



HAL
open science

Phasing out fossil fuel in the residential sector: Should new gas boilers be banned ?

Célia Escribe, Lucas Vivier

► **To cite this version:**

Célia Escribe, Lucas Vivier. Phasing out fossil fuel in the residential sector: Should new gas boilers be banned ?. 2024. hal-04538870v2

HAL Id: hal-04538870

<https://hal.science/hal-04538870v2>

Preprint submitted on 3 Jun 2024 (v2), last revised 15 Nov 2024 (v3)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Phasing out fossil fuel in the residential sector: Should new gas boilers be banned ?

¹, Célia Escribe^{*,1,2,4}, and Lucas Vivier^{*,1,3,4}

¹CIREN-CNRS, 45 bis, Avenue de La Belle Gabrielle, 94736, Nogent sur Marne, France

²CMAP, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, Route de Saclay, Palaiseau, France

³ENPC, Ecole des Ponts ParisTech, France

⁴These authors contributed equally.

*Corresponding authors: celia.escribe@polytechnique.edu, lucas.vivier@enpc.fr

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 a ban on gas boilers under 11,664 scenarios covering major uncertainties. Taking France as a case study, we demonstrate that a ban is critical to meet carbon neutrality. The ban achieves a reduction in total system cost in over 75% of scenarios, as costly investments in heat pumps are offset by a more efficient energy system. We demonstrate that the implementation of the ban, when coupled with the existing subsidy framework, mitigates inequalities among owner-occupied households but generate adverse affect for those in privately rented homes. Overall, our findings support the introduction of a ban on gas boilers, emphasizing the need to assess policies not only for their cost-effectiveness but also for their robustness to address uncertainties.

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

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 agents' 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 investment decisions of heating system. Without proper policy instruments, this 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 & Fabre, 2022), and realistic subsidy designs cannot be individually targeted. Consequently, and despite efforts to implement market-based instruments (Alberini & 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 the subsidies are high. In addition, the long lifetimes of heating systems 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. In this context, 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, a recent agreement in the Energy Performance Building Directives mandates that Member States implement measures to completely phase out fossil fuel heating and cooling by 2040 (Commission, 2023). 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 ban on gas boilers could also lead to significant energy system externalities. Specifically, an increase in space heating electricity demand, concentrated during peak load, could require further investments in the energy sector, significantly increasing overall costs. Few engineering research investigates how a rapid roll-out on heat pumps impacts the electricity system (Zeyen *et al.*, 2021; Roth, 2023; Maxim & Grubert, 2023). In particular, RTE (2023) calculated that the French electricity grid could technically handle an increased demand from heat pumps up to the year 2035. Yet, these studies do not explore the cost-effectiveness and fairness of a ban on fossil fuel boilers. 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 ?

Integrated demand-supply modelling framework

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. 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 & Giraudet, 2024). The policy mix includes

subsidies for home insulation and low-carbon heating systems as well as a residential carbon tax of €45/tCO₂.

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 & Vivier, 2023).

Scenario design

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 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 & 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 & Parry, 2008).

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 , High

Table 1: Uncertainty scenarios for model parameters (supply-side, demand-side and global). The total number of combinations leads to 11,664 distinct scenarios. Reference configuration is in bold letters.

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. Scenarios that achieve carbon neutrality without the ban also succeed under the ban, indicating no adverse effects from its implementation. The critical factor for meeting climate targets is the residual gas demand in the residential sector. From a policy perspective, failure in achieving carbon neutrality is primarily due to a misspecified policy design in the residential sector that does not adequately address the impact of this excessive residual gas demand. Figure 1 identifies the key uncertainties that undermine the climate objective in the absence of the ban. Interactions among uncertainties play a large role in the increased robustness of the ban, as evidenced by larger total order indices compared to first order indices.

First, the implementation of the ban drastically reduces the reliance on low-carbon biogas potential. Second, achieving carbon neutrality without the ban crucially depends on the level of ambition of home insulation policy to reduce the residual space heating demand. The ban introduces a shift in heating demand from gas to electricity, offering the energy system greater adaptability to such adverse outcomes. Third, lower-than-expected households' response to the incentives (low price elasticity of the heat pump) or insufficient subsidies for low-carbon heating systems (heater policy) may lead to a failure to meet the climate targets. 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 sector.

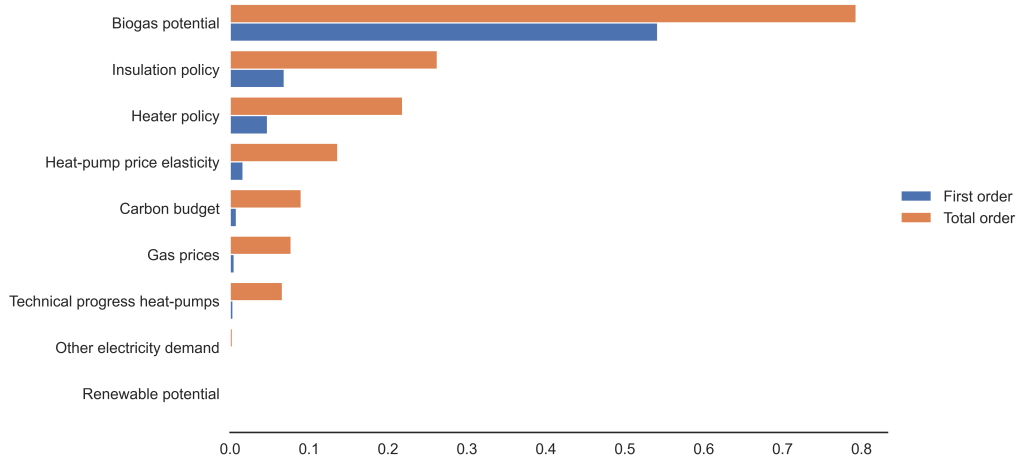
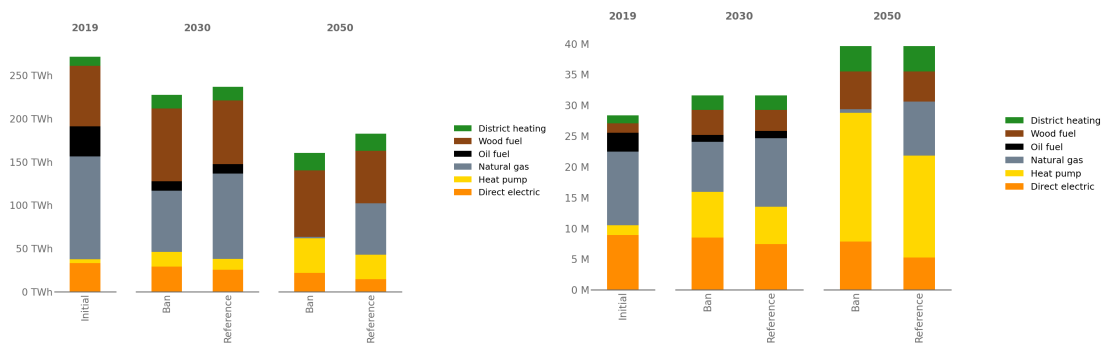


Figure 1: Main uncertainties that undermine the achievement of climate targets in the current policy scenario. First-order Sobol indices illustrate the share of variance explained by each uncertainty independently, while total order Sobol indices represent the share of the variance explained by each uncertainty in interaction with other uncertainties, which can cumulatively exceed 1 (interaction terms are counted multiple times).

