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

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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 assess this measure by simulating 3,072 scenarios covering major uncertainties in a framework that includes both realistic policy response and key interactions between the residential and energy sectors. Taking France as a case study, we demonstrate that the ban is critical to meet carbon neutrality. Despite costly investments in heating system, the ban leads to higher cost-effectiveness across uncertainties, by saving additional flexibility capacity in the energy system. We finally illustrate how a well-designed subsidy program is instrumental in mitigating horizontal and vertical inequalities that may arise from the policy's implementation.

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. In Europe, residential space heating represents 17% of total final energy consumption, with approximately 75% still relying on fossil fuels (Eurostat, 2023). Choosing appropriate policy instruments to transition to low-carbon heating systems is overall complex. Residential energy prices fail to capture both environmental externalities and the cost of decarbonization of the energy system. These inaccurate price signals divert agents away from investments aligned with environmental goals. Additionally, behavioral anomalies like present bias, statu-quo bias for technology in place and energy prices myopia lead to suboptimal investments, resulting in excessive gas demand to meet climate targets. From an economic perspective, these externalities and the heterogeneous market failures 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 the optimum : carbon taxes at the socially optimal level are often politically unfeasible (Douenne & Fabre, 2022), and realistic subsidy designs do not achieve the necessary precision. The long lifespans of heating systems introduce further complexity due to lock-in effects, complicating decarbonization strategy and policy planning in the residential sector. Consequently, and despite efforts to implement market-based instruments (Alberini & Bigano, 2015),

uptake rates of low-carbon heating systems across Europe remain too low (Camarasa *et al.,* 2022), leading authorities to consider more ambitious measure. 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 excessively high. 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 at national level.

However, such regulatory measures face opposition due to concerns about cost-effectiveness. The ban overlooks household heterogeneity by imposing the same measure on all households. In contrast, price instruments tend to select the most privately cost-efficient investments across households (Hepburn, 2006). Additionally, a poorly designed ban could increase electricity demand through the adoption of heat pumps to levels beyond what is socially desirable, casting doubt on the electric system's capacity to handle the increased demand at a reasonable cost while reducing its own carbon footprint. Despite the massive impact and this controversial position, this measure has been little studied.

The objective of this paper is to comprehensively assess the impact of implementing the ban of gas boilers in the residential sector. Specifically, 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). Specifically, the framework links Res-IRF, a model of the residential sector (Vivier & Giraudet, 2024) and EOLES, a model of energy supply (Shirizadeh & Quirion, 2021), both tailored for the French context. These models are run jointly in a dynamic recursive manner in which endogenous space heating demand shapes investment decisions in the energy system which, in turn, drive residential energy prices. The framework relies on two key features to comprehensively assess the ban of fossil fuel boilers. First, the model simulates endogenous investments in home insulation and heating systems, considering households' heterogeneity and market barriers like credit constraints, behavioral anomalies, and hidden costs of energy-efficiency technologies. The model is therefore suitable for comparing the effects of a ban with a counterfactual scenario that mimics current policy in France (Vivier & Giraudet, 2024). 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 resulting investment needs in the electricity sector. In addition, the model allocates gas production to both residential gas boilers and the use of peaking power plants in the electricity sector. The 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, thus readily adaptable to different economic contexts.

Taking France as a case study, we examine how the implementation of the ban on gas boilers - which is synonymous with a ban on all fossil fuels in France, as the ban on oil boilers has already been enacted - contributes to achieving carbon neutrality in the long term. To this end, we simulate 3,072 scenarios 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. The level of policy ambition also faces political instability (Vivier & Giraudet, 2024), while estimating household reactions to price changes is challenging (Allcott & Greenstone, 2017). Additionally, the future efficiency and cost advancements of heat pumps span a wide range (Chaudry *et al.,* 2015). Lastly, the 2050 carbon budget for the energy and residential sectors hinges on evolving carbon sinks and abatement in other sectors. We assess the ban in terms of its robustness to achieve carbon neutrality target under uncertainty, its cost-effectiveness and its distributional effect amidst the large set of plausible future scenarios.

To our knowledge, no other study evaluates the impact of banning fossil fuel boilers in the academic literature. Our study builds on three strands of the literature: the engineering approach on how demand affects energy systems, ex-ante demand-side policy assessment, and policy design under uncertainty. Engineering research, like the studies by Zeyen *et al.* (2021), Roth (2023), and Maxim & Grubert (2023), investigates how a rapid roll-out on heat-pumps impacts the electricity system. For France, RTE (2023) demonstrated that the electricity grid can handle the increased demand from these 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. This critic can be extended to other modeling approach, like integrated assessment models or sectoral bottom-up analysis (Berrill *et al.,* 2022). These methodologies not only fall short of representing the detailed interactions between energy supply and demand, but also rely on oversimplified policy modeling, such as shadow carbon pricing or exogenous trajectories, which offer only limited insight into the design of climate policies (Pollitt *et al.,* 2024). In contrast, our study enriches the framework developed in Escribe *et al.* (2023), which focused on optimal policy design, by assessing real-world policies and their detailed impact on heterogeneous households' investment choices. Specifically, we complement recent simulation studies that assess real-world policies (Knobloch *et al.,* 2021; Giraudet *et al.,* 2021), by also considering how these policies interact with the energy system. Lastly, we draw upon Lempert (2019)'s introduction of the Robust Decision Making framework which moves away from seeking the 'optimal' policy to design policies that perform well across a variety of scenarios (Pye *et al.,* 2015; Bosetti *et al.,* 2015; Guivarch & Monjon, 2017).

