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

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Abstract

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

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

1 Introduction

The building sector contributes significantly to energy consumption and greenhouse gas (GHG) emissions in temperate and high-income countries (Cabeza *et al.*, 2022; IEA, 2023). Most of these contributions stem from residential space heating. To mitigate the associated GHG externality, three main actions can be pursued: (i) improving the energy performance of the building envelope, e.g., through home insulation; (ii) switching to low-carbon heating systems, e.g., through the adoption of heat pumps and wood boilers; and (iii) decarbonizing heating fuels, e.g., by investing in wind

power, solar power or renewable gas production (e.g. through methanation or biogas). Mitigation strategies therefore result in a trade-off between demand- and supply-side investments to abate GHG emissions while maintaining energy balance at the hourly scale. In particular, the strong seasonality in space heating demand drives peak energy load, thus impacting the investments needed in the energy sector (Maxim *et al.*, 2023). These strategies also result from an interplay between centralized decisions about the energy system and decentralized decisions from households in the residential sector, which makes them challenging to assess together.

From a policy perspective, the optimal effort allocation between the three mitigation channels would theoretically be guided by a carefully designed carbon price – the textbook economic solution to the GHG externality. In the residential sector, however, investment barriers are at the source of the ‘energy efficiency gap’ – i.e., suboptimal investment in energy efficiency (Gerarden *et al.*, 2017). Chief among these barriers are credit constraints keeping low-income households in poorly insulated dwellings, where significant adverse health effects have recently been identified (Dervaux *et al.*, 2022). In this context, a first-best policy aimed at maximizing social welfare would combine a common carbon price with individually tailored energy efficiency subsidies in the residential sector (Allcott *et al.*, 2014; Chan *et al.*, 2023). In practice, however, carbon prices are rarely set at their socially optimal level, nor do they cover all relevant sectors – if they are implemented at all¹ –, and subsidies cannot realistically be individually tailored.

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

Most related analyses, however, keep at least one channel exogenous – e.g., home insulation and fuel switch in energy system models (Brown *et al.*, 2018; Shirizadeh *et al.*, 2022b), fuel decarbonization in building stock models (Mastrucci *et al.*, 2021; Giraudet *et al.*, 2021; Cabeza *et al.*, 2022; Berrill *et al.*, 2022). This limitation may result in inconsistencies between energy demand projections and the transformations they imply in the supply system. A few recent studies have made significant progress towards endogenizing all three channels (Zeyen *et al.*, 2021; Mandel *et al.*, 2023) for all EU. They however focus on optimal investment and ignore distortions in household decision-making. Finally, mitigation strategies have recently been investigated in the building sector using REMIND, a global integrated assessment model (Levesque *et al.*, 2021), but its processes are too coarse to capture the heterogeneity inherent in the building sector and the detailed impact of demand-side policies on the energy mix.

In this paper, we contribute to the integrated assessment of mitigation strategies in the residential sector by assessing different effort allocations under various subsidy designs. To do so, we develop an integrated framework combining a detailed representation of technology with advanced decision-making processes. Specifically, we link Res-IRF, a model of household energy demand (Vivier *et al.*, 2024) and EOLES, a model of energy supply (Shirizadeh *et al.*, 2021), both focusing on France. The linkage is realized through joint optimization in a dynamic recursive perspective. The different policy options are assessed by a social planner seeking to minimize total system costs – including investment, energy operation and health costs – while achieving carbon neutrality by 2050. The added value of our framework lies in providing a detailed, endogenous description of all three mitigation channels while relying on an optimiza-

¹For instance, in France, the government froze the "household" carbon tax rate in response to the Yellow Vest protest movement (Douenne *et al.*, 2022).

tion framework fit for discussing first- and second-best approaches. Specifically, we introduce four policy scenarios, each including a shadow price of carbon in the energy system alongside ad-valorem subsidies for heat pumps. The differences among scenarios arise from the specification of home insulation subsidies. The first scenario adopts a first-best approach, offering perfectly targeted subsidies for home insulation. In contrast, the subsequent three scenarios correspond to a second-best approach, offering more realistic, albeit coarser, subsidy specifications (see Table 1).

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

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

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

Table 1: Summary of the interaction between decarbonization channels and policies.

