the ban (left) and total system cost lower without the ban (right).

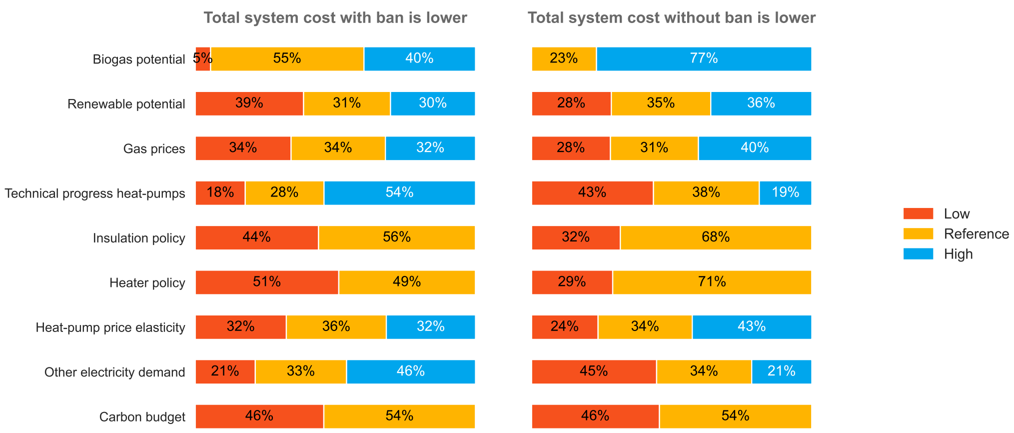


Figure 4.B.6 – Average additional annual costs by household group if the ban is implemented (€per year). 'C1' means the first income quintile, i.e. very low income, and 'C5' means the last income quintile, i.e. very high income. A negative value means that the ban reduces household expenditure, while a positive value means that the ban increases household expenditure. Total cost is shown net of subsidies and taxes (black diamond) and without including these factors in order to measure the strict effect of the ban before redistribution (red cross).

Figure 4.B.7 – Distribution of income group among landlords in France in 2018.

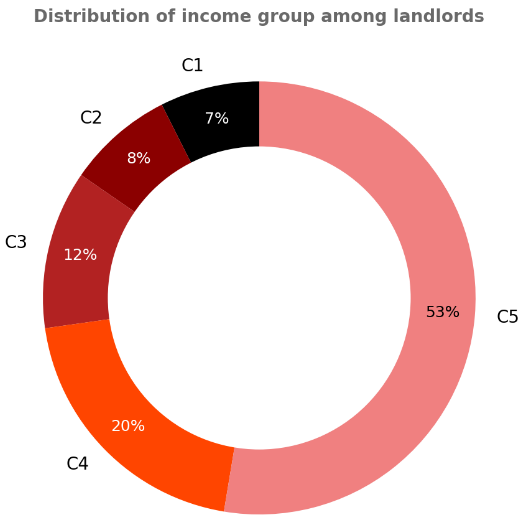


Figure 4.B.8 – Cost of households in 2018 including energy cost, heater systems investment cost, and taxes due to subsidies.