Parameter	Description	Values
Supply		
Biogas potential	Available potential for methanization and pyrogazification	Low, **High**
Renewable capacity	Available potential for solar pv, onshore and offshore wind	Low, **High**
Gas prices	Growth rate for wholesale natural gas prices	Low, **Ref**, High
Residential Demand		
COP heat-pumps	Performance coefficient of heat pumps	Low, **Ref**
Technical progress heat-pumps	How much cost will 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 Response, **Ref**
Global parameters		
Other electricity demand	Level of electricity demand for all sectors excluding residential space heating	Sufficiency, **Ref**
Carbon budget	Trajectory of available carbon budget for residential and electricity sector	Low, **Ref**

Table 1: Uncertainty scenarios for model parameters (supply-side, demand-side and global). The total number of combinations leads to 1,536 distinct scenarios. Reference configuration is in bold letters.

2 Results

2.1 Ability of the ban to meet carbon neutrality under uncertainty

We conduct simulations across 3,072 scenarios, and find that 95 % of these scenarios achieve carbon neutrality with the ban in place, compared to only 13 % in the counterfactual 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. Our findings illustrate that the implementation of the ban mitigates these adverse effects, facilitating the achievement of climate target amidst prevailing uncertainties. Figure 1 identifies the key uncertainties that undermine the climate objective in the absence of the ban. It quantifies the role of individual uncertainties, as indicated by the first-order Sobol index, and of their interactions with other factors, as reflected by the total order Sobol index. Interestingly, the total order indices are significantly larger than first-order indices, highlighting the nonlinear interactions among uncertainties, and suggesting that 'One At a Time' analysis would inadequately capture the ability of the ban to address uncertainties.

First, poor design of subsidies for heat pumps leads to a failure to meet the climate targets when the ban is not implemented, due to 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). The ban, by design, is not affected by these scenarios with misaligned incentives. 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, the implementation of the ban drastically reduces the reliance on low-carbon biogas potential. 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.

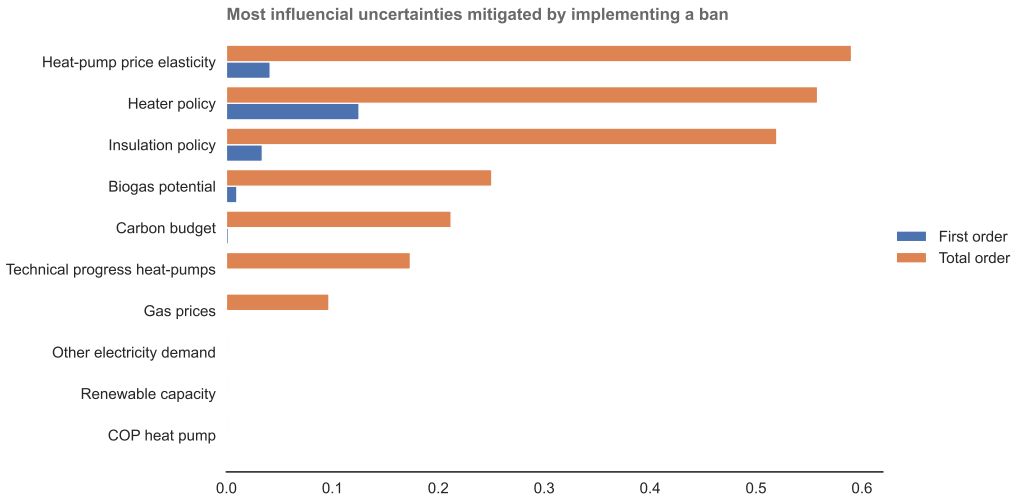
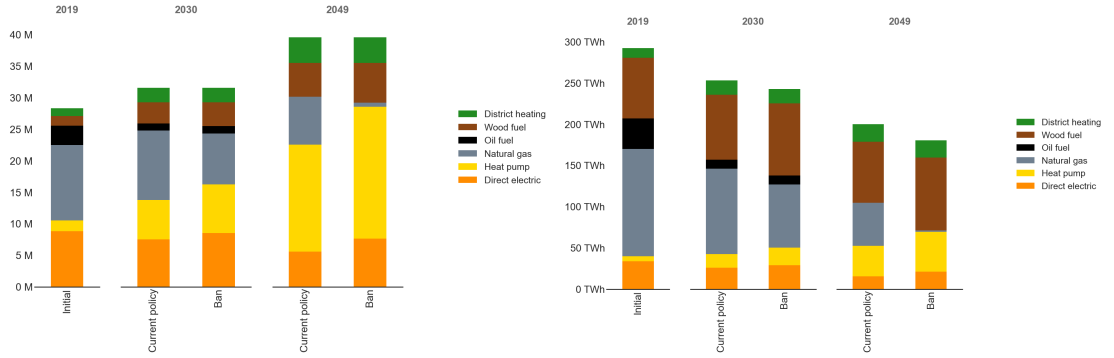


Figure 1: Main uncertainties that undermine the achievement of climate targets in the counterfactual scenario and that are mitigated by implementing the ban on gas boilers, using Sobol analysis. The unit corresponds to the share of variance explained by each of the parameter, in first order and in total order.

2.2 Impact of the ban on the energy system

Figure 2b 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 2a), 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 10b illustrates that the ban could raise peak electricity loads by up to 10 GW in 2050 compared to the counterfactual scenario.

Our results show that the impact on the energy system of implementing the ban boils down to shifting gas allocation strategy. Given that low-carbon gas, produced either through biogas or power-to-gas technologies, has a limited potential, its use changes significantly with the ban. Low-carbon gas is used either in gas boilers or, if the ban is implemented, in peaking power plants that feed electricity heating system. The overall efficiency of the latter option depends on the chosen heating systems. In particular, this option is more efficient with heat pumps but less efficient with direct electric heating (see Supplementary Figure 9). Since heat pumps are the preferred choice (Figure 2), the latter option is more efficient overall and lowers the need for electricity capacity compared to maintaining gas boilers. Specifically, Figure 3 illustrates that the ban saves the installation of 21 GW in renewable capacities (offshore wind and solar PV) combined with 3 GW in batteries, by opting instead for an additional 11 GW in peaking plants. While critics argue that a ban on gas boilers could