2 Methods

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

2.1 Modelling parts

Res-IRF is a dynamic microsimulation model of energy demand for space heating in the French building stock (Vivier *et al.*, 2024). Developed with the goal of improving behavioral realism (Mundaca *et al.*, 2010), the model provides a rich description of insulation levels (for walls, roofs, floors and windows) and heating systems (heat pumps, electric heating, gas-, oil- and wood-fired boilers). It simulates the evolution of energy consumption through three endogenous processes – the construction and demolition of buildings, the renovation of existing dwellings through insulation and fuel switch, and adjustments in heating behaviour. Energy efficiency investments are made by households and influenced by key economic costs and benefits, namely investment and

financing costs, energy bill savings, and subsidy amounts. When making these investments, households face various barriers, such as credit constraints (decreasing with income), landlords’ inability to pass energy efficiency investment onto rents, decision frictions in collective housing, and hidden costs (e.g., the inconvenience of insulation works). The model also takes into account a wedge between predicted and realized energy consumption in order to capture the much-discussed energy performance gap (Christensen *et al.*, 2021). This wedge varies endogenously in response to energy efficiency improvements, energy prices and household income and captures the rebound effect in particular. The exercise presented here uses Version 4.0 of the model. Its main features and data are outlined in Section A.1 of the Supplementary material.

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

2.2 Coupling

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

The coupled modelling framework is illustrated in Figure 1. The social planner’s objective function is the annualized system cost, i.e., the sum of the annualized costs of the energy supply system, the annualized costs of heating and insulation investment, and the annualized health costs from poor insulation. Our inclusion of health costs in the social planner’s objective function is motivated by recent evidence of high

²Reversible heat pumps are not included in the analysis.

³Initially scheduled to increase, the French carbon tax was frozen at €45/tCO₂ from 2020 to 2050 in response to the yellow vest movement.

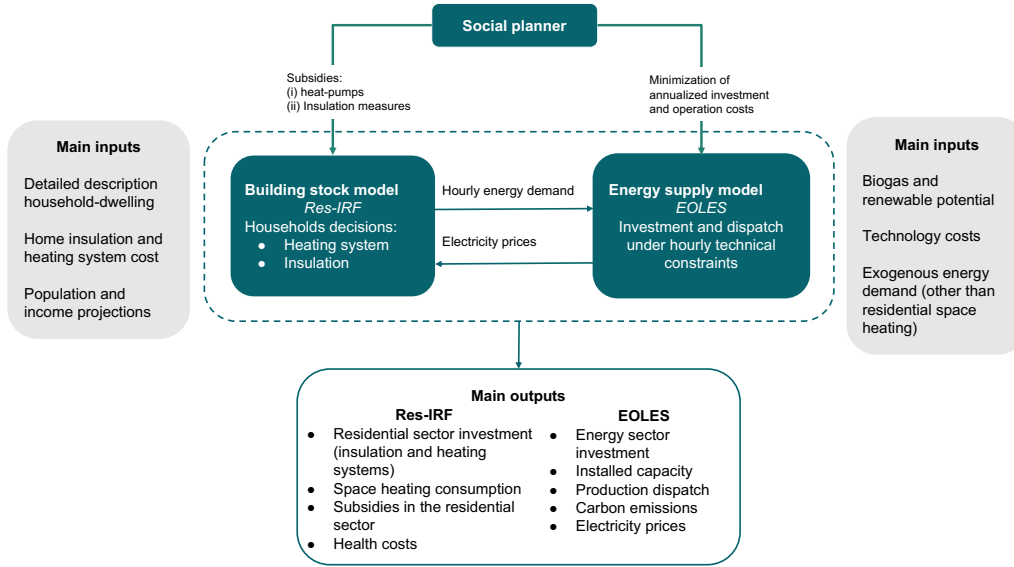


Figure 1: Joint optimization of demand and supply investments for a single time step. Control variables for the social planner include subsidies in the building sector and investment and dispatch in the energy sector.

morbidity and mortality rates among low-income households living in the least energy efficient dwellings (Dervaux *et al.*, 2022).⁴ Within a given time step, a given set of subsidy parameters determines final energy demand for residential heating in the Res-IRF model. At the same time, the EOLES model is run to optimize capacity investment and dispatch while meeting total energy demand. The social planner therefore effectively sets the subsidy parameters so as to minimize total system cost under the carbon budget constraint. This optimization is particularly challenging from a computational perspective, since the objective function depends on the subsidy parameters in a nonlinear way. To cope with this difficulty, we use a bayesian optimization framework relying on the Expected Improvement algorithm (Vazquez *et al.*, 2010). Further details can be found in Section A.8 in the Supplementary material.