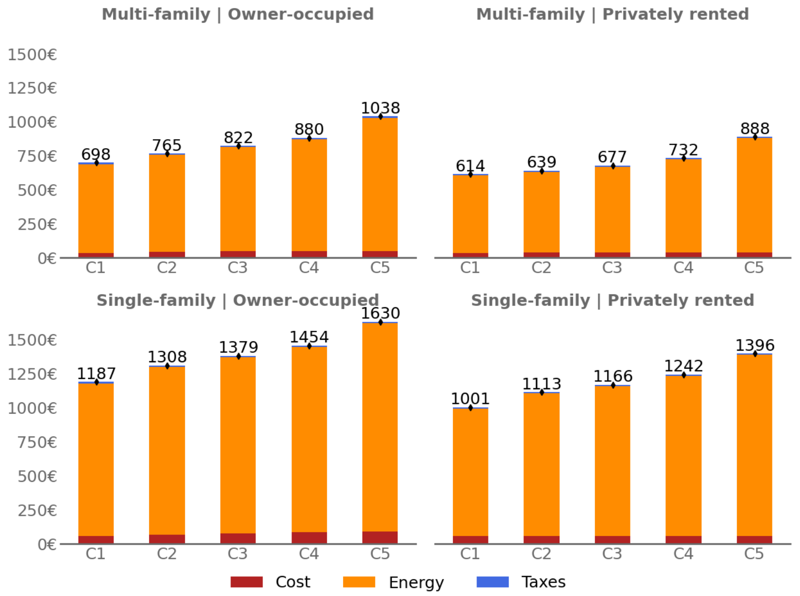


Figure 4.B.9 – Stock of heating system by household group in 2018.

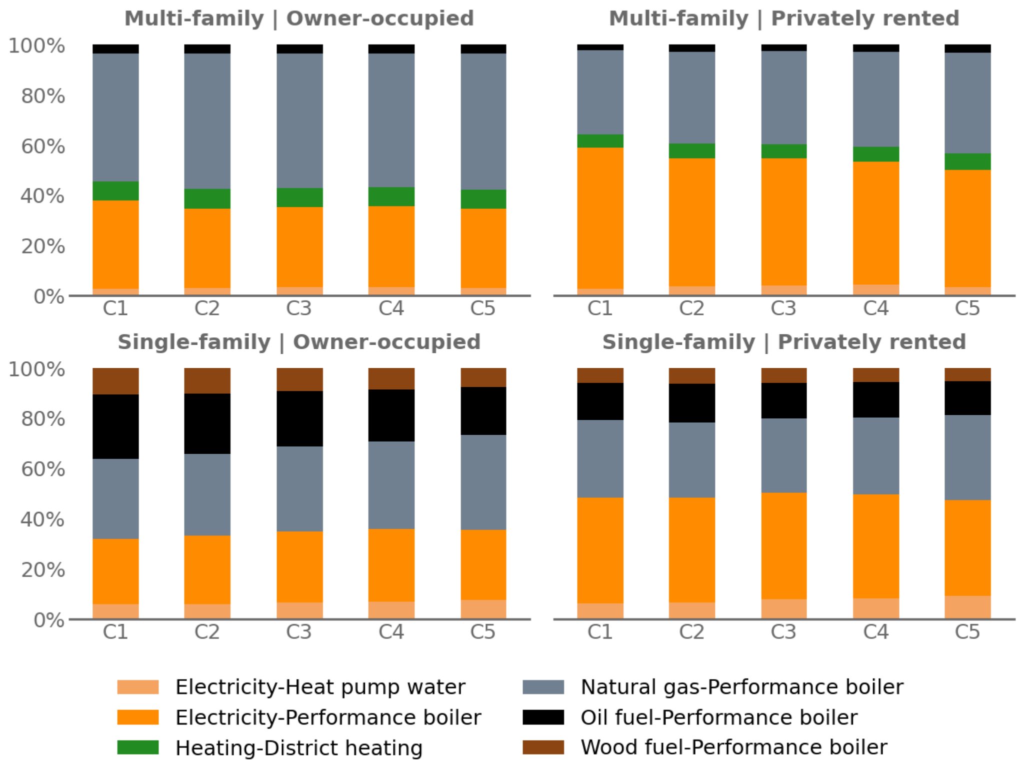


Figure 4.B.10 – Additional boilers in 2050, if the ban is implemented, in millions of boilers.