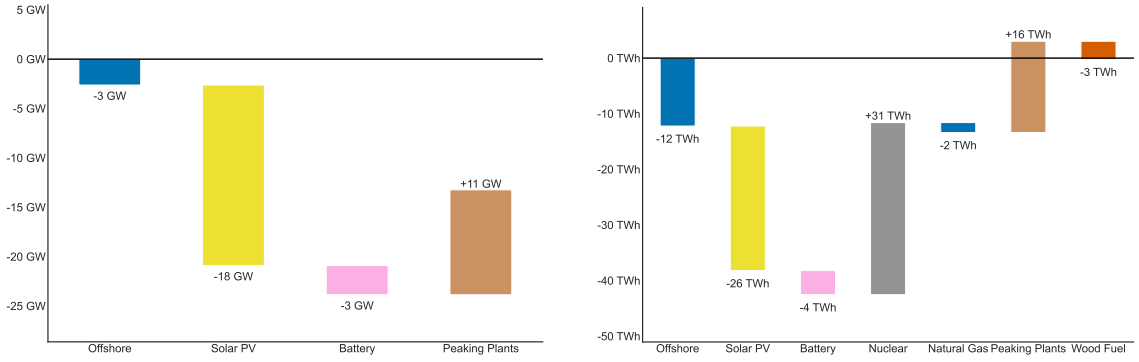


(a) Heating system stock (Million)

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

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. In 2050, such heating systems will rely on renewable gas and not fossil gas.

overburden the energy system, our results show that it is a more efficient strategy that saves on the development of flexible options in the electricity system.



(a) Additional installed capacity (GW)

(b) Additional energy generation (TWh)

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

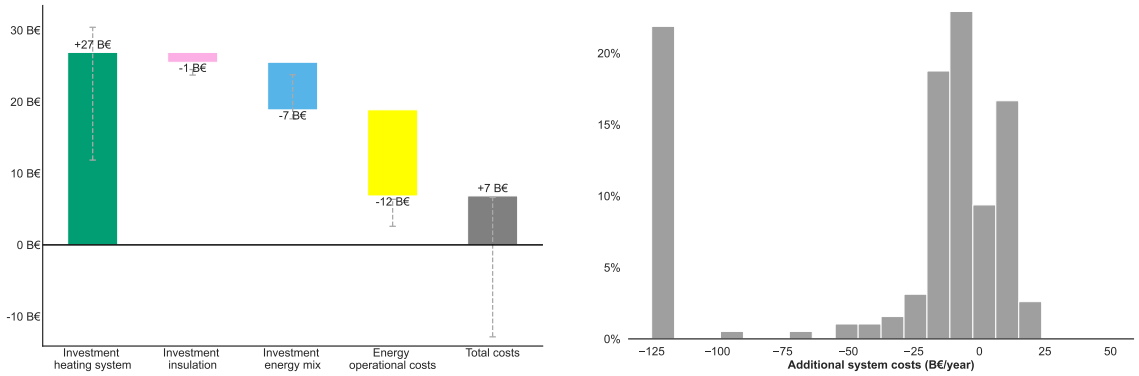
2.3 Cost-effectiveness analysis

Figure 4a shows that in the reference configuration, the scenario with the ban is slightly more expensive than the counterfactual 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, investments costs and operation costs of the energy system 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, as discussed in Section 2.2.

The comparison of total system costs across all uncertain scenarios where both the ban and the counterfactual scenario achieve the carbon constraint however draws a different picture. In 75 % of scenarios, implementing the ban is cost-effective. Noticeably, in 20 % of scenarios, the difference in system costs is significantly favourable to

the ban (Figure 4b). These scenarios often involve pessimistic assumptions necessitating ambitious and expensive investments in energy system flexibility to accommodate the current policy scenario in the residential sector.

Factors identified in Section 4.3 as contributing to the increased robustness of the ban in achieving carbon neutrality also enhance its cost-effectiveness (see Supplementary Figure 12). This underscores that the current policy scenario is only more cost-effective than the ban under a narrow set of specific conditions.



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

(b) Distribution of additional cost across uncertainties.

Figure 4: Distribution and breakdown of additional cost when implementing the ban of gas boilers compared to the counterfactual scenario. In Figure 4a, error bars represent the 25$^{\text{th}}$ and 75$^{\text{th}}$ 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.

2.4 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, inclusive of taxes (meant to cover subsidy costs). Our analysis reveals significant disparities in how the ban affects households, with additional annual costs varying from -€24 to €23 across groups (Figure 5). Theses 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 across households, mainly due to differences in heating system choices and eligibility for subsidies. In short, switching to heat pumps is the only profitable option, contingent on receiving subsidies for 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 cost of heating systems, do not benefit from the subsidies that correspond to their level of income. This affects disproportionately low-income tenants. 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 due to unobserved characteristics 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, the share of gas boilers in privately rented and single-family homes is lower in the counterfactual scenario 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.

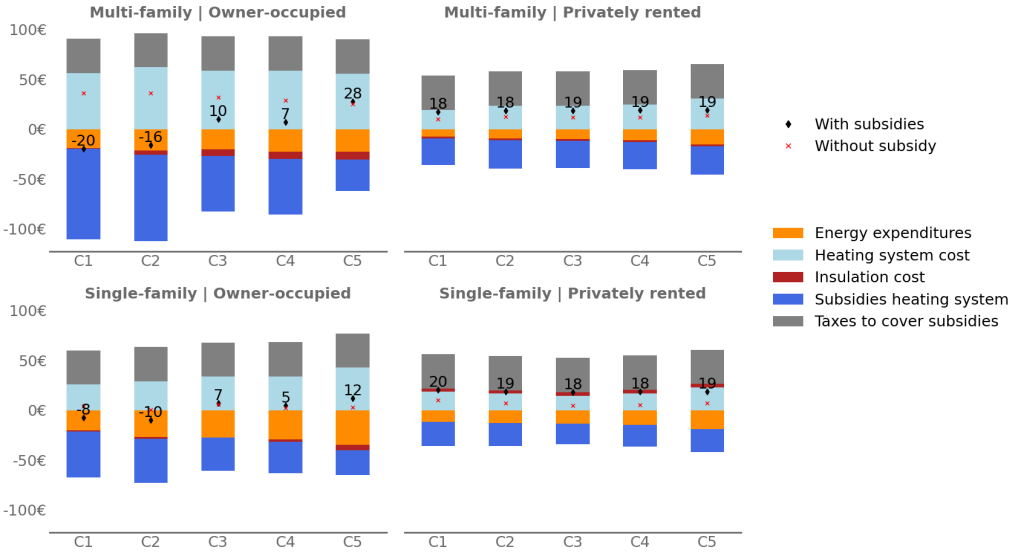


Figure 5: Average additional annual costs by household group if the ban is implemented (€per year). 'C1' means the first income quintile, i.e. very low income, and 'C5' means the last income quintile, i.e. very high income. A negative value means that the ban reduces household expenditure, while a positive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

