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Banning new gas boilers as a no-regret mitigation option

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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 simulate the impacts of introducing this ban in France under 11,664 scenarios covering major uncertainties. We find that the ban induces major changes in the energy system, leading to efficiency gains. Additionally, we find that the ban increases the likelihood of reaching carbon neutrality while reducing total system cost in over 75% of scenarios. Finally, we show that the implementation of the ban, when coupled with the existing subsidy framework, mitigates inequalities among owner-occupied households but generates adverse effects for those in privately rented homes.

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 heating¹. In Europe, residential space heating represents 17% of total final energy consumption, with approximately 75% still relying on fossil fuels². A major obstacle to the transition to low-carbon heating systems is that the social cost of carbon is typically not included in residential energy prices, so homeowners' investments are not aligned with environmental goals. In addition, homeowner behavior may deviate from the perfectly rational consumer assumed in standard microeconomic models, leading to suboptimal levels of investment. In particular, homeowners tend to undervalue future energy benefits³ or express a bias for the existing technology⁴ when making heating system investment decisions. Without proper policy instruments, these behaviors could drive excessive gas demand in the residential sector, hindering the achievement of climate targets. Environmental externalities and heterogeneous behavioral anomalies in the residential sector imply that the first-best policy mix should be a two-part instrument including perfectly targeted subsidies and a carbon tax⁵. 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 unfeasible⁶, and realistic subsidy designs cannot be individually targeted. Consequently, and despite efforts to implement market-based instruments⁷, uptake rates of low-carbon heating systems across Europe remain low⁸, 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

36 ambitious, or distributional issues among households— between those receiving sub-
37 sidies and those bearing the costs—if subsidies are high. In addition, the long heating
38 systems lifetimes require a complex intertemporal approach to instrument design to
39 avoid lock-in effects. Given these difficulties, a ban on fossil fuel boilers emerges as a
40 pragmatic policy choice that makes it easier to achieve climate targets without having
41 to rely on excessive subsidies.

42 Although several European Union (EU) Member States have already introduced
43 ban measures to phase out fossil fuel boilers, these regulations affect only a minor
44 share of the EU’s heating energy consumption⁹. They mostly target new buildings,
45 specific fuels like oil, or include numerous exemptions. Therefore, the EU Commission
46 has proposed to extend the ban to all standalone fossil fuel boilers across the EU
47 from 2029, as per the EU Save Energy Plan¹⁰. Furthermore, the recent adoption of
48 the Energy Performance Building Directives mandates that Member States implement
49 measures to completely phase out fossil fuel heating and cooling by 2040¹¹. In this
50 context, EU Member States are currently considering implementing a complete ban
51 on installing new fossil fuel boilers.

52 Economists often argue that regulatory instruments are less cost-effective than
53 price-based policies. These policies fail to account for the heterogeneity of households
54 by imposing uniform requirements that may not be consistent with individual cost-
55 effectiveness¹². A major concern of the ban on gas boilers is the induced energy
56 system externalities. Specifically, a rapid increase in space heating electricity demand
57 concentrated during peak load could require further investments in the electricity
58 sector, increasing overall costs and hampering the ability to achieve carbon neutrality.
59 Little engineering research investigates how a large roll-out on heat pumps impacts the
60 electricity system¹³⁻¹⁶, but none considers the dynamics associated with a ban on gas
61 boilers. In addition, these studies do not explore the cost-effectiveness and fairness of
62 this ban. Despite the potentially massive impact and this controversial position, this
63 measure has been little studied.

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

68 To answer these questions, we extend a modelling framework that integrates de-
69 tailed bottom-up models for the energy and residential sectors¹⁷. The framework relies
70 on two key features to assess the ban of fossil fuel boilers. First, the model simulates
71 endogenous investments in home insulation and heating systems. Each homeowner up-
72 grades their heating system or insulates their home based on a discrete choice model
73 influenced by existing policies and market barriers such as credit constraints, behav-
74 ioral anomalies, and hidden costs of energy efficient technologies. This model is there-
75 fore suitable for comparing the effects of a ban, which is represented as restriction of
76 homeowners’ choice set, with a current policy scenario that mimics implemented poli-
77 cies in France¹⁸. The policy mix includes subsidies for home insulation and low-carbon
78 heating systems as well as a residential carbon tax of €45/tCO₂. Second, the model
79 includes the main interactions between the residential sector and the energy system.
80 The hourly resolution finely captures the impact of additional residential electricity de-
81 mand on peak power load and the resulting investment needs in the electricity sector.
82 In addition, the energy model allocates gas production to both residential gas boilers
83 and the use of peaking power plants in the electricity sector. Low-carbon gas is pro-
84 duced either by biogas with its limited supply or by power-to-gas technologies, which
85 in turn increase electricity demand. Consequently, our framework captures significant
86 cross-sectoral interactions between residential and energy sectors, as well as between
87 the two main energy vectors: gas and electricity. Finally, the model is open-source¹⁹.

88 Taking France as a case study, we examine how the implementation of a ban on
89 gas boilers - which is synonymous with a ban on all fossil fuels in France, as a ban
90 on oil boilers has already been enacted - contributes to achieving carbon neutrality

91 in the long term. To this end, we systematically compare two policy scenarios: the
92 current policy scenario and an alternative scenario that adds a ban on gas boilers
93 to the current policies. All simulations are done under a carbon budget constraint.
94 We simulate 11,664 scenarios (half with the ban and just as many only with the
95 current policy mix) capturing the main uncertainties driving investment dynamics in
96 the energy and residential sectors (see Table 1). These include uncertain renewable and
97 biomass potential capacities^{20,21}, volatile natural gas prices and uncertain electricity
98 demand in other sectors. We also consider the level of policy ambition to be uncertain,
99 as it has varied considerably between 2005 and 2024¹⁸. The response of households to
100 price changes, which is represented here by an average price elasticity parameter, is
101 difficult to estimate and is also considered uncertain. Additionally, the future efficiency
102 and cost of heat pumps span a wide range²². Lastly, the 2050 carbon budget for the
103 energy and residential sectors hinges on uncertain carbon sinks and abatement in
104 other sectors. We evaluate the ban in terms of its robustness to achieving the carbon
105 neutrality target under uncertainty, its cost-effectiveness, and its distributional effects
106 among the large set of plausible future scenarios²³.

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

118 Results

119 A ban addresses energy service demands more efficiently

120 Despite the increasing number of dwellings (see Fig. ??), home insulation policies
121 reduce overall energy demand (Fig. ??). The ban on gas boilers shifts residential
122 gas consumption primarily to electricity, due to the limited availability of wood and
123 district heating. In particular, gas boilers are mostly replaced by heat pumps as the
124 most cost-efficient available option. This shift results in a 75% increase in electricity
125 demand, which is particularly pronounced in the cold months, when space heating
126 demand peaks, and the technical efficiency of heat pumps is at its lowest due to low
127 outside temperatures. Supplementary Figure 3b illustrates that the ban could raise
128 peak electricity demand by up to 10 GW in 2050 compared to the current policy
129 scenario.

130 Banning gas boilers leads to significant transformations within the energy system
131 by (i) reducing primary energy need, and (ii) improving the capacity factors.

132 First, Figure ?? shows that the system relies on less primary energy to deliver the
133 same energy services. By 2050, the ban reduces the primary energy requirements by
134 12 TWh. These shifts are driven by different strategies for allocating gas resources,
135 which are constrained by climate targets and limited biogas potential. While low-
136 carbon gas is currently used in gas boilers, it could be redirected to peaking power
137 plants that support electric heating systems if the ban is enforced. Overall, as shown
138 in Supplementary Figure 2, we find that the combination of peaking power plants and
139 heat pumps meets energy service demands more efficiently

140 Second, meeting peak demand with peaking power plants eliminates the need for
141 the combination of renewable capacity and battery storage as a flexibility solution.

142 Specifically, Figure ?? demonstrates that the ban avoids the installation of 12 GW of
143 renewable capacity (offshore wind and solar PV) and 3 GW of battery storage, while
144 instead requiring an additional 12 GW of peaking plants (Table 1). This reduction
145 in renewable capacity leads to a more efficient use of nuclear power as a base-load
146 generator, thereby increasing its capacity factor.