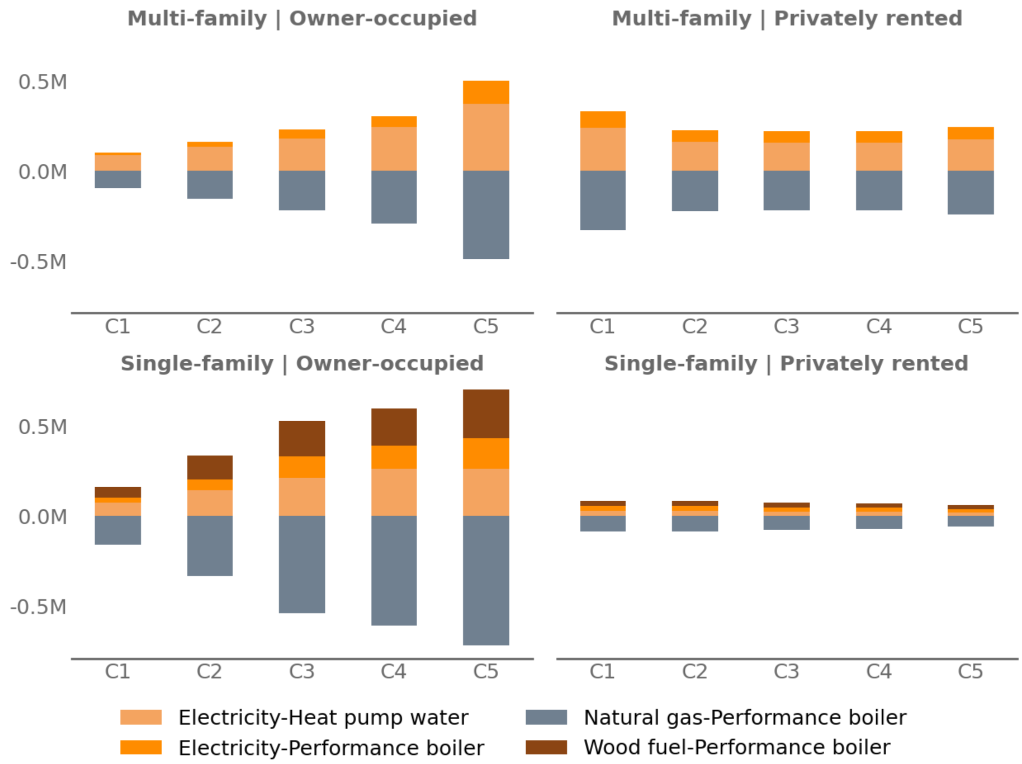
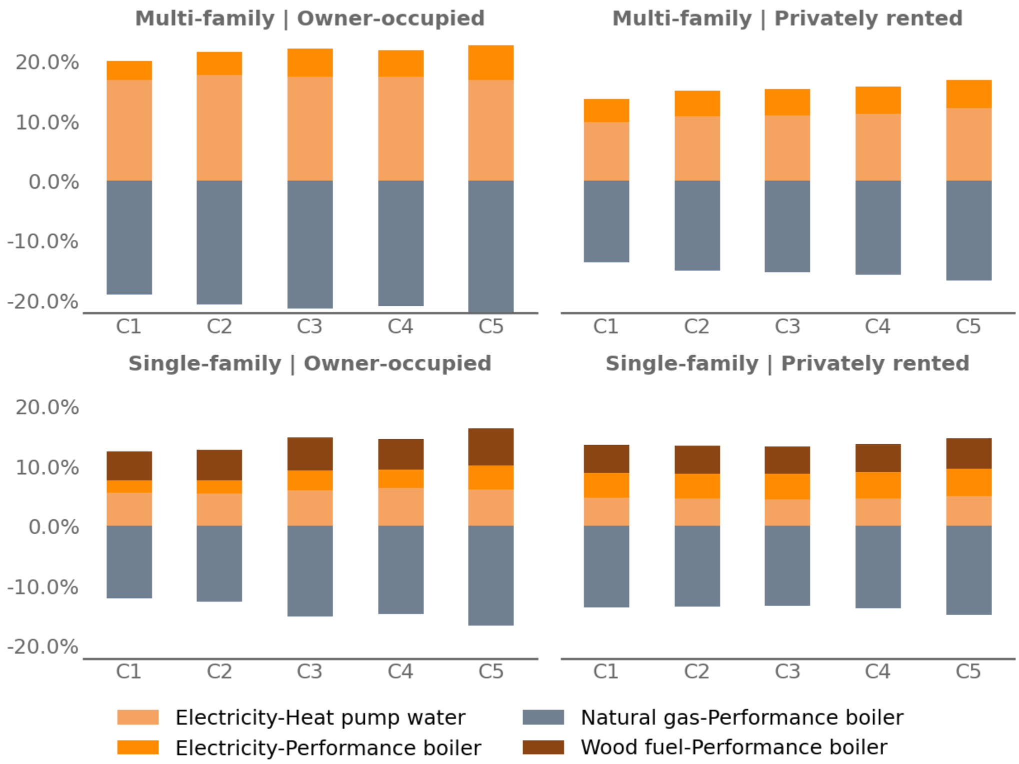