3 Discussion

In this study, we present the first evaluation of the highly debated ban on new fossil fuel boilers by assessing its effectiveness in achieving carbon neutrality under uncertainty, its cost-efficiency, and its distributional effects. To that end, we rely on a detailed bottom-up framework of the residential and energy sector, that strives to simulate the impact of realistic demand-side policy on the energy system, addressing an important gap in the existing literature (Pollitt *et al.,* 2024). 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).

First, we demonstrate that achieving carbon neutrality in the residential sector is out-of-reach 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 impact of the ban on the energy system can be reduced into a trade-off between heat pumps and peak power plants or gas boilers. Overall, implementing the ban is a more efficient strategy, which saves the development of additional renewable energy capacities in combination with batteries. Third, despite costly investments in heating system, the ban leads to higher cost-effectiveness over a large range of plausible futures. Fourth, we show that the implementation of the ban, when coupled with the existing subsidy framework, results in diverse distributional outcomes. While vertical inequalities among owner-occupied households are mitigated, this effect does not extend to those in privately rented homes.

Overall, our results support the implementation of a ban on fossil fuel boilers conditional upon accompanying subsidy measures. In particular, the design of subsidies is crucial to guide households towards the more socially profitable option, namely heat pump, and to mitigate the regressive financial effects of the more expensive heating system. In addition, the authorities should consider alternative redistribution mechanisms beyond the lump-sum tax to tackle more effectively both horizontal and vertical inequalities.

4 Online Methods

4.1 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 a companion paper (Escribe *et al.,* 2023).[1]

Our assessment is anchored within the SNBC carbon budget, which targets net zero emissions for France by 2050. More specifically, the allocated carbon budget for

[1]In this companion paper, we endogenously determine the optimal level for energy-efficiency subsidies, while in this paper we assess the introduction of exogenous real-world policy, namely the ban on gas boiler.

the residential sector, together with the power sector, is projected to be 4 MtCO2 annually by 2050.

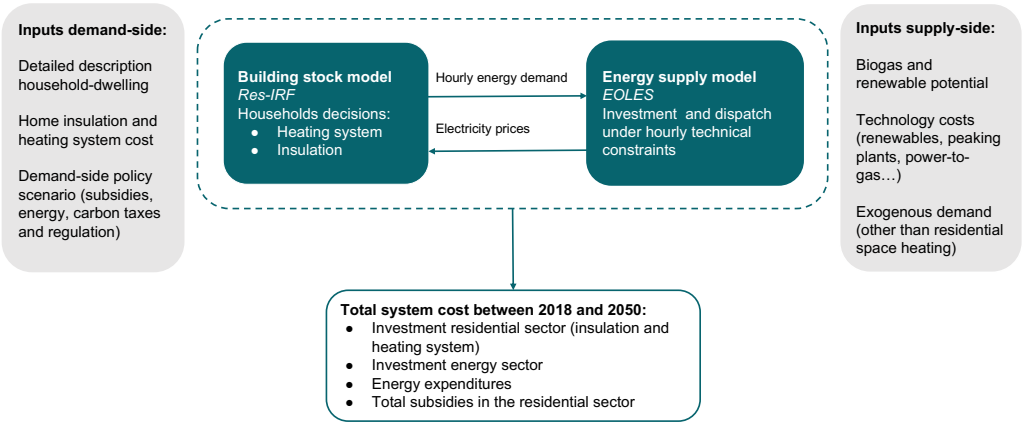


Figure 6: Schema of the modeling framework.

4.2 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.[2] 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. In that regard, our method could overestimate the impact of the ban on the increase in electricity demand.

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[3]. 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 gas boiler. These costs include the additional costs of the heating system net of subsidies, the energy costs and a lump-sum tax that represents the funding of additional subsidies. We differentiate the costs according to income,

[2]District heating projection are determined exogenously, as they rely not on individual homeowner investments but on broader infrastructural investment decisions.

[3]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.

occupation status (owner-occupied and private) and housing type (single-family and multi-family dwellings).

4.3 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.

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 X_i alone.[4]. 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.

4.4 Limitation

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

As with any prospective scenario analysis, there are uncertainties in the model input parameters that increase the further into the future the model extends. These uncertainties were addressed by simulating a large number of scenarios covering the influence of these individual uncertainties alone and in interaction.

Second, 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.

Finally, 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 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,

[4]This effect is averaged over the variations in all other uncertain parameters

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, 2017).

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: XX.

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.

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A Supplementary information

A.1 Supplementary table

	Unit	Counterfactual	Ban
Number of heat pumps	Million	16	20
Number of direct electric	Million	5	7
Number of gas boilers	Million	7	0
Number of wood boilers	Million	5	6
Subsidies insulation	€Billion	78	78
Subsidies heater	€Billion	66	90
Investment heating system	€Billion	324	351
Investment insulation	€Billion	170	169
Consumption Electricity	TWh	52	69
Consumption Gas	TWh	52	2
Consumption Wood	TWh	74	88
Offshore capacity	GW	45	42
Onshore capacity	GW	60	60
Solar PV	GW	92	74
Battery	GW	4	1
Peaking plants capacity	GW	52	63
Methanization capacity	GW	5	5
Pyrogazification capacity	GW	2	2
Hydroelectricity capacity	GW	18	18
Offshore production	TWh	210	198
Onshore production	TWh	171	171
Solar PV production	TWh	131	105
Battery production	TWh	4	0
Hydroelectricity production	TWh	51	51
Peaking plants production	TWh	17	34
Nuclear production	TWh	127	158
Methanization production	TWh	46	46
Pyrogazification production	TWh	19	19

Table 2: 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.