The one-step optimization is then iterated over the entire time horizon, assuming a 5-year time step, from 2020 to 2050.⁵ Note that our framework is myopic in that the social planner only considers one time step at a time. We argue this is fit for capturing short-sightedness in both the politicians’ and stakeholders’ behavior (Victoria *et al.*, 2020), resulting in slow capital accumulation in both the building stock and the energy mix. Electricity prices are endogenously determined through demand-supply equilibrium. Technically, electricity prices for a given period are computed as the levelized cost to meet endogenous demand from the previous period. The resulting prices are topped with exogenous taxes. The prices of other fuels (gas, oil, wood) are exogenous.

Building on ADEME (2022), we consider an emission target of 4 MtCO₂ in 2050 for the electricity and residential sectors, representing a 93% reduction compared to 2018 emissions, and we assume a convex decrease in emissions along the trajectory (as displayed in Table S10 in the Supplementary material). All investments costs are

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

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

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

2.3 Scenarios

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

In contrast, insulation investments offer a multitude of options. Hence, we explore diverse specifications for this subsidy design, presenting different scenarios that reflect different paradigms (refer to Table 2). In a first-best, ‘optimal’ scenario, households behave as if they were facing no investment barrier and thus invest in the most socially profitable option. In second-best scenarios, the barriers are taken into account and subsidies are implemented to overcome them, with a rate to be determined. In an effort to mimic the key programs implemented in France, we consider three subsidy regimes: a ‘uniform’ one, similar to the tax credit program that ran from 2005 to 2020; a ‘comprehensive’ one, similar to a scheme called ‘Habiter mieux sérénité’; and a ‘proportional’ one, similar to white certificate obligations (Giraudet *et al.*, 2021). By design, the ‘uniform’ subsidy is less targeted than the ‘comprehensive’ and the ‘proportional’ subsidies.

The endogenously-determined subsidy levels and the effort allocation they implement are sensitive to underlying assumptions regarding the potential for low-carbon energy sources – biogas (including methanization and pyrogazeification), solar, onshore and offshore wind and nuclear. As pointed out by public authorities, the magnitude of these potentials is highly uncertain (ADEME, 2022; RTE, 2022). To assess the robustness of our results to such uncertainty, we re-run our scenarios with more conservative assumptions regarding the potentials for biogas, renewables and nuclear power (Table 2). The potentials for renewable energies (photovoltaics, onshore wind power, offshore wind power) and nuclear power in the reference scenario are given in the supplementary material.

2.4 Effect decomposition

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

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

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

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

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

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

Table 2: Description of insulation policy scenarios and supply-side assumptions. All scenarios include *ad valorem* subsidies for heat pumps. Variants for supply-side assumptions are based on scenarios from ADEME (2022) (scenario S2) and RTE (2022).

where sh_i is the share of heating system i in the the building stock (%), I_i is the specific energy consumption (kWh/m²) determined by the insulation level and C_i is the carbon content of the fuels used (gCO₂/kWh). Next to these three channels of interest, we consider the contributions of total housing surface (m²) and the varying intensity with which households heat their dwelling (HI_i , dimensionless).⁹ Additional details about the methodology can be found in Section A.4 in the Supplementary material.

3 Results

3.1 First-best scenario

In the ‘optimal’ scenario, home insulation (net of rebound effect) accounts for 19% of total GHG emission reduction in 2050 compared to 2020, fuel switch for 36%, and fuel decarbonization for 45% (Figure 2). In addition, energy consumption is reduced by 37% in 2050 compared to 2020, mainly through insulation (column ‘Optimal’ in Table 3). This order of magnitude is consistent with that found in related assessments of the building sector, e.g., 21-35% energy consumption reduction in Mandel *et al.* (2023), 44-51% in Zeyen *et al.* (2021) and 32% in Palzer *et al.* (2014).¹⁰

Unconstrained by investment barriers in energy efficiency markets, the social planner targets insulation efforts towards upgrading the least efficient dwellings, i.e., those with EPC ratings G and F. This approach significantly reduces energy bills, operational costs in the electricity sector and health costs. As a result, the count of F- and G-rated dwellings sharply decreases and 80% of dwellings are rated C or better in 2050 (Figure S7 in the Supplementary material).