A ban leads to a more efficient energy system

Figure 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 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 9b illustrates that the ban could raise peak electricity demand by up to 10 GW in 2050 compared to the current policy scenario.



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

(b) Heating system stock (Million)

Figure 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.

Banning gas boilers influences the strategy for allocating gas resources, which are limited due to the limited biogas potential and carbon constraints. While low-carbon gas is used in gas boilers under the current policy scenario, it can instead be 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 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 8, thus reducing the need for primary energy generation (Figure 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 2) and lead to a lower total installed capacity. Specifically, Figure 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.

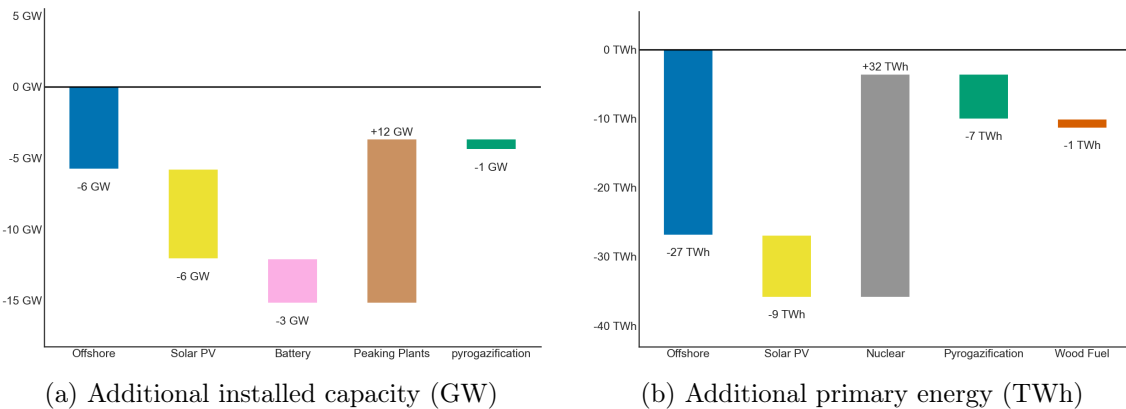


Figure 3: Additional installed capacity and generation in 2050 when the ban on gas boilers is implemented.

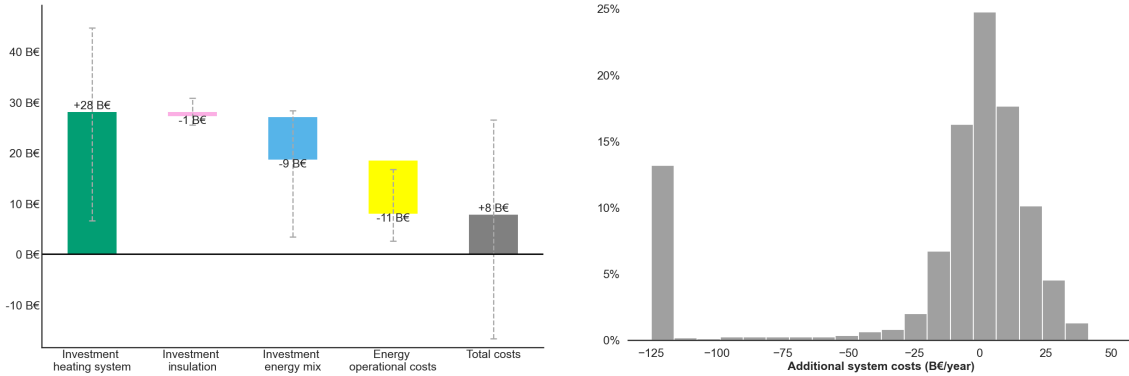
A nuanced impact on total system costs

Comparison of total system costs is done across scenarios where both the ban and the current policy scenario achieve the carbon constraint. Total system costs are defined as the sum of annualized costs over the 2025-2050 period.

Figure 4a 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 as the ban relies on additional peaking power plants capacity while reducing the need for more costly 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 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 current policy scenario in the residential sector (Figure 4b). 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 11). This underlines that the current policy scenario reduces total system costs compared to the ban scenario only under a set of specific conditions. Overall, in

more than 75% of all scenarios analyzed, implementing the ban results in lower total system costs.



(a) Breakdown of additional cost in the Ban scenario.

(b) Distribution of additional cost across uncertainties.

Figure 4: Breakdown and distribution of additional cost when implementing the ban of gas boilers compared to the counterfactual scenario. In Figure 4a, error bars represent the 25th and 75th percentiles of the data set, focusing solely on scenarios featuring plausible energy systems. Figure 4b reveals that 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€/year or readability.

Distributional impacts of the ban

We investigate the distributional consequences of implementing a ban by assessing the additional cost incurred by different income groups and housing categories (occupancy status and housing type). This includes heating system purchase costs and energy expenditure, supplemented by lump-sum taxes meant to cover additional subsidy costs. We assume that these taxes are evenly distributed among French households. While accounting 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 5). 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 emerges as the only profitable choice, provided that subsidies are available to offset the purchase costs. Without substantial subsidies, or if opting 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, 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 13) and are eligible for

smaller subsidies. As a result, tenants, who bear the investment cost of heating systems passed on through their 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 12 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 17), implying that a smaller fraction of these households is affected by the ban and thus uses subsidies, even though they bear the cost of the lump-sum tax. This situation is especially pronounced for low-income households in privately rented dwellings, who bear the tax burden without reaping the subsidy benefits aligned with their income level.