A.2 Supplementary figures

A.2.1 Supplementary figures that assess the vulnerabilities of policy scenario

We assess the vulnerabilities of each policy scenario to uncertain assumptions separately. This analysis reveals differences in how each scenario's ability to achieve carbon neutrality is affected by uncertainties. Notably, comparison of Figure 7 and Figure 8 illustrates that heat pump price elasticity, along with heater and insulation subsidy policies, exert a more pronounced direct impact (i.e., Sobol first-order effect) on the counterfactual scenario's ability to meet carbon constraints compared to the scenario that includes the ban. This indicates that the counterfactual scenario is more susceptible to individual uncertainties, whereas the vulnerabilities when the ban is implemented are more a result of the interaction among multiple uncertainties. Again, this suggests that the ban is more robust than the counterfactual scenario in the face of deep uncertainties.

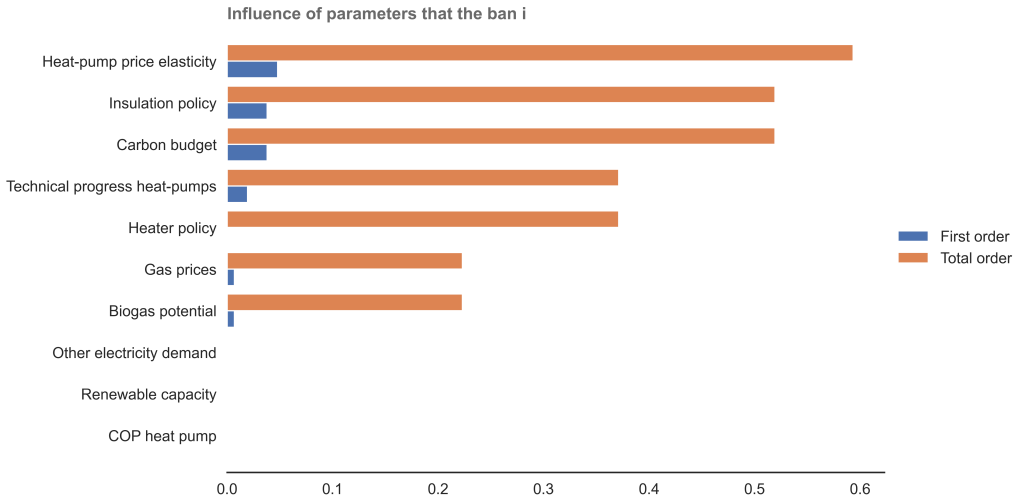


Figure 7: Ranking of most influential parameters driving the capacity of the Ban scenario to achieve carbon neutrality.

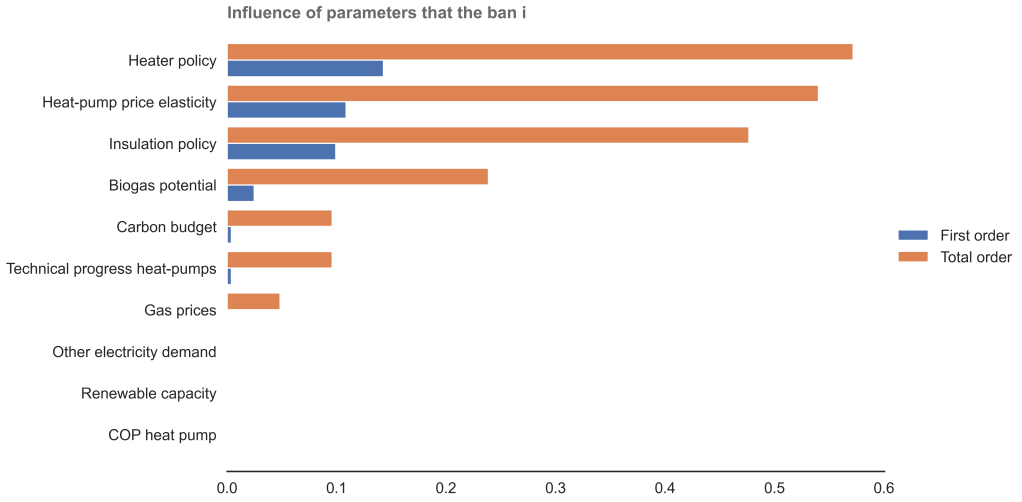
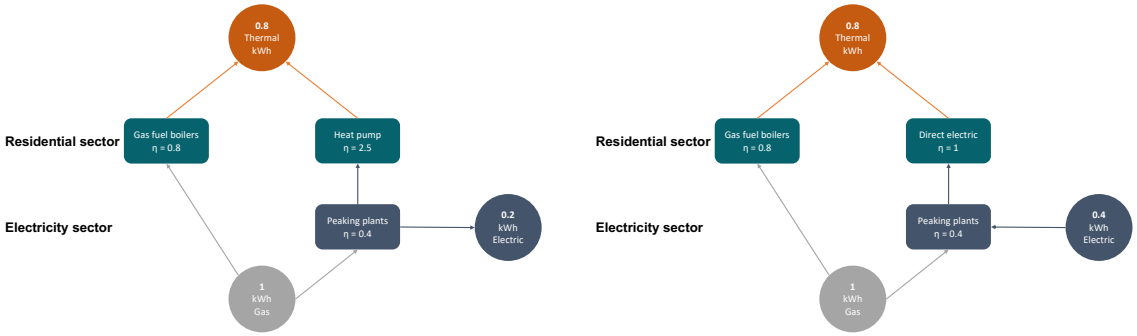


Figure 8: Ranking of most influential parameters driving the capacity of the counterfactual scenario to achieve carbon neutrality.