Figure 4.B.11 – Additional boilers in 2050 if the ban is implemented, as a proportion of total installed boilers in 2050 by household group.



4.C Supplementary methods

Sobol analysis In Section 3.2, we define a new outcome for each scenario. The outcome is defined as 1 if the Ban scenario achieves carbon neutrality while the counterfactual scenario does not, -1 if the contrary holds, and 0 if both scenarios either meet or do not meet the carbon constraint. In our case, we actually never observe the -1 case. This outcome therefore directly measures the scenarios responsible for increased vulnerability of the counterfactual policy scenario compared to the ban policy scenario. Since Sobol analysis is a variance decomposition method, the most influential drivers are therefore the parameters responsible for this increased vulnerability.

The first-order Sobol index is equal to:

$$S_i = \frac{\mathrm{Var}\left(\mathbb{E}\left[Y \mid X_i\right]\right)}{\mathrm{Var}(Y)}$$

It measures the effect of varying X_i alone, but averaged over variations in other input parameters.

The total effect Sobol index is equal to:

$$S_{T_i} = 1 - \frac{\mathrm{Var}\left(\mathbb{E}\left[Y \mid \boldsymbol{X}_{-i}\right]\right)}{\mathrm{Var}(Y)}$$

It measures the contribution to the output variance of X_i, including all variance caused by its interactions, of any order, with any other input variables.

Other global sensitivity analysis include regression-based analysis (Pye et al., 2015). These approaches typically assume linearity, attributing the residual sum-of-squares to variance unexplained by the model, due to nonlinear interactions. Given the significant nonlinear dynamics observed among uncertain drivers in our analysis, we opted for a variance decomposition methodology.

Total cost incurred by households 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, $\hat{p_{i,t}}^{\mathrm{k}}$ net of subsidies, $s^{\mathrm{k}}_{i,t}$, and energy expenditure $p^{\mathrm{energy}}_t \cdot \mathrm{Conso}_{i,t}$, 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.

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

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

$$\bar{C_{I,t}}^{\mathrm{investment}} = \sum_{i \in I} (p^{\mathrm{heater}}_{i,t} - s^{\mathrm{heater}}_{i,t}) \cdot N^{\mathrm{switch}}_{i,t} + (p^{\mathrm{insulation}}_{i,t} - s^{\mathrm{insulation}}_{i,t}) \cdot N^{\mathrm{insulation}}_{i,t}$$

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:

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

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

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

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 3.4 show the difference of average total cost for househol group I when the ban is implemented compared to the counterfactual scenario.

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

4.C.1 Data

Description of EOLES

The hourly capacity factors for variable renewable energy (VRE) sources, including offshore and onshore wind, as well as solar PV, are defined at the departmental level across France, based on historical data from 2000-2018. Technological cost parameters predominantly derive from the French Transmission System Operator (TSO)'s most recent long-term assessment (RTE, 2022), with additional data from ADEME (2018) and Zeyen et al. (2021) where necessary.