147 **A ban is critical to meet carbon neutrality under uncertainty**

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

156 Figure 3 shows the key uncertainties that undermine the climate objective in the
157 absence of the ban. We show that the implementation of the ban significantly reduces
158 reliance on biogas potential. Given that meeting residential gas demand is constrained
159 by available biogas potential, the shift to heat pumps driven by the ban hedges against
160 biogas supply shortages. This effect is exacerbated by the more efficient use of gas
161 resources detailed in the precedent section. Furthermore, the regulatory nature of the
162 ban ensures that the adoption of heat pumps is less dependent on uncertain demand-
163 side factors, such as the ambition of subsidy policies or households' responsiveness.
164 Conversely, without the ban, failure to meet climate targets may be prompted by
165 an insufficient level of ambition in home insulation policies to reduce residual space
166 heating demand, lower-than-expected household response to incentives (i.e., low price
167 elasticity of heat pumps), or inadequate subsidies for low-carbon heating systems.
168 Interactions among demand-side and supply-side uncertainties play a large role in the
169 increased robustness of the ban, as evidenced by larger total order indices compared to
170 first order indices. Overall, the ban appears as a more robust strategy to meet carbon
171 neutrality against the uncertainty of various factors driving the decarbonization of the
172 residential and energy sectors.

173 **A nuanced impact on total system costs**

174 Comparison of total system costs is done across scenarios where both the ban and the
175 current policy scenario achieve carbon neutrality. Total system costs are defined as
176 the sum of annualized costs over the 2025-2050 period. All investment costs are annu-
177 alized using a 3.2% discount rate, as recommended for public investment in France²⁴.
178 Supplementary Table 3 demonstrates that the choice of this parameter does not affect
179 our findings.

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

189 The comparison of total system costs across all uncertain scenarios however draws
190 a different picture. In 49% of scenarios where both policy scenarios satisfy the carbon
191 constraint, implementing the ban reduces total system costs. In particular, pessimistic
192 assumptions on uncertain parameters require ambitious and expensive investments

193 in energy system flexibility to accommodate the additional residual gas demand in
194 the current policy scenario (Figure ??). The same factors that contribute to the
195 increased robustness of the ban in achieving carbon neutrality, also make the scenario
196 less costly (see Supplementary Figure 5). This underlines that the current policy
197 scenario only reduces total system costs compared to the ban scenario under specific
198 conditions. Overall, in more than 75% of all scenarios - including those failing to
199 meet carbon constraints and considered infinitely more costly -, implementing the
200 ban results in lower total system costs. Our results highlight that relying solely on a
201 reference configuration can be misleading, as it overlooks the nuanced cost-effectiveness
202 of the ban amid existing uncertainties.

203 **Distributional impacts of the ban**

204 We investigate the distributional consequences of implementing a ban in the reference
205 configuration by comparing the cost incurred by different income groups and housing
206 categories (occupancy status and housing type) under the ban versus the current policy
207 scenario. By doing so, we assess the marginal impact of the ban on households. Costs
208 include heating system purchase costs and energy expenditure, supplemented by taxes
209 meant to cover additional subsidy costs. We assume these taxes are evenly distributed
210 among French households in a lump-sum manner, which is a standard approach in
211 economic models^{5,25,26}. Although these additional costs account for a small percentage
212 of overall household energy costs, our analysis reveals significant disparities in the
213 impact of the ban on households, with additional annual costs varying from -€18 to
214 €40 across groups (see Figure 5). These disparities are shaped by the financial impact
215 of replacing the gas boiler on the intensive margin and the proportion of households
216 affected by the ban on the extensive margin.

217 First, the financial impact of the ban depends on the profitability of adopting an
218 alternative heating system, which varies widely among households. This variation pri-
219 marily stems from differences in heating system choices and eligibility for subsidies.
220 In short, adopting heat pumps is the only profitable choice, provided that subsidies
221 are available to offset the purchase costs. Without substantial subsidies, or if house-
222 holds opt for wood fuel boilers or direct electric heating, the switch is not financially
223 profitable for households. For owner-occupied households, the progressive nature of
224 the French subsidy system, which adjusts the subsidy level to income, creates posi-
225 tive redistributive effects for low-income households (the first two income quintiles),
226 while high-income households (the last two income quintiles) face adverse outcomes.
227 Importantly, market and behavioral failures such as credit constraints and a strong
228 present bias are prevalent among low-income households, leading them to choose less
229 profitable investments such as direct electric systems. The subsidy design is therefore
230 also instrumental in encouraging low-income households to invest in heat pumps, their
231 most profitable option. In contrast, for privately rented homes, investment decisions
232 are made by landlords, who typically have higher incomes (see Supplementary Figure
233 7) and are eligible for smaller subsidies. As a result, tenants, who bear the invest-
234 ment cost of heating systems through increased rent, do not benefit from the subsidies
235 that correspond to their level of income. This affects disproportionately low-income
236 tenants (the first two income quintiles), as shown in Supplementary Figure 6 through
237 the relative impact on households' budget. Consequently, while the implementation of
238 the ban in France leads to progressive financial outcomes for owner-occupiers, it ad-
239 versely impacts tenants. We also observe significant differences between housing types.
240 Households in single-family homes, typically with more space, benefit more from the
241 energy savings of switching to heat pumps, enhancing the profitability of their in-
242 vestment compared to those in multi-family homes. Conversely, some households in
243 single-family homes may opt for wood boilers despite lower profitability. Overall, these
244 mixed effects lead to a smaller range of distribution effects in single-family homes com-
245 pared to multi-family homes.

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

258 Discussion

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

275 From a modelling perspective, we address a gap in the existing literature, which
276 typically relies on simplified policy, such as shadow carbon pricing, and thus offers
277 limited insights into climate policy design²⁷. Specifically, we complement recent sim-
278 ulation studies that assess real-world policies in the residential sector²⁸⁻³⁰, by also
279 considering how these policies interact with the energy system. Our open-source mod-
280 elling framework paves the way for investigating the impact of banning fossil fuel boilers
281 in other economies like Germany or Netherlands, which have the largest share of fossil
282 fuel boilers among EU countries⁹.

283 Choosing appropriate policy instruments for the transition to low-carbon heating
284 systems is inherently difficult because of competing evaluation criteria²³. We show
285 that the ban on gas boilers is justified when moving beyond mere cost-effectiveness
286 to consider the robustness of policies under uncertainty. Focusing only on a reference
287 configuration can be misleading as it overlooks the nuanced cost impact of the ban
288 amid existing uncertainties. This measure also involves trade-offs with distributional
289 impacts, which can be mitigated through further research on the design of subsidies.
290 Finally, our approach focuses on physical costs rather than the welfare criteria often
291 used in economics. Assessing the welfare impact of a ban in contexts with behavioral
292 biases would however require more sophisticated models than those commonly used³¹,
293 at the expense of technical details.

294 Methods

295 Integrated energy demand-supply framework

296 Our framework integrates two detailed bottom-up models¹⁷: (i) Res-IRF, which sim-
297 ulates energy demand for space heating, and (ii) EOLES, a comprehensive energy
298 system model (Fig. 6). Within a given time step, the exogenous policy scenario
299 determines final energy demand for residential space heating in the Res-IRF model.
300 The EOLES model is subsequently run to optimize capacity investment and dispatch
301 in the energy sector while meeting total energy demand and carbon budget. This
302 process is then iterated in 5-year time steps, from 2020 to 2050. For a given period,
303 wholesale electricity prices are endogenously computed as the levelized cost to meet
304 demand from the previous period. The resulting prices are topped with exogenous
305 energy taxes. The prices of other fuels (gas, oil, wood) are exogenous. Overall, the
306 framework represents a high level of technological granularity both for the energy sys-
307 tem (offshore, onshore, solar PV, nuclear, peaking plants, etc...) and residential sector
308 (gas, oil and wood boilers, direct electric and heat pumps).