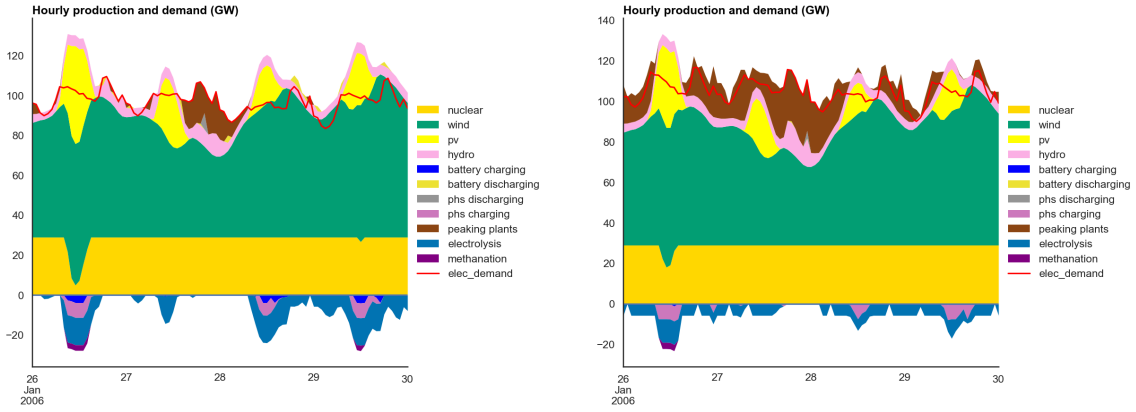
A.2.2 Supplementary figures to assess the consequences of implementing the ban on the energy system



(a) When heat pump is chosen

(b) When direct electric is chosen

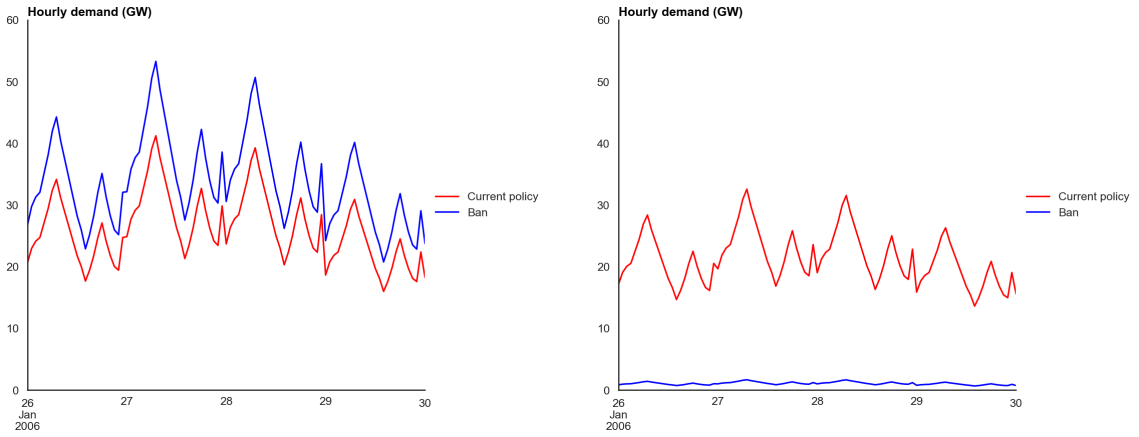
Figure 9: Simplified diagram showing the overall efficiency of replacing gas boilers with heat pumps and direct electricity.



(a) Current policy scenario.

(b) Ban scenario.

Figure 10: Hourly dispatch to meet electricity demand in 2050 over a typical week in January.



(a) Electricity demand.

(b) Gas demand.

Figure 11: Load profile for electricity and gas heating demands in 2050 over a typical week in January.

A.2.3 Supplementary figures to identify the determinant of the cost-effectiveness of the ban

In this situation where only the subset of scenarios that achieve carbon neutrality under both the ban and the current policy framework is considered, conducting a global Sobol sensitivity analysis becomes infeasible. This is because the prerequisite of independent inputs for such an analysis is no longer met.

The figure Supplementary Figure **??** identify the determinants responsible for the higher cost-effectiveness of the counterfactual scenario compared to the ban. Scenarios showing higher system costs for the ban predominantly 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 many conditions must be met for the ban to be less cost-effective compared to the current policy scenario. Conversely, no specific condition to the ban is needed to guarantee its greater cost-effectiveness over the current policy scenario. It is important to note that the success of the counterfactual scenario in achieving carbon neutrality – and thus the basis for a cost-effectiveness comparison – is contingent upon the adoption policies to promote ambitious low-carbon heating system.

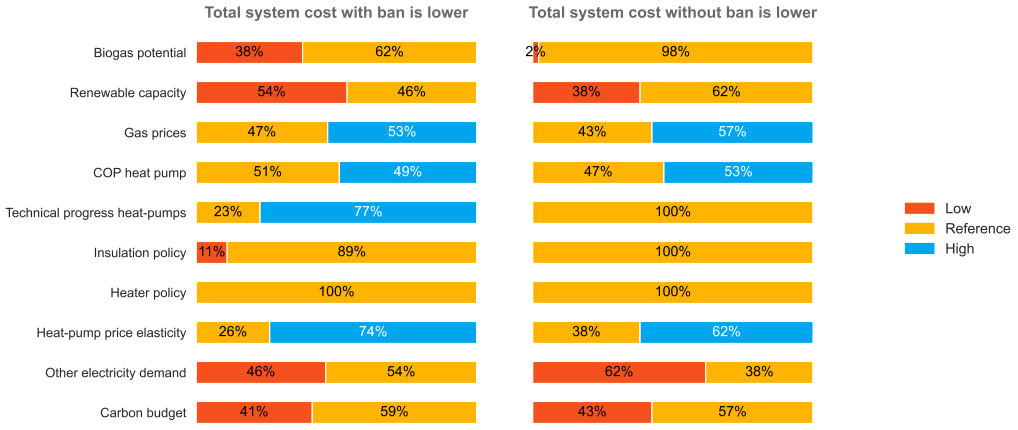


Figure 12: Frequency of scenarios with total system cost lower with the ban (left) and total system cost lower without the ban (right).