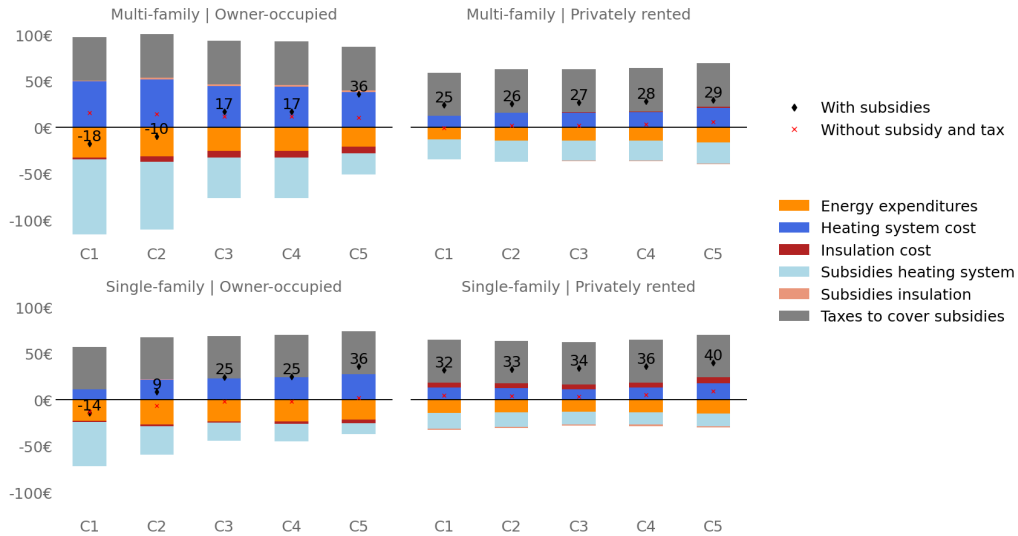


Figure 5: Average additional annual costs by household group if the ban is implemented (€/per year). ‘C1’ refers to the first income quintile, i.e. very low income, and ‘C5’ refers to the last income quintile, i.e. very high income. A negative value means that the ban reduces household expenditure, while 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).

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, we demonstrate that achieving carbon neutrality in the residential sector is highly uncertain under the current policy regime. In contrast, the ban is a robust strategy to meet climate targets against the uncertainty of various factors driving the decarbonization of the residential and energy sectors. Second, 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 is more efficient, characterized by a reduced need for primary energy generation and an optimized utilization of electricity capacities. 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 implementation of the ban, when coupled with the French existing subsidy framework, mitigates vertical inequalities among owner-occupied households but does not extend to those in privately rented homes.

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 & 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. 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 & Segerson, 2014), at the expense of technical details.

Online Methods

Model

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).

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.

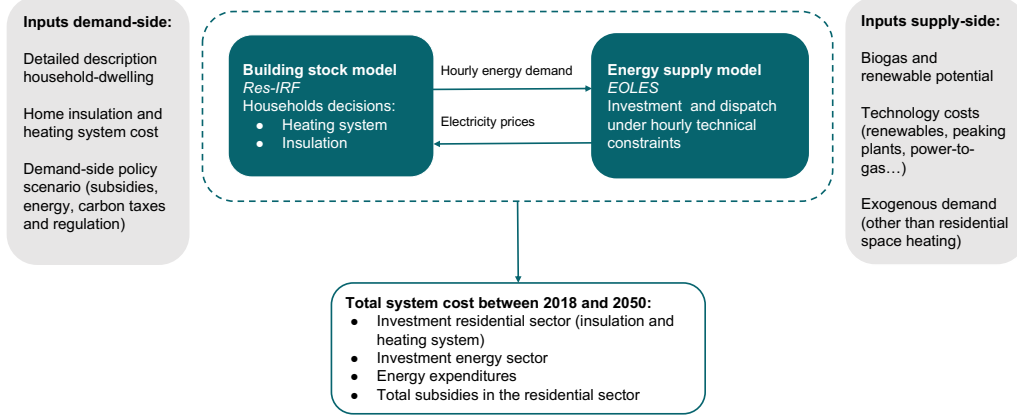


Figure 6: Schema of the modeling framework.

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 & 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).

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 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 A.3).

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 A.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 & 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 & Greenstone, 2024).

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](https://doi.org/10.5281/zenodo.10405492) or on GitHub: <https://github.com/CIREDD/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.

Declaration of competing interest

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

Acknowledgments

This research was supported by Agence Nationale de la Recherche (ANR) project PRE-MOCLASSE (contrat ANR-19-CE22-0013-01). Lucas Viver thanks Palladio Foundation for their funding and support. Célia Escribe thanks ADEME and Chaire Stress Test for their funding and support. We thank Adrien Fabre, Louis-Gaëtan Giraudet, Simon Jean, Philippe Quirion, Thibault Briera, Romain Fillon, Céline Guivarch for useful comments and suggestions on previous versions of this paper. We would also like to thank the participants of the CIREDD internal PhD seminar.