309 **Residential model: Res-IRF** Res-IRF is a dynamic microsimulation model of
310 the energy demand for space heating in the French building stock¹⁸. The model was
311 developed with the aim of improving behavioral realism. The model provides a com-
312 prehensive description of insulation levels (for walls, roofs, floors and windows) and
313 heating systems (heat pumps, electric heating, gas, oil and wood boilers). It simu-
314 lates the evolution of energy consumption through three endogenous processes – the
315 construction and demolition of buildings, the renovation of existing dwellings through
316 insulation and fuel switching, and adjustments in heating behavior. Investments in
317 energy efficiency are made by households and are influenced by the main economic
318 costs and benefits, namely investment and financing costs, savings on energy bills and
319 subsidy amounts. In making these investments, households face various investmnet
320 frictions, such as credit constraint, the inability of landlords to pass on energy effi-
321 ciency investments to rents, decision frictions in collective housing, and hidden costs
322 (e.g. the inconvenience of insulation work). The model also takes into account a gap
323 between predicted and realized energy consumption to capture the much-discussed
324 energy performance gap³². This wedge varies endogenously depending on energy effi-
325 ciency improvements, energy prices and household income and captures the rebound
326 effect in particular. The study presented here uses version 4.0 of the model. The data
327 sources are listed in the Supplementary Information.

328 The model uses an hourly profile of heat pump efficiency to account for reduced
329 performance during cold weather, which is crucial for determining peak demand.
330 This efficiency is calculated based on the temperature difference between indoors and
331 outdoors³³ and by assuming an indoor temperature of 55°C. By doing so, we capture
332 the relationship between heat pump efficiency, space heating demand, and renewable
333 energy generation.

334 **Energy system model: EOLES** The EOLES model is designed to optimize
335 investment and operational decisions in France’s energy system to satisfy a specified
336 energy demand³⁴. Its total costs cover annualized capital expenditures, maintenance
337 expenses, and operational costs. The model is built on a comprehensive representa-
338 tion of various energy technologies. Electricity generation options include solar PV,
339 onshore and offshore wind, hydropower, open-cycle (OCGT) and combined-cycle gas
340 turbines (CCGT), and nuclear power. Hydrogen production is achieved through water
341 electrolysis. Gas sources range from fossil gas to biogas (produced via methanization
342 or pyrogazeification) and synthetic methane through methanation. Energy storage is
343 available in batteries, pumped-hydro storage, hydrogen storage in salt caverns, and
344 methane storage in gas reservoirs. Technology dispatch operates on an hourly basis,

345 accounting for weather-related fluctuations in supply and demand as well as flexibil-
346 ity requirements. Given the residential sector’s significant reliance on gas, the gas-
347 electricity interaction becomes essential. While the Res-IRF model focuses solely on
348 residential energy demand, EOLES encompasses electricity demand across all end-use
349 sectors. As such, non-residential energy demand projections (covering sectors such
350 as commercial buildings, industry, transport, and agriculture) are integrated as ex-
351 ogenous inputs, drawn from the latest French TSO projections³⁵. This exogenous
352 demand includes cooling requirements, making it unaffected by endogenous rebound
353 effects. The analysis is confined to France, without accounting for cross-border energy
354 exchanges. Further model specifics are detailed in Supplementary Information.

355 Policy assessment

356 Our assessment is anchored within the carbon budget detailed in SNBC (Low Carbon
357 National Strategy), France’s national plan aiming for net zero emissions by 2050.
358 Specifically, the allocated carbon budget for the residential sector, together with the
359 power sector, is projected to be 26.5 MtCO₂ annually by 2030, 20.5 MtCO₂ by 2035,
360 14.5 MtCO₂ by 2040, 9 MtCO₂ by 2045, and 4 MtCO₂ by 2050.

361 Our analytical framework is based on the comparison of scenarios that include the
362 ban on gas boilers with counterfactual scenarios without the ban. Building on Vivier
363 and Giraudet³⁶, we outline counterfactual scenarios that closely mimic the current
364 policy mix for low-carbon heating in France. The current policy mix includes various
365 energy efficiency measures, in particular a direct subsidy for heat pumps and wood
366 fuel boilers of €4,000 for low-income households (the first two income quintiles) and
367 €2,500 for high-income households (the last two income quintiles). It also includes
368 mandatory insulation for private landlords, a carbon tax and an oil boiler ban. The
369 ban of gas boilers is introduced in 2025 and applied indiscriminately to single and
370 multi-family dwellings. Concretely, when their heating system reaches the end of its
371 lifetime, homeowners pick one replacement option among non-fossil fuel options, such
372 as wood-fuel boilers, direct-electric, and heat pumps. District heating projection are
373 determined exogenously, as they rely not on individual homeowner investments but
374 on broader infrastructural investment decisions. We assume that homeowners only
375 consider replacing their heating system when it is no longer working and therefore
376 do not consider premature replacement. We also assume that the lifetime of heating
377 systems remains constant over time, which means that we do not take into account
378 repairs to extend the lifetime of a system. This effect could reasonably be triggered
379 by the implementation of the ban delaying the replacement of gas boilers.

380 Our analysis focuses on three key outcomes: the ability of a scenario to satisfy the
381 carbon constraint, and, provided this constraint is met, the total system costs and a
382 measure of distributional effects. Overall total system costs is defined as the sum of
383 annualized costs over the 2025-2050 period. Building on Hirth et al.³⁷’s work with the
384 EMMA model, we use a 0% rate of pure time preference to give equal weight to all
385 years when adding up annualized costs over the whole time horizon. The annualized
386 system costs comprise both the investment and operational costs of the energy supply
387 system, along with the costs associated with heating and insulation investments. The
388 distributional indicator is defined as the average additional cost (or benefit) paid by
389 the household group due to the introduction of a ban on gas boilers. These costs
390 include the additional costs of the heating system net of subsidies, the energy costs
391 and a lump-sum tax meant to cover additional subsidy costs. We differentiate the costs
392 according to income, occupation status (owner-occupied and private) and housing type
393 (single-family and multi-family dwellings).

394 Uncertainty assessment

395 The model processes rely on a large set of parameters, many of which are deeply
396 uncertain. Such key uncertainties impact the supply energy system, the residential
397 sector and the other sectors (here only represented by the total electricity demand).
398 Regarding the energy supply system this corresponds to the potential for renewable
399 technologies and renewable gas, as well as fuel prices. In the residential sector, it
400 encompasses technological parameters such as the evolution of the efficiency and the
401 price of heat pumps and behavioral parameters such as the average heat pump price
402 elasticity. Table 1 summarizes the uncertain parameters and values used in this study.
403 We perform extensive simulations over all possible combinations of uncertain param-
404 eters to estimate the distribution of outcomes.

405 **Global sensitivity analysis** We perform a global sensitivity analysis to identify
406 the most influential vulnerabilities in the current policy scenario that are mitigated
407 with the ban in place. We rely on variance decomposition methodology and we esti-
408 mate Sobol indices based on our set of scenarios obtained by testing all combinations
409 of uncertainty³⁸. The variance decomposition is done to identify the uncertain deter-
410 minants that increase the vulnerability of the current policy scenario.

411 For each scenario, we set the value 1 if the Ban scenario achieves carbon neutrality
412 while the current policy scenario does not, -1 if the contrary holds, and 0 if both
413 scenarios either meet or do not meet the carbon constraint. In our case, we actually
414 never observe the -1 case. This outcome therefore directly measures the scenarios
415 responsible for increased vulnerability of the current policy policy scenario compared
416 to the ban policy scenario. Since Sobol analysis is a variance decomposition method,
417 the most influential drivers are therefore the parameters responsible for this increased
418 vulnerability.

419 The first-order Sobol index is equal to:

$$S_i = \frac{\text{Var}(\mathbb{E}[Y | X_i])}{\text{Var}(Y)} \quad (1)$$

420 It measures the effect of varying X_i alone, but averaged over variations in other in-
421 put parameters. A high S_i value indicates that X_i significantly influences the outcome
422 by itself.