A.2.4 Supplementary figures to assess the distributional consequences of implementing the ban

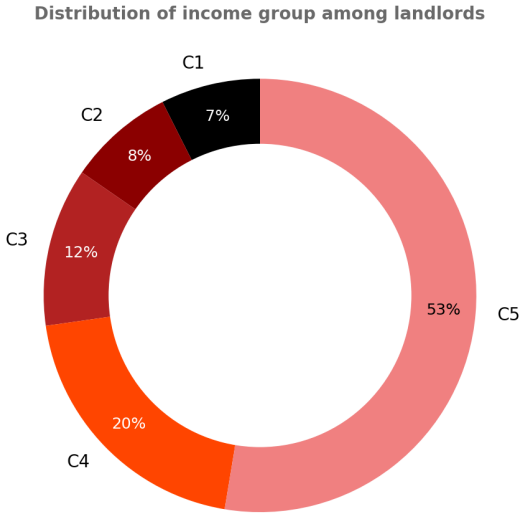


Figure 13: Distribution of income group among landlords in France in 2018.

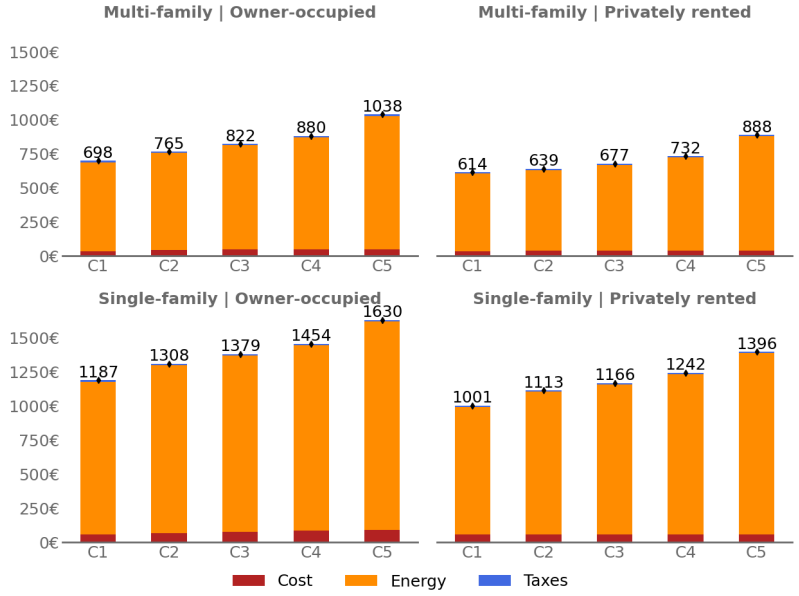


Figure 14: Cost of households in 2018 including energy cost, investment cost, and taxes due to subsidies.

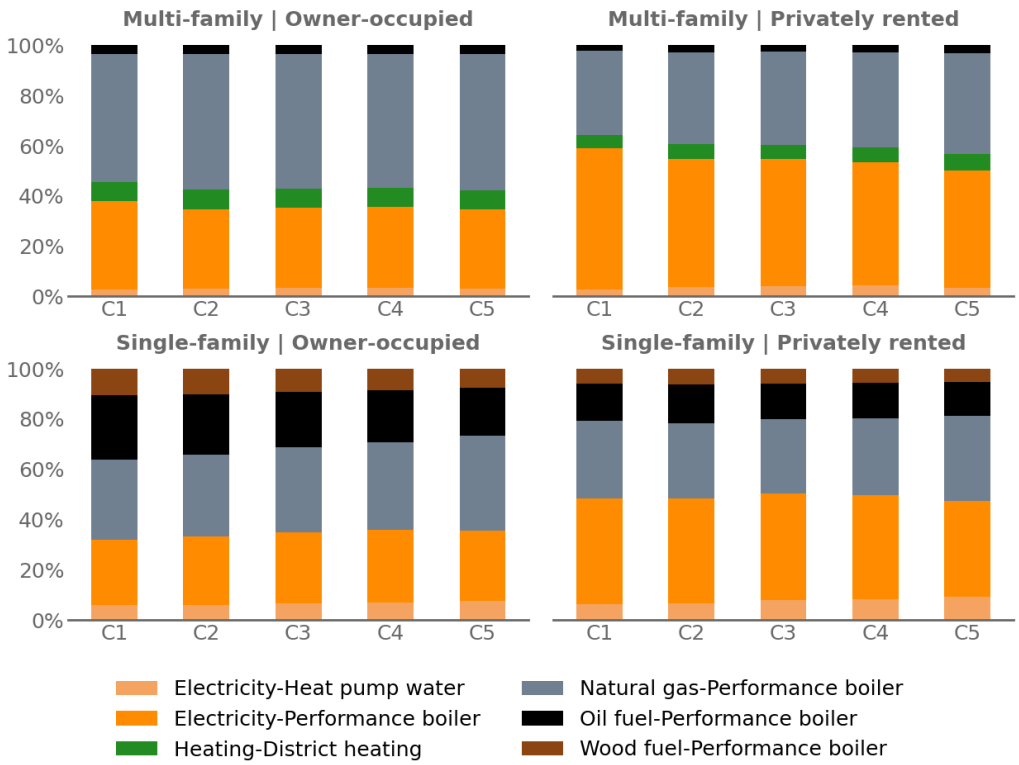


Figure 15: Stock of heating system by household group in 2018.