The central scenario for the energy mix incorporates several exogenous assumptions. First, residual electricity demand not endogenously determined by the Res-IRF model — covering uses other than heating — is based on the TSO's central projection of 595 TWh by 2050, factoring in the increased penetration of electric vehicles. Additionally, a demand for 40 TWh of hydrogen by 2050 is anticipated. Second, maximum capacities for VRE and nuclear technologies align with the TSO's central production scenario. Third, the potential for biogas production, through both methanization and pyrogazification processes, is derived from ADEME, adjusted to fit the energy and residential sectors' context.

The main simplification assumptions in the EOLES are consistent with other versions in the EOLES family:

- The power system operates under the copper plate assumption, indicating that electricity produced anywhere in continental France is assumed to be instantaneously available at any consumption point. This assumption treats France as a single node in the model.

Table 4.C.1 – Evolution of CAPEX (€/kWe). New nuclear power can only be installed starting in 2035. Methanation is calculated as the sum of electrolysis CAPEX and Sabatier reaction CAPEX.

Technology	2025	2030	2035	2040	2045	2050	Reference
Offshore wind, Floating	3580	3280	3130	2980	2830	2680	RTE (2022)
Offshore wind, Fixed	2930	2480	2380	2280	2180	2080	RTE (2022)
Onshore wind, Fixed	1250	1210	1190	1170	1150	1130	RTE (2022)
Solar PV, ground	672	597	557	517	497	477	RTE (2022)
Solar PV, Mounted	967	867	812	757	717	677	RTE (2022)
Nuclear power	NA	NA	5391	5035	4505	4500	RTE (2022)
Methanation	1700	1341	1300	1274	1240	1207	RTE (2022)
Methanization	370	370	370	370	370	370	ADEME (2018)
Pyrogazeification	2500	2500	2500	2500	2500	2500	ADEME (2018)
OCGT	600	600	600	600	600	600	RTE (2022)
CCGT	900	900	900	900	900	900	RTE (2022)
CCGT for hydrogen	1100	1100	1100	1100	1100	1100	RTE (2022)

Table 4.C.2 – Evolution of Fixed Operation and Maintenance (FOM) costs (€/kWe/yr).

Technology	2025	2030	2035	2040	2045	2050	Reference
Offshore wind, Floating	95	80	70	60	55	50.3	RTE (2022)
Offshore wind, Fixed	70	58	51	47	41	36	RTE (2022)
Onshore wind, Fixed	37.5	35	32.5	30	27.5	25	RTE (2022)
Solar PV, ground	10.5	10	9.5	9	8.5	8	RTE (2022)
Solar PV, Mounted	10.5	10	9.5	9	8.5	8	RTE (2022)
Nuclear power	100	100	100	100	100	100	RTE (2022)
Methanation	59	59	59	59	59	59	RTE (2022)
Methanization	37	37	37	37	37	37	ADEME (2018)
Pyrogazeification	225	225	225	225	225	225	ADEME (2018)
OCGT	20	20	20	20	20	20	RTE (2022)
CCGT	40	40	40	40	40	40	RTE (2022)
CCGT for hydrogen	40	40	40	40	40	40	RTE (2022)

- Electricity, methane, and hydrogen demands are considered inelastic. However, due to sector coupling between electricity, methane, and hydrogen networks, demands for electricity in hydrogen production and for gas in electricity generation are elastic and determined endogenously.
- The model employs linear optimization.

The cost projections for key electricity supply technologies utilized in our simulations primarily derive from RTE (2022). When RTE provides only partial data points between 2025 and 2050, we employ linear extrapolation to estimate the missing values. The annuities are calculated by considering the interest incurred during construction, assuming a uniform discount rate of 3.2% per year. The evolution of Capital Expenditure (CAPEX) is detailed in Table 4.C.1, while the evolution of Fixed Operation and Maintenance (FOM) costs is presented in Table 4.C.2.

The energy system strongly relies on available potential for different technologies, namely biogas (Table 4.C.5 and low-carbon technologies (Table 4.C.4).