References

1. Cabeza, L. F. *et al.* in *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022).
2. Eurostat. *Energy consumption in households* en. June 2023.
3. Schleich, J., Gassmann, X., Meissner, T. & Faure, C. A large-scale test of the effects of time discounting, risk aversion, loss aversion, and present bias on household adoption of energy-efficient technologies. en. *Energy Economics* **80**, 377–393 (May 2019).
4. Lang, G., Farsi, M., Lanz, B. & Weber, S. Energy efficiency and heating technology investments: Manipulating financial information in a discrete choice experiment. en. *Resource and Energy Economics* **64**, 101231 (May 2021).
5. Allcott, H., Mullainathan, S. & Taubinsky, D. Energy policy with externalities and internalities. en. *Journal of Public Economics* **112**, 72–88 (Apr. 2014).
6. Douenne, T. & Fabre, A. Yellow Vests, Pessimistic Beliefs, and Carbon Tax Aversion. en. *American Economic Journal: Economic Policy* **14**, 81–110 (Feb. 2022).
7. Alberini, A. & Bigano, A. How effective are energy-efficiency incentive programs? Evidence from Italian homeowners. en. *Energy Economics. Frontiers in the Economics of Energy Efficiency* **52**, S76–S85 (Dec. 2015).
8. Camarasa, C. *et al.* A global comparison of building decarbonization scenarios by 2050 towards 1.5–2 °C targets. en. *Nature Communications* **13**. Number: 1 Publisher: Nature Publishing Group, 3077 (June 2022).
9. Braungardt, S., Tezak, B., Rosenow, J. & Bürger, V. Banning boilers: An analysis of existing regulations to phase out fossil fuel heating in the EU. *Renewable and Sustainable Energy Reviews* **183**, 113442 (Sept. 2023).
10. Commission, E. *EU Save Energy Communication* en. May 2022.
11. Commission, E. *New rules to boost energy performance of buildings* en. Dec. 2023.
12. Hepburn, C. Regulation by Prices, Quantities, or Both: A Review of Instrument Choice. *Oxford Review of Economic Policy* **22**, 226–247 (July 2006).
13. Zeyen, E., Hagenmeyer, V. & Brown, T. Mitigating heat demand peaks in buildings in a highly renewable European energy system. en. *Energy* **231**, 120784 (Sept. 2021).
14. Roth, A. *Power sector impacts of a simultaneous European heat pump rollout* arXiv:2312.06589 [econ, q-fin]. Dec. 2023.
15. Maxim, A. & Grubert, E. Highly energy efficient housing can reduce peak load and increase safety under beneficial electrification. en. *Environmental Research Letters* **19**. Publisher: IOP Publishing, 014036 (Dec. 2023).
16. RTE. *Bilan prévisionnel. Édition 2023* tech. rep. (RTE, 2023).
17. 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* en. Sept. 2023.
18. Vivier, L. & Giraudet, L.-G. *Is France on track for decarbonizing its residential sector? Assessing recent policy changes and the way forward*. Jan. 2024.
19. Escribe, C. & Vivier, L. *CIREN/EOLES-Coupling: v1.0.0* Dec. 2023.
20. Bosetti, V. *et al.* Sensitivity to energy technology costs: A multi-model comparison analysis. *Energy Policy* **80**, 244–263 (May 2015).
21. Pye, S., Sabio, N. & Strachan, N. An integrated systematic analysis of uncertainties in UK energy transition pathways. en. *Energy Policy* **87**, 673–684 (Dec. 2015).
22. Chaudry, M., Abeysekera, M., Hosseini, S. H. R., Jenkins, N. & Wu, J. Uncertainties in decarbonising heat in the UK. en. *Energy Policy* **87**, 623–640 (Dec. 2015).
23. Goulder, L. H. & Parry, I. W. H. Instrument Choice in Environmental Policy. *Review of Environmental Economics and Policy* **2**. Publisher: The University of Chicago Press, 152–174 (July 2008).
24. Pollitt, H., Mercure, J.-F., Barker, T., Salas, P. & Scricciu, S. The role of the IPCC in assessing actionable evidence for climate policymaking. en. *npj Climate Action* **3**. Number: 1 Publisher: Nature Publishing Group, 1–9 (Jan. 2024).
25. Knobloch, F. *et al.* FTT:Heat — A simulation model for technological change in the European residential heating sector. en. *Energy Policy* **153**, 112249 (June 2021).
26. Giraudet, L.-G., Bourgeois, C. & Quirion, P. Policies for low-carbon and affordable home heating: A French outlook. en. *Energy Policy* **151**, 112140 (Apr. 2021).

27. Müller, A. *et al.* Why renovation obligations can boost social justice and might reduce energy poverty in a highly decarbonised housing sector. *Energy Policy* **191**, 114168 (Aug. 2024).
28. Tsvetanov, T. & Segerson, K. The Welfare Effects of Energy Efficiency Standards When Choice Sets Matter. *Journal of the Association of Environmental and Resource Economists* **1**. Publisher: [Association of Environmental and Resource Economists, The University of Chicago Press], 233–271 (2014).
29. Hirth, L., Ruhnau, O. & Sgarlato, R. *The European Electricity Market Model EMMA - Model Description* eng. Working Paper (Kiel, Hamburg: ZBW - Leibniz Information Centre for Economics, 2021).
30. Sobol, I. M. Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. *Mathematics and Computers in Simulation. The Second IMACS Seminar on Monte Carlo Methods* **55**, 271–280 (Feb. 2001).
31. Jacobsen, M. R. & van Benthem, A. A. Vehicle Scrappage and Gasoline Policy. en. *American Economic Review* **105**, 1312–1338 (Mar. 2015).
32. Fowlie, M., Greenstone, M. & Wolfram, C. Are the Non-monetary Costs of Energy Efficiency Investments Large? Understanding Low Take-Up of a Free Energy Efficiency Program. en. *American Economic Review* **105**, 201–204 (May 2015).
33. Allcott, H. & Greenstone, M. *Measuring the Welfare Effects of Residential Energy Efficiency Programs* Working Paper. 2024.

A Supplementary information

A.1 Supplementary table

	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 2: 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.

	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

Table 3: Summary of main results in the residential sector in the configuration setting by 2050.

A.2 Supplementary figures

We assess the key uncertainties that undermine the climate objective under the current policy scenario in Figure 7.

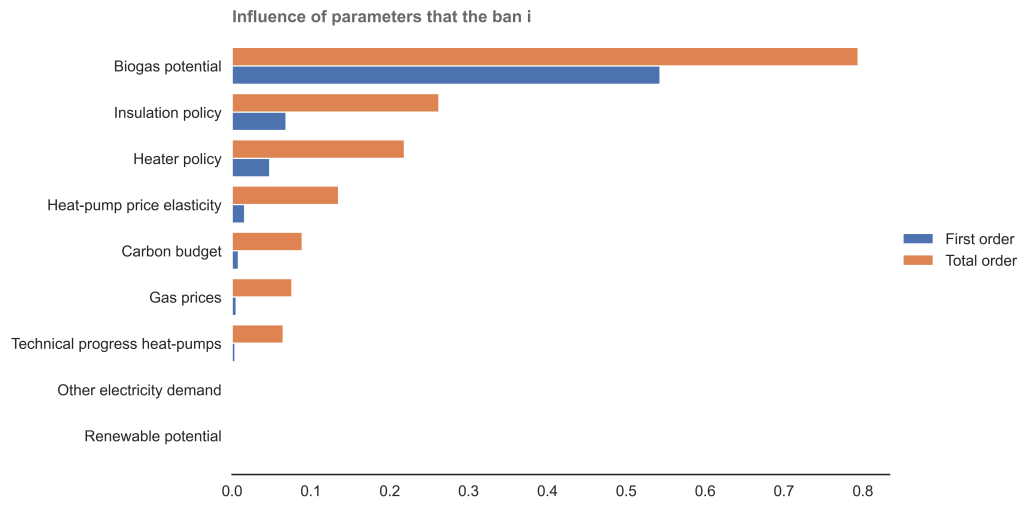


Figure 7: Ranking of most influential parameters driving the capacity of the counterfactual scenario to achieve carbon neutrality.