423 The total effect Sobol index is equal to:

$$S_{T_i} = 1 - \frac{\text{Var}(\mathbb{E}[Y | \mathbf{X}_{-i}])}{\text{Var}(Y)} \quad (2)$$

424 It measures the contribution to the output variance of X_i , including all variance
425 caused by its interactions, of any order, with any other input variables. A low S_{T_i}
426 suggests that X_i has minimal overall impact. Therefore, if S_i is low but S_{T_i} is high,
427 it suggests that X_i primarily affects the outcome through its interactions with other
428 variables.

429 Other global sensitivity analysis include regression-based analysis²¹. These ap-
430 proaches typically assume linearity, attributing the residual sum-of-squares to vari-
431 ance unexplained by the model, due to nonlinear interactions. Given the significant
432 nonlinear dynamics observed among uncertain drivers in our analysis, we opted for a
433 variance decomposition methodology.

434 Limitation

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

436 First, our framework does not fully account for some costs associated with banning
437 fossil fuel boilers. These include potential investments needed to expand the distri-
438 bution network to enable increased heat pumps uptake, or the financial impact of

439 stranded gas networks due to falling household demand for gas. We argue that these
440 additional costs can be partially captured with high heat pump cost scenarios. More-
441 over, previous research has shown that residential electrification is expected to require
442 far fewer distribution capacity additions than electric vehicle adoption Elmallah et
443 al.³⁹. We thus believe that this would not significantly alter our results.

444 Second, the building models overlook certain behavioral options. Following a ban
445 on gas boilers, agents might choose to forego heating systems altogether or delay
446 replacing their existing systems. Similar behavior has been observed in the automotive
447 sector, where delayed vehicle replacement led to a rebound effect of 11% in energy
448 savings⁴⁰.

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

456 Fourth, regulatory instruments, and ban in particular, can generate significant hid-
457 den costs, as they may conflict with consumers’ preferences that are unobserved by the
458 regulator. These hidden costs can be additional monetary costs, such as the laying of
459 pipes or circuits, or non-monetary costs, such as the inconvenience of finding out about
460 a new heating system, the cost of obtaining information or the inconvenience during
461 the works⁴¹. We do not include these hidden costs in our cost analysis primarily be-
462 cause they are difficult to identify without further empirical research. Moreover, these
463 costs could fluctuate over time with changes in consumer preferences and may also be
464 directly affected by the implementation of the ban. However, they would amount to
465 additional costs for heat pumps and can again be partially captured by the high cost
466 scenario for heat pumps. Such potential additional costs, though they could reduce
467 the cost-effectiveness of banning gas boilers, would however not alter the conclusion
468 that the ban is critical to meet climate targets. Overall, further research could move
469 away from the ‘accounting approach’ used here to assess cost-effectiveness towards a
470 ‘welfare approach’ that takes into account the unobserved utility (i.e including hidden
471 cost) of households in adopting a particular technology²⁶.

472 Data Availability

473 The results data generated in this study have been deposited in the Zenodo reposi-
474 tory under accession code <https://doi.org/10.5281/zenodo.14039683>. Source data are
475 provided with this paper.

476 Code availability

477 The code of the integrated modeling framework has been deposited in the Zenodo
478 repository under accession code <https://doi.org/10.5281/zenodo.14039620>.

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587 Author Contributions Statement

588 C.E. and L.V. conceptualized, designed the study, curated data, supported model de-
589 velopment, ran the model, created visualizations and wrote the original draft and
590 reviewed and edited the manuscript.

591 Competing Interests Statement

592 The authors declare no competing interests.

Tables

Table 1: **Uncertainty scenarios for model parameters.**

Parameter	Description	Values
Energy system		
Biogas potential	Available potential for methanization and pyrogazification	Low, Reference*, High
Renewable potential	Available potential for solar pv, onshore and offshore wind	Low, Reference*, High
Gas prices	Growth rate for wholesale natural gas prices	Low, Reference*, High
Residential Demand		
Technical progress heat pumps	How much will cost decrease in 2035 compared to 2018 ?	Low, Reference*, 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, Reference*, High
Global parameters		
Other electricity demand	Level of electricity demand for all sectors excluding residential space heating	Low, Reference*, High
Carbon budget	Trajectory of available carbon budget for residential and electricity sector	Low, Reference*

* Corresponds to the value used in the reference configuration.

Figures Legends/Captions

Figure 1: **Evolution of heating system stock under policy scenarios.** a. Space heating consumption in the residential sector (TWh per year). b. Heating system stock (Million). 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. Source data are provided as a Source Data file.

Figure 2: **Changes in installed capacity and primary energy under a ban compared to the current policy scenario.** a. Additional installed capacity (GW) in 2050 when the ban on gas boilers is implemented. b. Additional primary energy (TWh) in 2050 when the ban on gas boilers is implemented. PV refers to photovoltaic. Source data are provided as a Source Data file.

Figure 3: **Ranking of uncertainties undermining the achievement of climate targets in the current policy scenario compared to the ban.** First order Sobol indices illustrate the share of variance explained by each uncertainty independently, while total order Sobol indices represent the share of the variance explained by each uncertainty in interaction with other uncertainties. The latter can cumulatively exceed 1 (interaction terms are counted multiple times). Source data are provided as a Source Data file.

Figure 4: **Breakdown and distribution of additional cost when implementing the ban of gas boilers compared to the current policy scenario.** a. Breakdown of additional cost in the Ban scenario, under the reference configuration. Error bars represent the 5th and 95th percentiles of the data set, including the 2566 scenarios that feature plausible energy systems. b. Distribution of additional cost across uncertainties. There are approximately 20% of the scenarios that incur significantly higher costs in the absence of the ban, including for example an exceptionally large amount of batteries. We winsorize at -125B€ for readability. Source data are provided as a Source Data file.

Figure 5: **Average yearly additional annual costs by household group under the reference configuration if the ban is implemented.** ‘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 (red cross), in order to measure the strict effect of the ban before redistribution. Source data are provided as a Source Data file.

Figure 6: **Integrated modeling framework.** The 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.

1 **Banning gas boilers as a no-regret mitigation**
2 **option**

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10 **Supplementary information**

11 **Supplementary Tables**

Supplementary Table 1: **Summary of results across policy scenarios in 2050.** Values in billion euros are the sum of actual invested values between 2025 and 2050.

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

Notes. PV refers to photovoltaic.

Supplementary Table 2: **Summary of main results in the residential sector in the configuration setting by 2050.**

	Current policy	Ban
Stock (M)	40	40
Surface (M m2)	3,490	3,491
Consumption (TWh)	183	160
Consumption (kWh/m2)	52	46
Consumption PE (TWh)	238	241
Consumption Electricity (TWh)	43	62
Consumption Natural gas (TWh)	59	2
Consumption Wood fuel (TWh)	60	77
Consumption Heating (TWh)	20	20
Energy poverty (M)	1.3	1.1
Emission (MtCO2)	13	3
Stock G (M)	0.3	0.4
Stock F (M)	0.6	0.6
Stock E (M)	1.1	1.1
Stock D (M)	7.6	6.4
Stock C (M)	11.4	9.9
Stock B (M)	5.7	7.2
Stock A (M)	12.9	13.9
Stock Electricity-Heat pump water (M)	16.6	20.9
Stock Electricity-Direct electric (M)	5.2	7.8
Stock Natural gas-Performance boiler (M)	8.8	0.6
Stock Wood fuel-Performance boiler (M)	4.9	6.1
Stock Heating-District heating (M)	4.1	4.1
Health cost (B €)	1	2
Energy expenditures (B €)	24	21
Cumulated Renovation (Thousand households)	17,736	17,297
Cumulated Investment insulation (B €)	212	209
Cumulated Subsidies insulation (B €)	61	61
Cumulated Investment heater (B €)	310	341
Cumulated Subsidies heater (B €)	49	74
Annual average Renovation (Thousand households)	572	558
Annual average Investment insulation (B €)	6.8	6.7
Annual average Subsidies insulation (B €)	2.0	2.0
Annual average Investment heater (B €)	10.0	11.0
Annual average Subsidies heater (B €)	1.6	2.4
Consumption saving (%)	33%	41%
Emission saving (%)	70%	93%
Energy poverty reduction (%)	64%	71%

Notes. A, B, C, D, E, F and G correspond to energy performance certificate classification in France. A stands for the best-performing dwellings while G stands for the worst-performing dwellings.