Table 4.C.3 – Other constant electricity generation technology parameters.

Technology	Lifetime (yr)	Variable O&M (€/MWh)	Efficiency (%)	Reference
Offshore wind, Floating	40	0	-	RTE (2022)
Offshore wind, Fixed	40	0	-	RTE (2022)
Onshore wind, Fixed	30	0	-	RTE (2022)
Solar PV, ground	30	0	-	RTE (2022)
Solar PV, Mounted	30	0	-	RTE (2022)
Nuclear power	60	6	-	RTE (2022)
Methanation	20	5	60	RTE (2022)
Methanization	20	50	-	ADEME (2018)
Pyrogazeification	20	32	-	ADEME (2018)
OCGT	30	-	40	RTE (2022)
CCGT	40	-	57	RTE (2022)
CCGT for hydrogen	40	-	57	RTE (2022)

Table 4.C.4 – Low-carbon technologies potential in 2050 (GW).

Technology	2050	Reference
Offshore wind, Floating	30	RTE (2022)
Offshore wind, Fixed	15	RTE (2022)
Onshore wind, Fixed	58	RTE (2022)
Solar pv, Ground	96	RTE (2022)
Solar pv, Mounted	66	RTE (2022)
New nuclear power	13.5	RTE (2022)

Table 4.C.5 – Evolution of biogas potential (TWh).

Potential	Scenario	2025	2030	2035	2040	2045	2050	Reference
Methanization	S2	0	14	19	24	29	35	ADEME (2018)
	S3	0	19	25	32	39	46	ADEME (2018)
Pyrogazeification	S2	0	0	0	0	0	0	ADEME (2018)
	S3	0	0	5	9	14	19	ADEME (2018)

Table 4.C.6 – Evolution of storage CAPEX (€/kWh).

Technology	2025	2030	2035	2040	2045	2050	Reference
PHS	20	20	20	20	20	20	RTE (2022)
1h Battery storage	537	439	340	332	324	315	RTE (2022)
4h Battery storage	370	299	228	214	200	185	RTE (2022)
Salt cavern	350	350	350	350	350	350	RTE (2022)

Conclusion

Key findings

Energy renovation provide significant benefits, including energy savings, reduced greenhouse gas emissions, alleviation of fuel poverty, and improved health outcomes. They are subject to various forms of public support in high-income and temperate economies, motivated by climate and energy security concerns. However, recent empirical assessments of these interventions find them economically inefficient. This situations calls for a deeper analysis of the impact of energy renovation to improve policy planning.

To that end, I build a modeling framework that permits socio-economic assessment of a range of residential energy efficiency policies implemented in economies subject to market failures and behavioral anomalies. In doing so, I bridge a gap between building stock models, which contain rich technological detail but lack key market and behavioral mechanisms, and microeconomic models, which typically consider frictions one at a time, in a stylized way.

Specifically, in the first chapter, I develop a detailed structural model of energy demand for space heating in France, incorporating various frictions in energy efficiency investments to evaluate their impact on welfare, energy use, and CO_2 emissions. This model is extended to the EU level in the second chapter, where it is coupled with the Message-ix Buildings model to assess a wide range of demand-side policy mixes across the EU-27. In the third chapter, the framework tailored to France is coupled to an energy sytem model to capture the trade-offs between home insulation, switching to low-carbon heating systems, and decarbonizing heating fuels. The fourth chapter uses this enhanced framework to evaluate the impact and robustness of a ban on new fossil fuel boilers under various forms of uncertainty.