A.2.1 Supplementary figures to assess the consequences of implementing the ban on the energy system

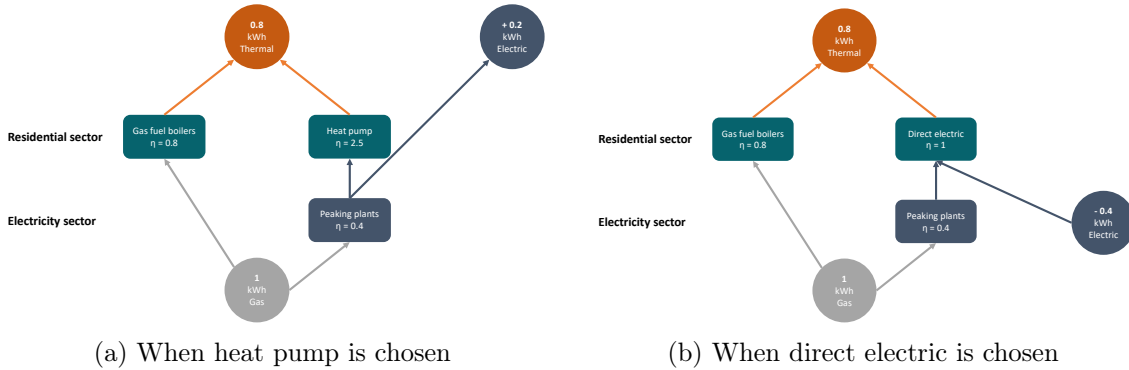


Figure 8: Simplified diagram showing the overall efficiency of replacing gas boilers with heat pumps and direct electricity.

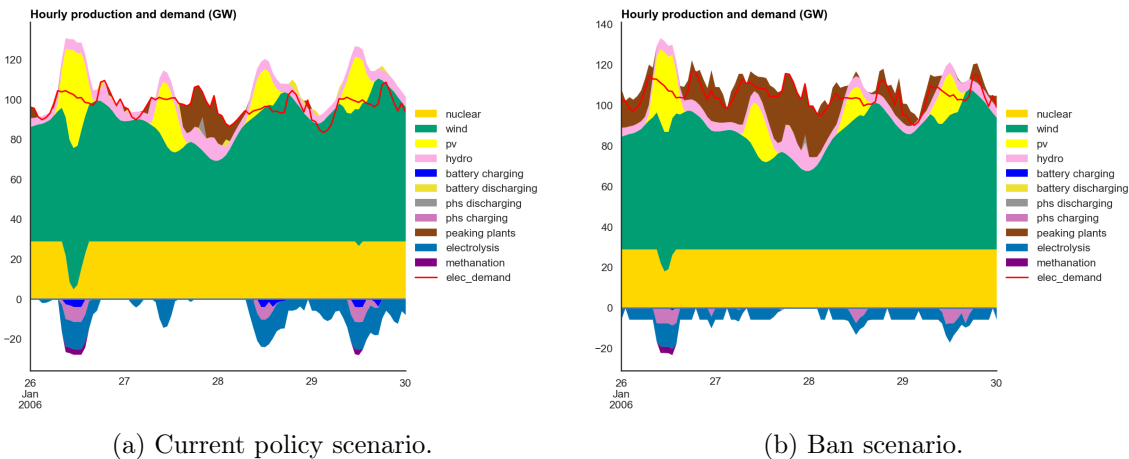


Figure 9: Hourly dispatch to meet electricity demand in 2050 over a typical week in January.

Supplementary Figure 11 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 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.

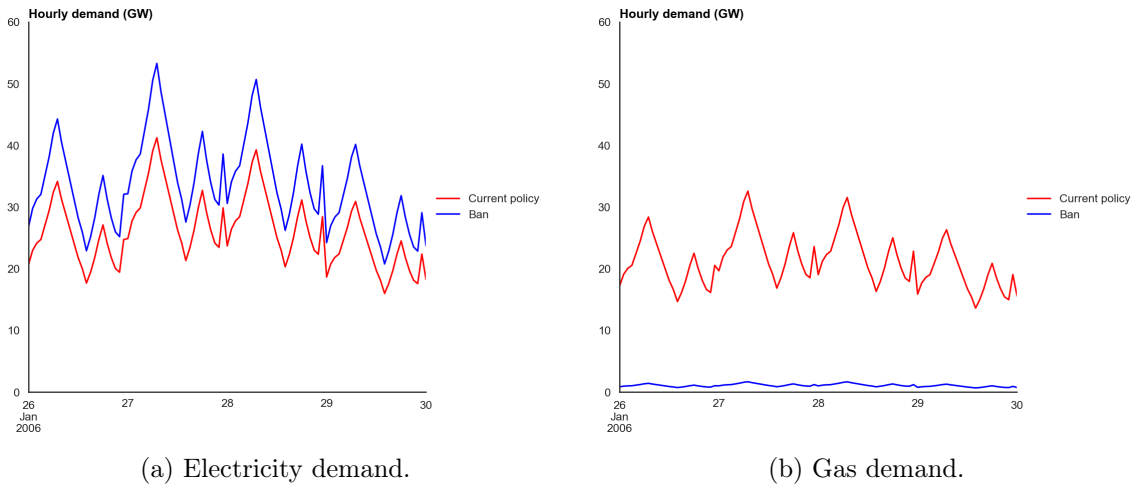


Figure 10: Load profile for electricity and gas heating demands in 2050 over a typical week in January.

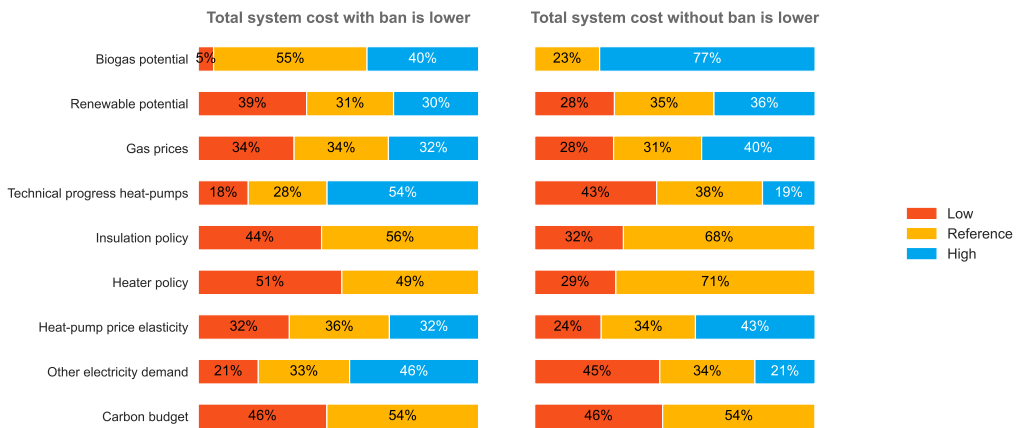


Figure 11: Frequency of scenarios with total system cost lower with the ban (left) and total system cost lower without the ban (right).