Supplementary Table 3: **Impact on discount rates on total system cost.** Sensitivity analysis across different discount rates of additional total system costs (in B€) when implementing the ban on gas boilers compared to the current policy scenario, in the reference configuration.

Discount rate	Additional total system costs
1.0%	5
2.0%	7
3.2%	8
4.0%	8
5.0%	8

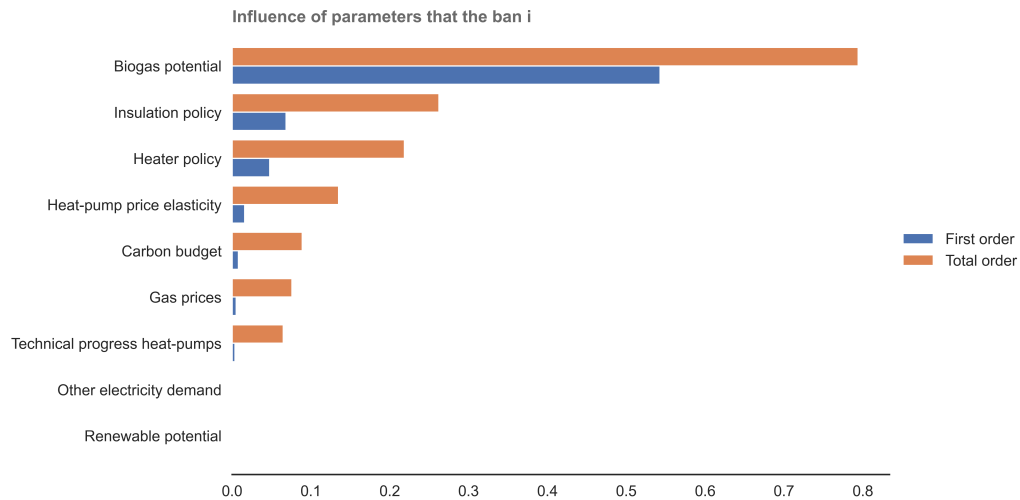
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Supplementary Figures

13

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

14



Supplementary Figure 1: **Ranking of most influential parameters driving the capacity of the current policy scenario to achieve carbon neutrality.** 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.

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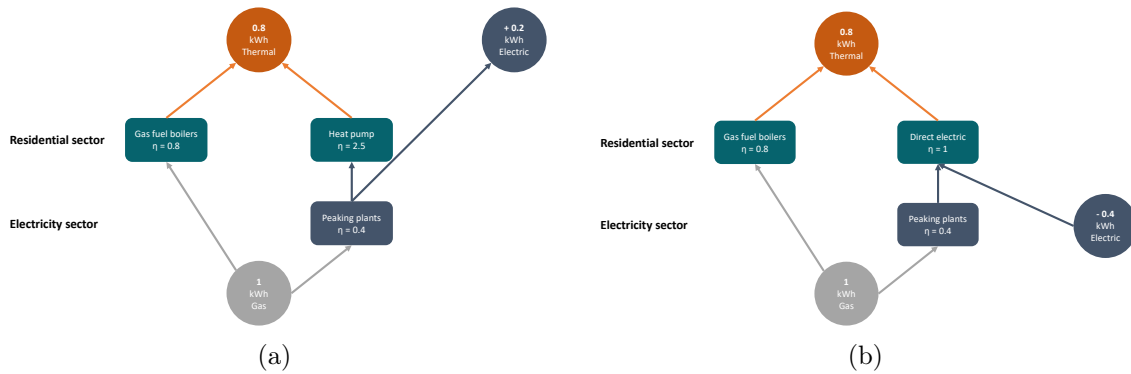
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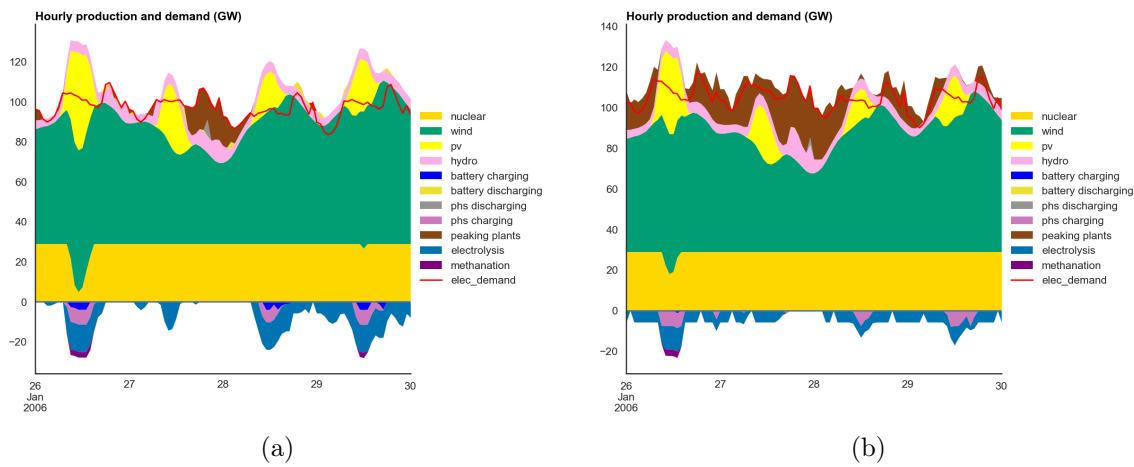
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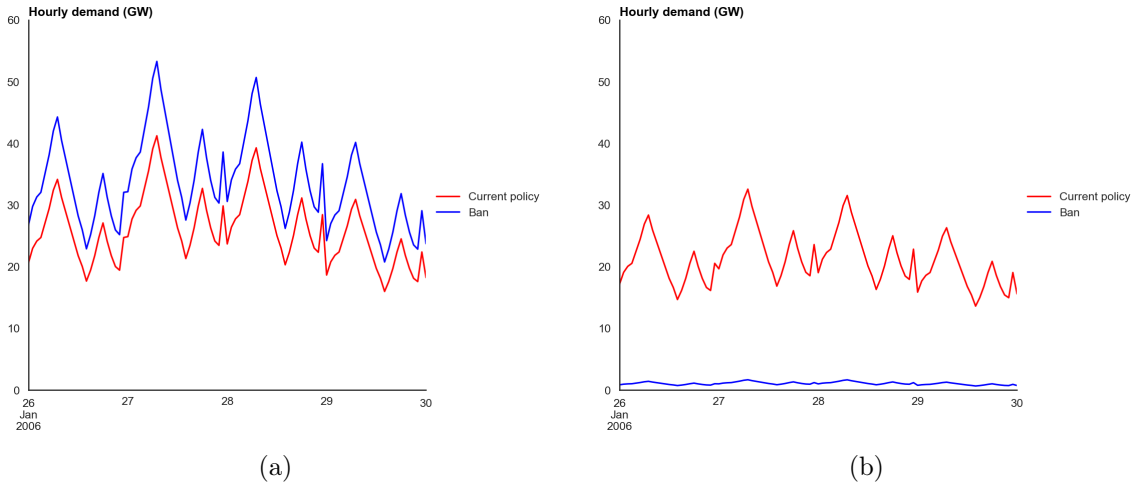
Supplementary Figure 5 identifies the determinants responsible for the higher cost-effectiveness of the current policy scenario compared to the ban. Scenarios exhibiting higher system costs under the ban typically feature high heat pump price elasticity—indicating a strong household investment response 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.