Taken together, the different research pieces generate the following insights: First, achieving carbon neutrality requires ambitious policies to promote heat pumps in most European countries (France in particular), alongside the full decarbonization of the electricity system. In particular, we demonstrate that adopting heat pumps shifts gas use from heating to electricity generation, which from a whole-system perspective is a more efficient use of low-carbon biogas, only available in limited supply. While regulatory measures underperform incentive-based instruments from a simple microeconomic perspective, they are crucial for meeting carbon neutrality, especially under uncertainty. Second, we that emission reduction is actually dominated by health, rental, and multi-family frictions in the ranking of justifications for energy efficiency policies. In particular, we highlight the importance of well-targeted subsidies for home insulation to address specific frictions and alleviate energy poverty. Finally, our assessment shows that the policies currently implemented in France close about half of the energy efficiency gap in space heating, pointing to the need for more effective targeting.

Limitations and avenues for further research

Improving the robustness of market barriers estimates

Our framework relies on the calibration of non-energy values and market frictions, such as the landlord-tenant dilemma and multi-family friction. Better estimates using modern causal techniques would improve the robustness of our results. In particular, we calibrate non-energy values to rationalize investment decisions. In line with the literature, we show that these non-energy values explain a substantial part of the investment decisions of marginal investors and also explain the low price elasticity of demand for energy renovations. Our findings suggests that policies designed to tackle market frictions are partly justified by these unrealized non-energy benefits. Further research should identify the components of non-energy benefits to distinguish between actual costs and benefits to households and possible modeling errors.

Improving the technical representation of synergies between home insulation and heat pump efficiency

The role of home insulation in mitigating climate change may depend largely on its ability to make homes suitable for the installation of efficient heat pumps. In this dissertation, I use contrasted assumptions regarding the relationship between heat pump efficiency and home insulation. In chapters 1, 3 and 4, I assume that heat pumps cannot be installed in the worst-performing dwellings based on field studies in France. However, I do not use this assumption in Chapter 2 as there is no consensus at European level. Future modeling systems should better represent the efficiency of heat pumps based on the energy performance of dwellings. Including such technical details could highlight the co-benefits of home insulation and the interaction between home insulation instruments and low-carbon heating systems. However, further empirical studies are needed to determine the level of home insulation required for effective heat pump installation. Recent research suggests that minimal work costing as little as €1,000 could be sufficient to install an efficient heat pump. If this is the case, targeting the worst homes for insulation and encouraging widespread adoption of heat pumps could be a straightforward and cost-effective way to reduce emissions.

Including the renovation industry

The framework assumes perfect competition in the renovation market, with the ability to adapt to increased demand. However, there are significant concerns about a shortage of skilled workers to carry out energy renovations. This shortage is expected to increase contractors' profit margins, reducing the impact of policy instruments and leading to inefficient transfers between public funds and the renovation industry. It is suspected that this mechanism is already at play, particularly in the heat pump market where profit margins are very high. In addition, theoretical work shows that contractors can exploit market imperfections to segment their supply. They do this by charging high prices for high-end options while denying low-income households access to the low-end options that would meet their needs (Nauleau et al., 2015). Another consequence could be that renovation contractors underprovide quality in a market characterized by information asymmetries (Giraudet et al., 2018). Further research could include the renovation industry in the model and thus enable the modeling of companies' profit margins. In particular, it would be possible to model subsidy pass-through. The calibration of such a model requires data on the reaction of companies to the increase in subsidies. Such empirical work could take advantage of the fact that the implementation of bonuses related to the white certificate obligation program was different for low-income and other households. A comparison of energy renovation quotes for the same renovations between low-income and other households could measure the value captured by contractors.

Including real-estate markets

The framework also does not include real-estate markets. However, the rental ban considered in our analysis for France is expected to have a major impact on home sales. In particular, landlords may prefer to sell their non-compliant property rather than undertake costly energy efficiency renovations. A recent qualitative survey in France showed that such reactions can vary depending on the landlord profile (Robert and Nadaï, 2023). It suggests that half of landlords are likely to respond to the tightening of requirements by carrying out energy renovation work, while the other half are unsure of the consequences or are considering exiting the non-seasonal rental market. This suggests that the tightening of requirements would have significant redistributive effects on the market. Such a situation could have a detrimental effect on the availability of housing, particularly in the current situation in France where there is a shortage of affordable housing.