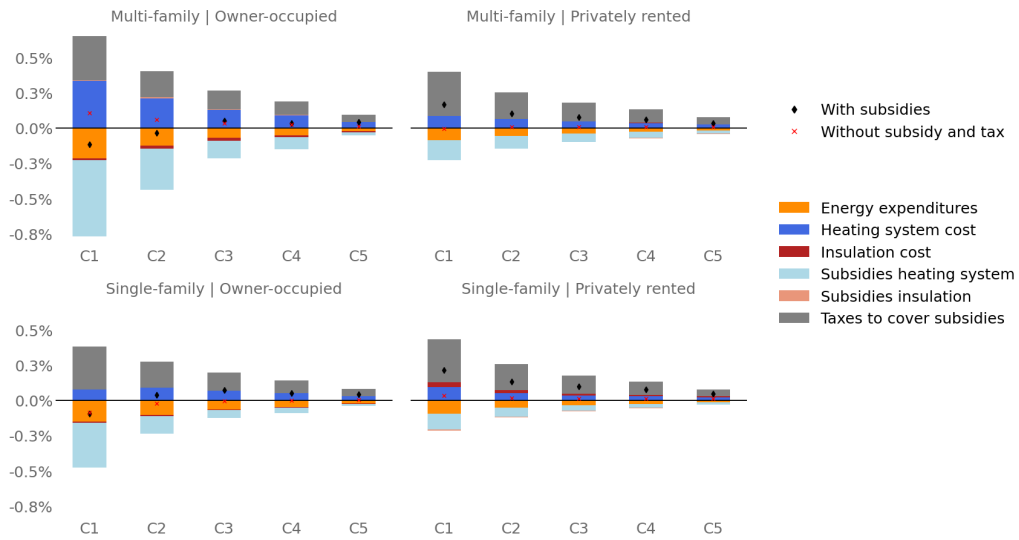


Figure 12: Average additional annual costs by household group if the ban is implemented (€per year). ‘C1’ means the first income quintile, i.e. very low income, and ‘C5’ means the last income quintile, i.e. very high income. A negative value means that the ban reduces household expenditure, while a positive 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).

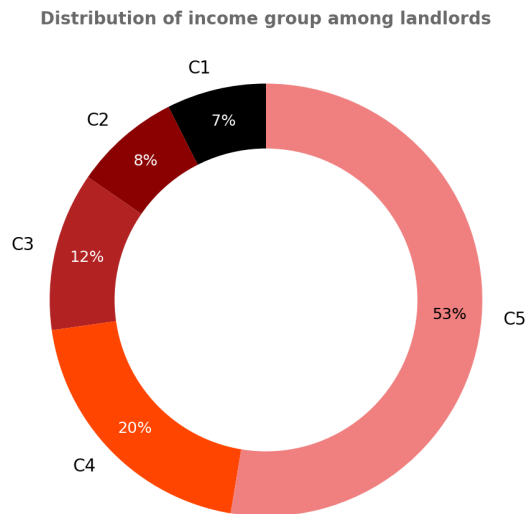


Figure 13: Distribution of income group among landlords in France in 2018.

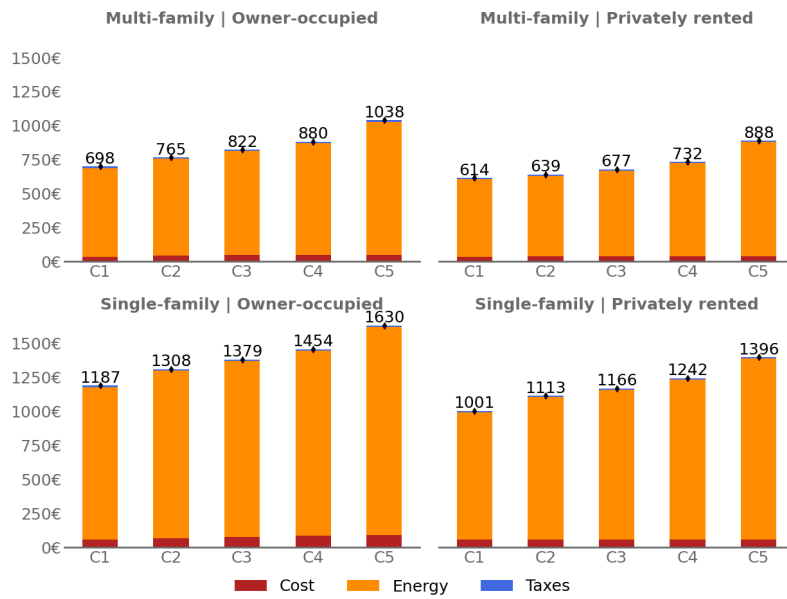


Figure 14: Cost of households in 2018 including energy cost, heater systems investment cost, and taxes due to subsidies.