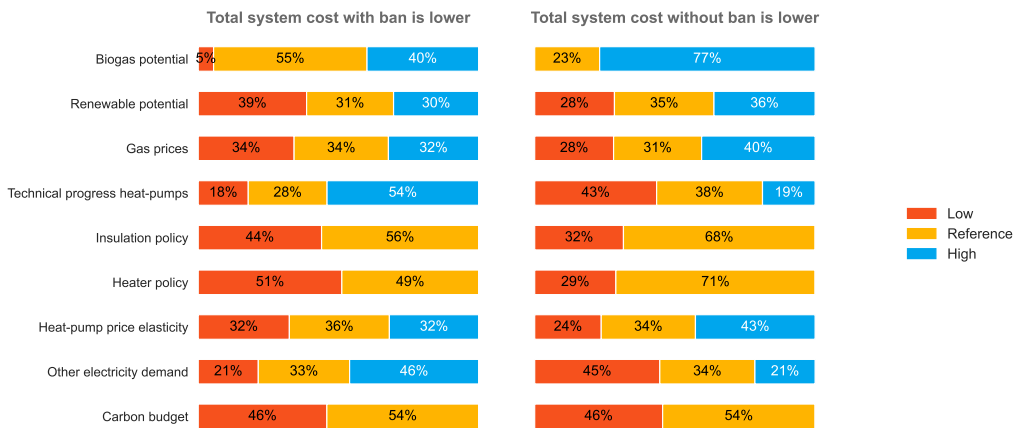
Supplementary Figure 2: **Simplified diagram of the the overall efficiency of replacing gas boilers with heat pumps and direct electricity.** η refers to efficiency of individual system. a. When heat pump is chosen. In the model, heat pump efficiency is not a constant value but varies with outdoor temperature across different days. For simplicity in this figure, we use a value of 2.5, which represents the lower end of the range but still illustrates the higher efficiency of the system. b. When direct electric is chosen.



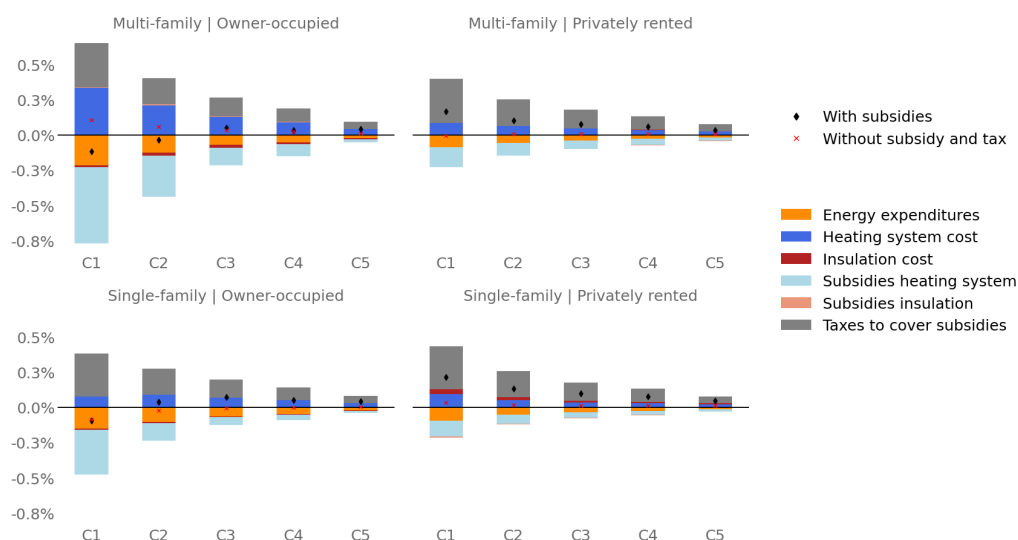
Supplementary Figure 3: **Hourly dispatch to meet electricity demand in 2050 over a typical week in January.** a. Current policy scenario. b. Ban scenario. PV stands for photovoltaic.



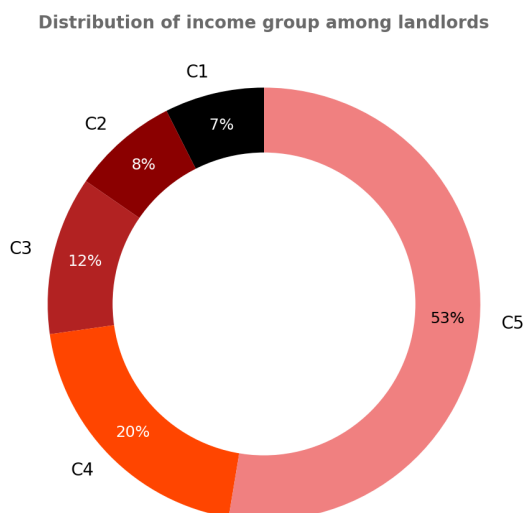
Supplementary Figure 4: Load profile for electricity and gas heating demands in 2050 over a typical week in January. a. Electricity demand. b. Gas demand.



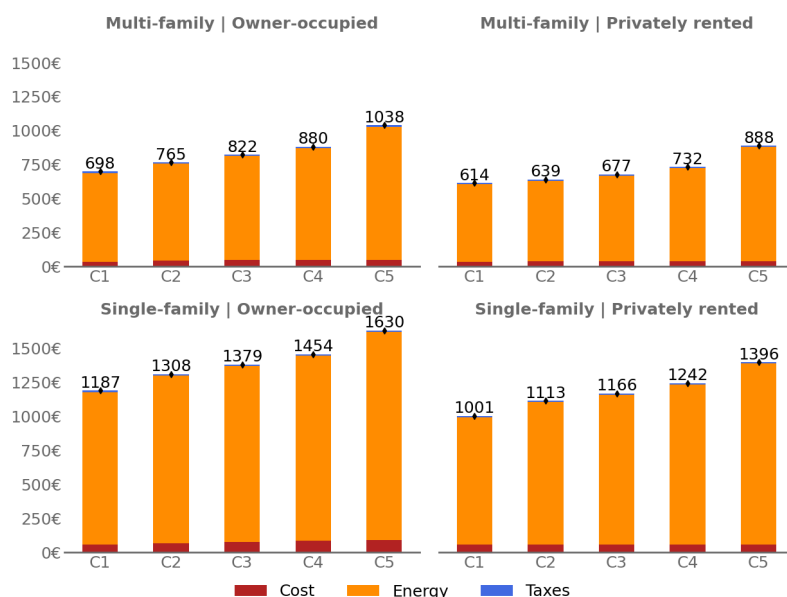
Supplementary Figure 5: Frequency of scenarios with total system cost lower with the ban (left) and total system cost lower without the ban (right).



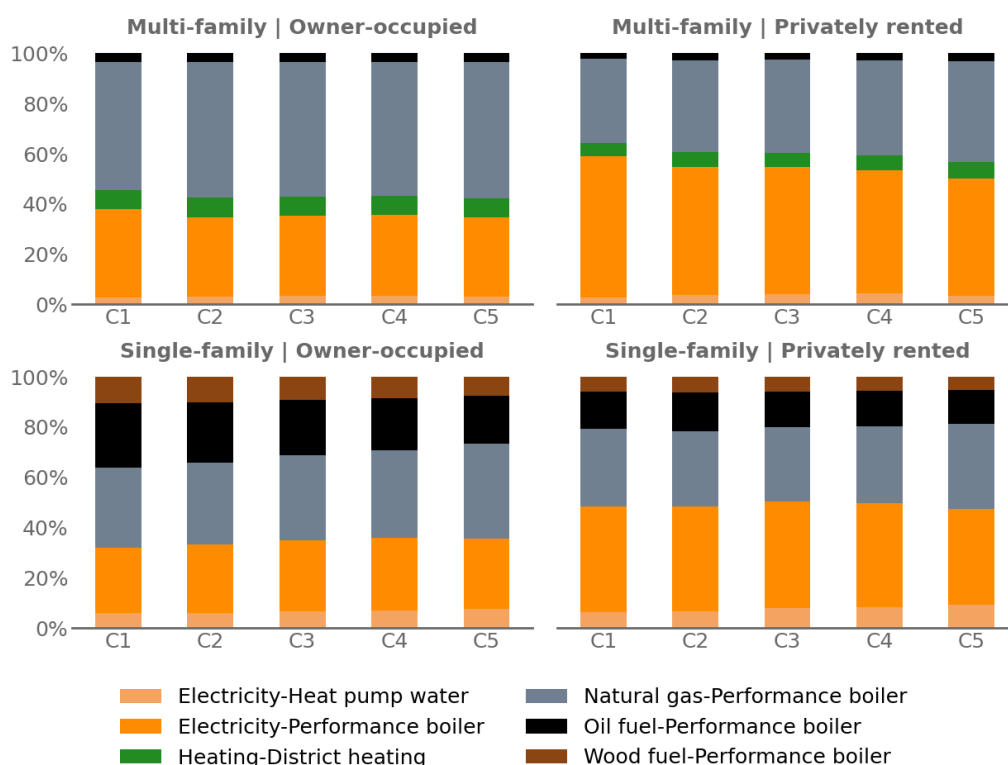
Supplementary Figure 6: **Average additional annual costs by household group if the ban is implemented (%)**. ‘C1’ means the first income quintile, i.e. very low income, and ‘C5’ means the last income quintile, i.e. very high income. A negative value means that the ban reduces household expenditure, 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).