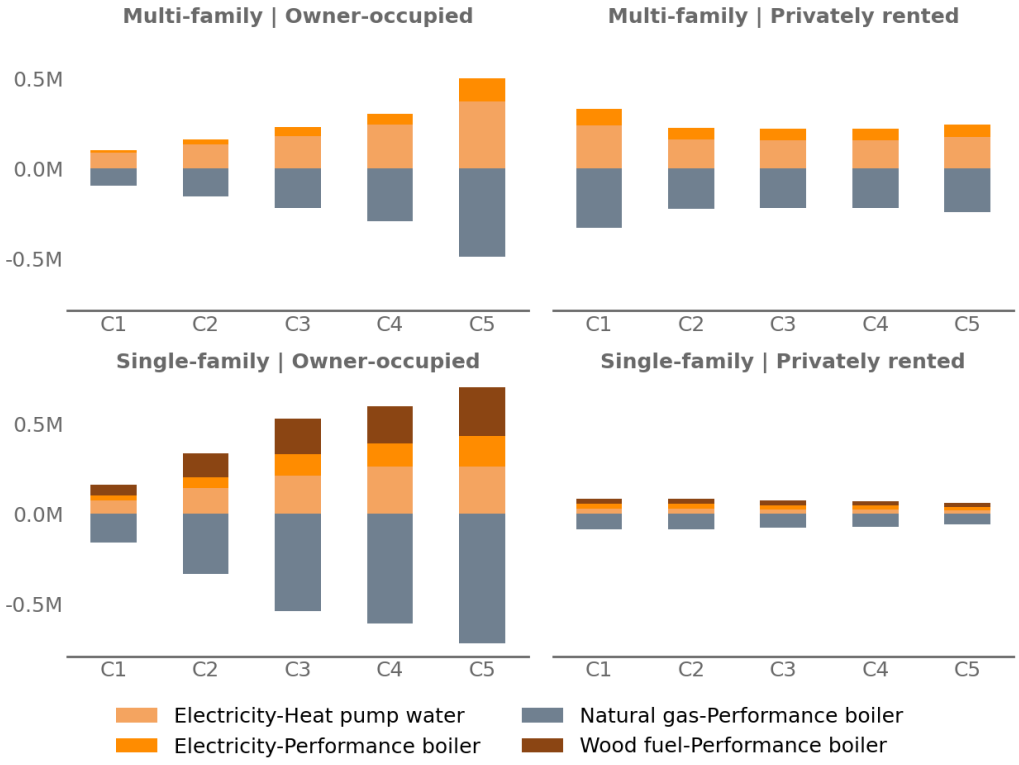


Figure 16: Additional boilers in 2050, if the ban is implemented, in millions of boilers.

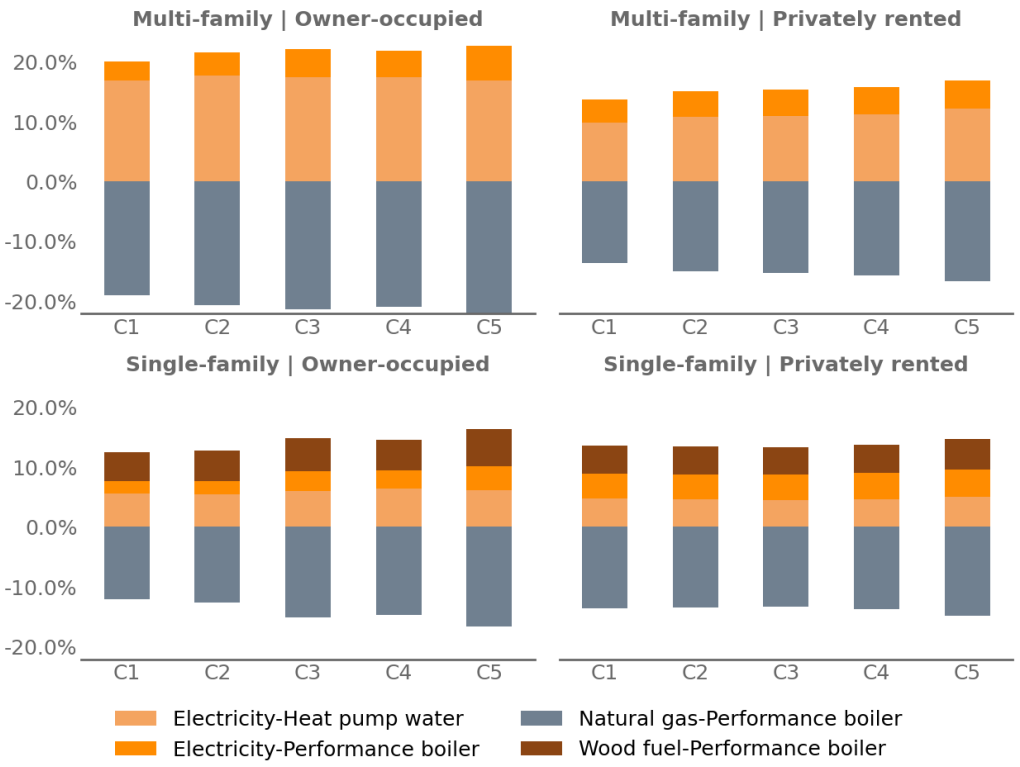


Figure 17: Additional boilers in 2050 if the ban is implemented, as a proportion of total installed boilers in 2050 by household group.

A.3 Supplementary methods

Sobol analysis In Section 2.1, 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 $p_t^{\mathrm{energy}} \cdot \mathrm{Conso}_{i,t}$, 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 $N^{\mathrm{switch}}_{i,t}$ is the number of households that buy a new heating system and $N^{\mathrm{insulation}}_{i,t}$ is the number of households that insulate their homes.

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

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

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

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

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

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

A.4 Data

Detailed data information can be found in the supplementary information of a companion paper (see (Escribe *et al.*, 2023)). Specifically for the case of this study, we recall here the cost assumptions for the heating system, which drive the cost-effectiveness of the ban on gas boielr.

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 3: Data derived from RTE & 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).

Supplementary References

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