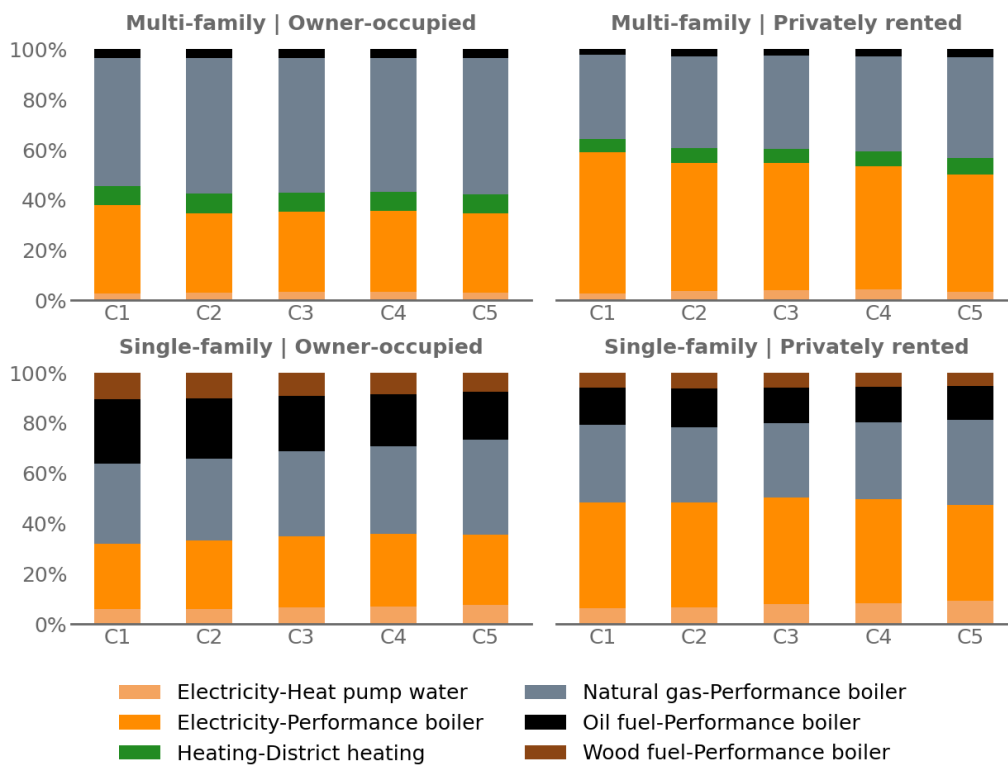


Figure 15: Stock of heating system by household group in 2018.

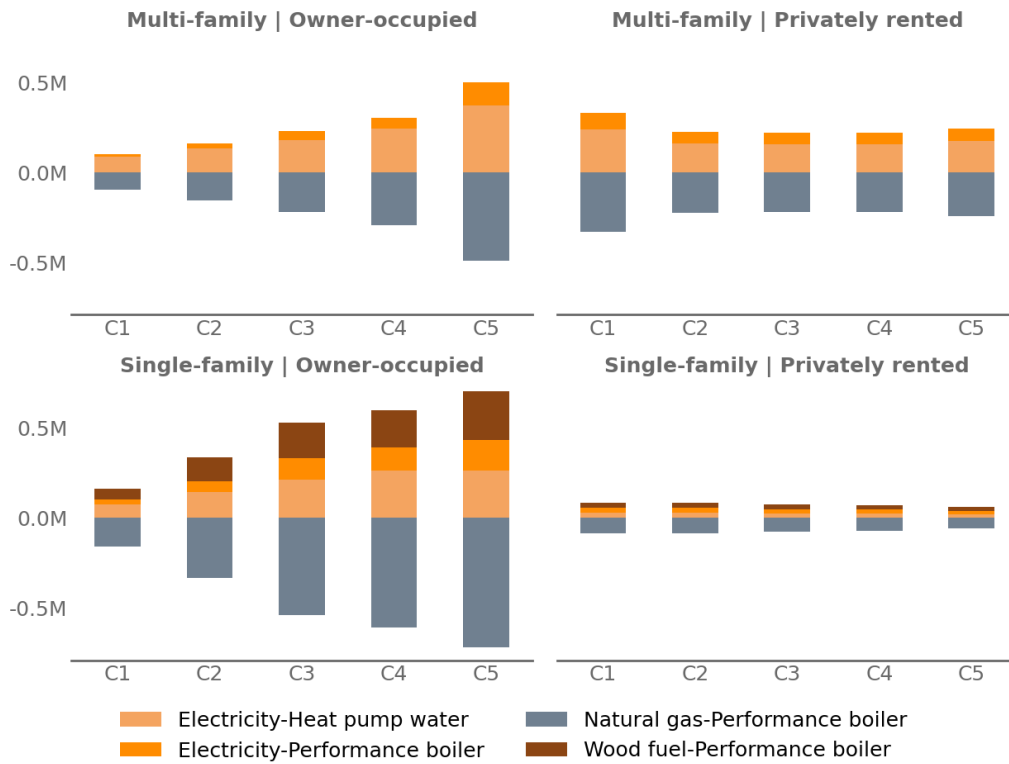


Figure 16: Additional boilers in 2050, if the ban is implemented, in millions of boilers.

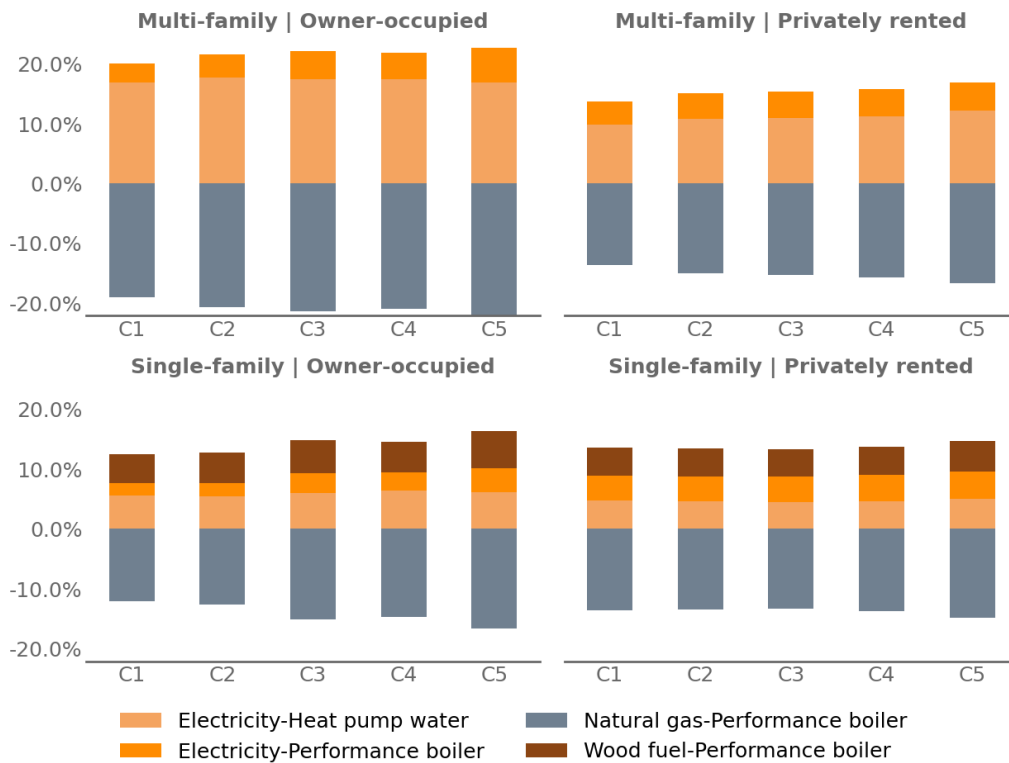


Figure 17: Additional boilers in 2050 if the ban is implemented, as a proportion of total installed boilers in 2050 by household group.