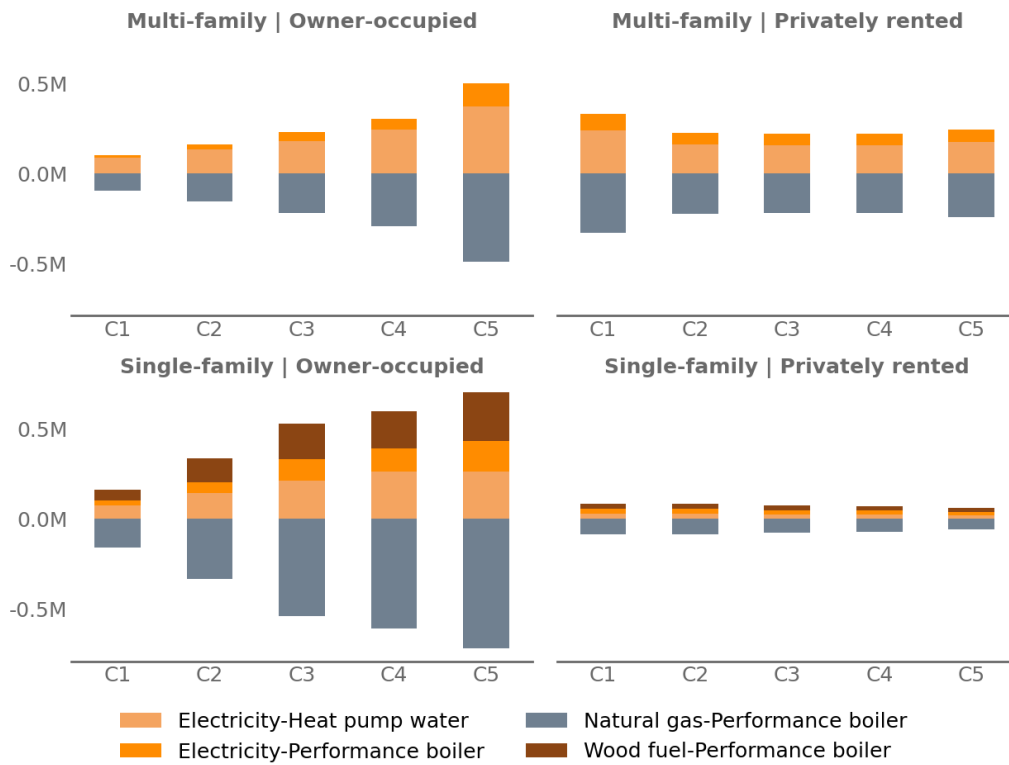
Supplementary Figure 7: **Distribution of income group among landlords in France in 2018**. ‘C1’ means the first income quintile, i.e. very low income, and ‘C5’ means the last income quintile, i.e. very high income.



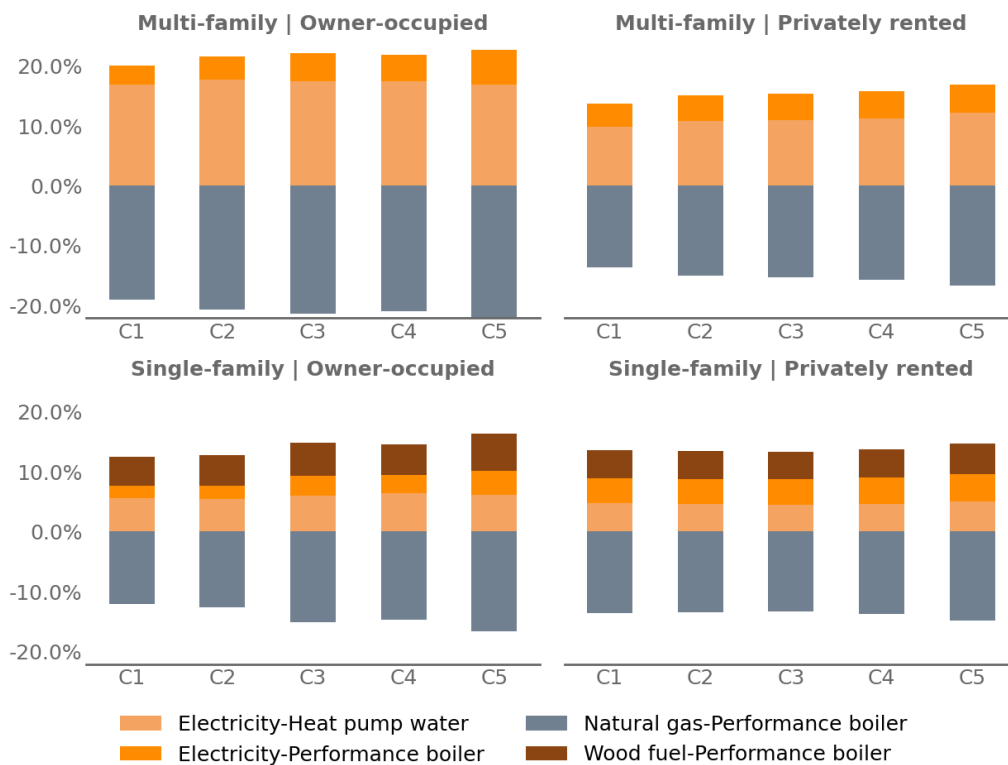
Supplementary Figure 8: **Cost of households in 2018 including energy cost, heater systems investment cost, and taxes due to subsidies.** ‘C1’ means the first income quintile, i.e. very low income, and ‘C5’ means the last income quintile, i.e. very high income.



Supplementary Figure 9: **Stock of heating system by household group in 2018.** ‘C1’ means the first income quintile, i.e. very low income, and ‘C5’ means the last income quintile, i.e. very high income.



Supplementary Figure 10: **Additional boilers in 2050, if the ban is implemented, in millions of boilers.** ‘C1’ means the first income quintile, i.e. very low income, and ‘C5’ means the last income quintile, i.e. very high income.



Supplementary Figure 11: **Additional boilers in 2050 if the ban is implemented, as a proportion of total installed boilers in 2050 by household group.** ‘C1’ means the first income quintile, i.e. very low income, and ‘C5’ means the last income quintile, i.e. very high income.

Supplementary Methods

Supplementary Method 1

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, $\hat{p}_{i,t}^k$ 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.

$$\forall k \in \text{heater, insulation} \quad p_{i,t}^k = \hat{p}_{i,t}^k / \gamma_{i,t,k,D} \quad (3)$$

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

$$\bar{C}_{I,t}^{\text{investment}} = \sum_{i \in I} (p_{i,t}^{\text{heater}} - s_{i,t}^{\text{heater}}) \cdot N_{i,t}^{\text{switch}} + (p_{i,t}^{\text{insulation}} - s_{i,t}^{\text{insulation}}) \cdot N_{i,t}^{\text{insulation}} \quad (4)$$

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:

$$C_{I,t}^{\text{investment}} = \sum_{tt=t-D}^t \bar{C}_{I,tt}^{\text{investment}} \quad (5)$$

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

$$C_{I,t} = \frac{C_{I,t}^{\text{investment}} + T(t, s) + \sum_{i \in I} p_t^{\text{energy}} \cdot \text{Conso}_{i,t}}{N_{I,t}} \quad (6)$$

The average costs over time is:

$$C_I = \frac{\sum_{t=2025}^{2050} C_{I,t} \cdot N_{I,t}}{\sum_{t=2025}^{2050} N_{I,t}} \quad (7)$$

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

$$\Delta C_I = C_I^{\text{ban}} - C_I^{\text{reference}} \quad (8)$$

Supplementary Method 2

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 assessment¹, with additional data from ADEME [2] and Zeyen *et al.* [3] 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

Technology	2025	2030	2035	2040	2045	2050	Reference
Offshore wind, Floating	3580	3280	3130	2980	2830	2680	RTE ¹
Offshore wind, Fixed	2930	2480	2380	2280	2180	2080	RTE ¹
Onshore wind, Fixed	1250	1210	1190	1170	1150	1130	RTE ¹
Solar PV, ground	672	597	557	517	497	477	RTE ¹
Solar PV, Mounted	967	867	812	757	717	677	RTE ¹
Nuclear power	NA	NA	5391	5035	4505	4500	RTE ¹
Methanation	1700	1341	1300	1274	1240	1207	RTE ¹
Methanization	370	370	370	370	370	370	ADEME ²
Pyrogazification	2500	2500	2500	2500	2500	2500	ADEME ²
OCGT	600	600	600	600	600	600	RTE ¹
CCGT	900	900	900	900	900	900	RTE ¹
CCGT for hydrogen	1100	1100	1100	1100	1100	1100	RTE ¹

Supplementary 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. PV stands for photovoltaic, OCGT stands for open cycle gas turbines, CCGT stands for combined cycle gas turbines.

58 capacities for VRE and nuclear technologies align with the TSO’s central production
59 scenario. Third, the potential for biogas production, through both methanization and
60 pyrogazification processes, is derived from ADEME, adjusted to fit the energy and
61 residential sectors’ context.

62 The main simplification assumptions in the EOLES are consistent with other ver-
63 sions in the EOLES family:

- 64 • The power system operates under the copper plate assumption, indicating that
65 electricity produced anywhere in continental France is assumed to be instanta-
66 neously available at any consumption point. This assumption treats France as a
67 single node in the model.
- 68 • Electricity, methane, and hydrogen demands are considered inelastic. However,
69 due to sector coupling between electricity, methane, and hydrogen networks, de-
70 mands for electricity in hydrogen production and for gas in electricity generation
71 are elastic and determined endogenously.
- 72 • The model employs linear optimization.

73 The cost projections for key electricity supply technologies utilized in our sim-
74 ulations primarily derive from RTE¹. When RTE provides only partial data points
75 between 2025 and 2050, we employ linear extrapolation to estimate the missing values.
76 The annuities are calculated by considering the interest incurred during construction,
77 assuming a uniform discount rate of 3.2% per year. The evolution of Capital Expen-
78 diture (CAPEX) is detailed in Table 4, while the evolution of Fixed Operation and
79 Maintenance (FOM) costs is presented in Table 5.

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

Technology	2025	2030	2035	2040	2045	2050	Reference
Offshore wind, Floating	95	80	70	60	55	50.3	RTE ¹
Offshore wind, Fixed	70	58	51	47	41	36	RTE ¹
Onshore wind, Fixed	37.5	35	32.5	30	27.5	25	RTE ¹
Solar PV, ground	10.5	10	9.5	9	8.5	8	RTE ¹
Solar PV, Mounted	10.5	10	9.5	9	8.5	8	RTE ¹
Nuclear power	100	100	100	100	100	100	RTE ¹
Methanation	59	59	59	59	59	59	RTE ¹
Methanization	37	37	37	37	37	37	ADEME ²
Pyrogazeification	225	225	225	225	225	225	ADEME ²
OCGT	20	20	20	20	20	20	RTE ¹
CCGT	40	40	40	40	40	40	RTE ¹
CCGT for hydrogen	40	40	40	40	40	40	RTE ¹

Supplementary Table 5: Evolution of Fixed Operation and Maintenance (FOM) costs (€/kWe/yr). PV stands for photovoltaic, OCGT stands for open cycle gas turbines, CCGT stands for combined cycle gas turbines.

Technology	Lifetime (yr)	Variable O&M (€/MWh)	Efficiency (%)	Reference
Offshore wind, Floating	40	0	-	RTE ¹
Offshore wind, Fixed	40	0	-	RTE ¹
Onshore wind, Fixed	30	0	-	RTE ¹
Solar PV, ground	30	0	-	RTE ¹
Solar PV, Mounted	30	0	-	RTE ¹
Nuclear power	60	6	-	RTE ¹
Methanation	20	5	60	RTE ¹
Methanization	20	50	-	ADEME ²
Pyrogazeification	20	32	-	ADEME ²
OCGT	30	-	40	RTE ¹
CCGT	40	-	57	RTE ¹
CCGT for hydrogen	40	-	57	RTE ¹

Supplementary Table 6: Other constant electricity generation technology parameters. PV stands for photovoltaic, OCGT stands for open cycle gas turbines, CCGT stands for combined cycle gas turbines.

Technology	2050	Reference
Offshore wind, Floating	30	RTE ¹
Offshore wind, Fixed	15	RTE ¹
Onshore wind, Fixed	58	RTE ¹
Solar pv, Ground	96	RTE ¹
Solar pv, Mounted	66	RTE ¹
New nuclear power	13.5	RTE ¹

Supplementary Table 7: Low-carbon technologies potential in 2050 (GW). PV stands for photovoltaic.

Potential	Scenario	2025	2030	2035	2040	2045	2050	Reference
Methanization	S2	0	14	19	24	29	35	ADEME ²
	S3	0	19	25	32	39	46	ADEME ²
Pyrogazeification	S2	0	0	0	0	0	0	ADEME ²
	S3	0	0	5	9	14	19	ADEME ²

Supplementary Table 8: Evolution of biogas potential (TWh).

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

Supplementary Table 9: Evolution of storage CAPEX (€/kWh). PHS stands for pumped hydro storage.

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Supplementary Method 4

83

Description of Res-IRF data sources Table 11 described all data sources in

84

Res-IRF. Specifically for the case of this study, we recall here the cost assumptions for

85

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

Supplementary Table 10: Data derived from RTE & ADEME [4]. 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). Costs are consistent with the JRC DataSet⁵ and a previous modeling study⁶.

Inputs	Source
Energy system	
Energy prices projection	Scenario AME 2021 ⁷
Energy taxes projection	Scenario AME 2021 ⁷
Amount of renewable gas for space heating	Scenario BAU ⁸
Number of dwelling connected to district heating	Scenario BAU ⁸
Housing market	
Demolition rate	Scenario BAU ⁸
Number of new buildings	Scenario BAU ⁸
Share of multi-family in new buildings	Scenario BAU ⁸
Market share heating system construction	Scenario BAU ⁸
Surface area of new housing	Fidéli (2018)
Macro	
Household income by decile in 2018	INSEE ⁹
Income growth	DGEC (2023)*
Initial housing stock	
Housing stock in 2018	MTE ^{10*}
Building performance characteristics by certificate	ADEME ¹¹
Landlords income	MTE ¹⁰
Wood and oil fuel housing	MTE ¹²
Surface area of dwelling by occupation status	Fidéli (2018)*
Technical data	
U-value of renovated envelope components	ADEME ¹³
Cost insulation by envelope component	Effinergie ¹⁴
Capex heating system	RTE & ADEME ⁴
Renovation rate	CEE 2017-2018 ¹⁵
Market share insulation work	TREMI ¹⁵
Heating system lifetime	Knobloch et al. ⁶
Market share heating system	ADEME ⁸
Behavioral parameters	
Time preferences discount factor	Stolyarova ¹⁶
Status quo bias	Stolyarova ¹⁶
Average price elasticity for heat pumps	Own assumption, from Risch ¹⁷
Financing information	
Maximum upfront cost by income class	Dolques et al. ¹⁸
Threshold credit constraint	Dolques et al. ¹⁸
Average interest rate of households savings	Own assumption
Average interest rate of home renovation loan	Dolques et al. ¹⁸
Indicators	
Health cost due to bad housing condition	Dervaux & Rochaix ¹⁹
Social discount rate	Ni & Maurice ²⁰
Thermal module data	
	Loga ²¹ and Arquin et al. ²²

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

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