A.3 Supplementary methods

Sobol analysis In Section , 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:

$$S_i = \frac{\text{Var}(\mathbb{E}[Y | X_i])}{\text{Var}(Y)}$$

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:

$$S_{T_i} = 1 - \frac{\text{Var}(\mathbb{E}[Y | \mathbf{X}_{-i}])}{\text{Var}(Y)}$$

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, $p_{i,t}^k$ net of subsidies, $s_{i,t}^k$, and energy expenditure $p_t^{\text{energy}} \cdot \text{Conso}_{i,t}$, inclusive of taxes meant to cover subsidy costs $T(t, s)$.

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

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

Therefore, the $\bar{C}_{I,t}^{\text{investment}}$ 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 show the difference of average total cost for household group I when the ban is implemented compared to the counterfactual scenario.

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

A.4 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.
- 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, while the evolution of Fixed Operation and Maintenance (FOM) costs is presented in Table 5.

The energy system strongly relies on available potential for different technologies, namely biogas (Table 8 and low-carbon technologies (Table 7).

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: 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	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

Table 5: Evolution of Fixed Operation and Maintenance (FOM) costs (€/kWe/yr).

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 6: Other constant electricity generation technology parameters.

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 7: Low-carbon technologies potential in 2050 (GW).

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
Pyrogazification	S2	0	0	0	0	0	0	ADEME, 2018
	S3	0	0	5	9	14	19	ADEME, 2018

Table 8: Evolution of biogas potential (TWh).

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

Table 9: Evolution of storage CAPEX (€/kWh).

Res-IRF data source

Table 11 described all data sources in Res-IRF. Specifically for the case of this study, we recall here the cost assumptions for the heating system, which drive the total cost of the ban on gas boiler.

Heating system	Cost (euro)	Lifetime installation
Heat pump	13,000	20
Natural gas boiler	6,000	20
Wood boiler	12,500	20
Direct electric	3,600	20

Table 10: Data derived from RTE & ADEME (2020). Cost data 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).

Inputs	Source
Energy system	
Energy prices projection	Scenario AME 2021 (MTE, 2021)
Energy taxes projection	Scenario AME 2021 (MTE, 2021)
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)
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	Effnergie & ADEME (2021)
Capex heating system	RTE & ADEME (2020)
Renovation rate	CEE 2017-2018 (MTE, 2020a)
Market share insulation work	TREMI (MTE, 2020a)
Heating system lifetime	Knobloch <i>et al.</i> (2021)
Market share heating system	ADEME (2022)
Behavioral parameters	
Time preferences discount factor	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 <i>et al.</i> (2022)
Threshold credit constraint	Dolques <i>et al.</i> (2022)
Average interest rate of households savings	Own assumption
Average interest rate of home renovation loan	Dolques <i>et al.</i> (2022)
Indicators	
Health cost due to bad housing condition	Dervaux & Rochaix (2022)
Social discount rate	Ni & Maurice (2021)
Thermal module data	
	Loga (2013) and Arquin <i>et al.</i> (2020)

Table 11: List of data sources used in Res-IRF. * means data are not publicly available.

Supplementary References

1. Pye, S., Sabio, N. & Strachan, N. An integrated systematic analysis of uncertainties in UK energy transition pathways. en. *Energy Policy* **87**, 673–684 (Dec. 2015).
2. RTE. *Futurs énergétiques 2050* fr. Tech. rep. (2022).
3. ADEME. *Mix de gaz 100% renouvelable en 2050 ? [A 100% renewable gas mix in 2050?]* tech. rep. (2018).
4. Zeyen, E., Hagenmeyer, V. & Brown, T. Mitigating heat demand peaks in buildings in a highly renewable European energy system. en. *Energy* **231**, 120784 (Sept. 2021).
5. RTE & ADEME. *Réduction des émissions de CO₂, impact sur le système électrique : quelle contribution du chauffage dans les bâtiments à l'horizon 2035 ? [Reducing CO₂ emissions, impact on the electricity system: what contribution will heating make to buildings by 2035?]* tech. rep. (Dec. 2020).
6. MTE. *Synthèse du scénario "Avec mesures existantes" 2021 (AME 2021)* tech. rep. (Ministère de la transition écologique, June 2021).
7. ADEME. *Transition 2050* tech. rep. (2022).
8. INSEE. *Revenu disponible des ménages* May 2021.
9. MTE. *Le parc de logements par classe de consommation énergétique [Housing stock by energy consumption class]* fr. Sept. 2020.
10. ADEME. *DPE Logements (avant juillet 2021)* Mar. 2021.
11. MTE. *Consommation d'énergie par usage du résidentiel* fr. 2018.
12. ADEME, C. *Fiches Bâtiment Résidentiel (BAR)*. 2024.
13. Effinergie & ADEME. *Les maisons renoués à basse consommation [Low-energy renovated homes]* tech. rep. (Observatoire BBC, Apr. 2021).
14. MTE. *Enquête sur les travaux de rénovation énergétique dans les maisons individuelles (TREMI)* tech. rep. (Jan. 2020).
15. Knobloch, F. *et al.* FTT:Heat — A simulation model for technological change in the European residential heating sector. en. *Energy Policy* **153**, 112249 (June 2021).
16. Stolyarova, E. *Rénovation énergétique de l'habitat en France : analyse microéconométrique du choix des ménages*. These de doctorat (Paris Sciences et Lettres (ComUE), Apr. 2016).
17. Risch, A. Are environmental fiscal incentives effective in inducing energy-saving renovations? An econometric evaluation of the French energy tax credit. en. *Energy Economics* **90**, 104831 (Aug. 2020).
18. Dolques, G., Ledez, M. & Hainaut, H. *Quelles aides publiques pour la rénovation énergétique des logements ?* tech. rep. (I4CE, Feb. 2022).
19. Dervaux, B. & Rochaix, L. *Socio-Economic Evaluation of the Health Effects of Public Investment Projects* tech. rep. (France Stratégie, Mar. 2022).
20. Ni, J. & Maurice, J. *Révision du taux d'actualisation [Revision of the discount rate]* tech. rep. (France Stratégie, Oct. 2021).
21. Loga, T. TABULA Calculation Method – Energy Use for Heating and Domestic Hot Water. en, 56 (2013).
22. Arquin, C., Parc, J., Daunay, J. & Tazi, A. *À quelles conditions le secteur résidentiel peut-il atteindre la neutralité carbone telle que définie dans la SNBC ?* fr. Tech. rep. (Pouget Consultants, Carbone 4, Jan. 2020).