By then, 25% of energy demand for space heating is met by electricity (Table 3) and 15 million heat pumps have been installed, providing heating service to about

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

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

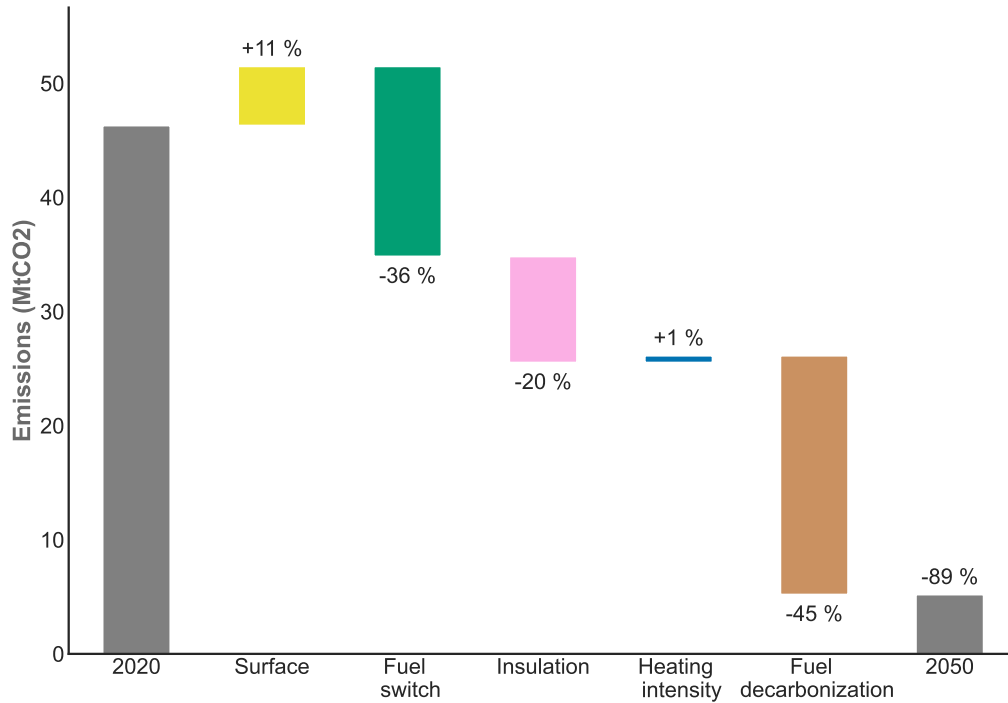


Figure 2: Decomposition analysis of the main decarbonization channels for the first-best scenario (‘optimal scenario’) using LDMI method (Section 2). The increase in heating intensity is due to the rebound effect. Home insulation accounts for 19% of total GHG emission reduction when accounting for rebound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

17% of dwellings. Annual electricity consumption remains relatively stable over time under the countervailing effects of insulation efforts and increased heat pump adoption. Overall, this first-best strategy requires approximately €150 billion investment in insulation (or €6 billion per year on average) and €77 billion investment in heat pumps (or €3 billion per year on average) (Table 3).

In 2050, 77% of electricity generation is met by solar, wind, and hydro power. This order of magnitude is consistent with that found in related works, e.g., 92-97% in Zeyen *et al.* (2021) and 90% in Mandel *et al.* (2023). Our somewhat lower figure can be attributed to the significant role played by nuclear in France, accounting for 20% of electricity generation in our assessment. As in Zeyen *et al.* (2021), the available potential for biogas is fully utilized, providing 46 TWh through methanization and 19 TWh through pyrogasification. Synthetic methane (obtained from methanation) is employed to fulfill the remaining gas demand for space heating and peak-load power plants, while hydrogen (obtained from electrolysis) is exclusively used for peak-load plants. Overall, peak-load power plants (gas turbines, such as OCGT and CCGT, and hydrogen turbines H₂-CCGT), contribute 2.4% of total electricity production. In 2050, 17 TWh of fossil gas are still used to meet total methane demand – including final gas demand from the residential sector and intermediary gas demand for peaking plants, which is low enough to stay within the 4 MtCO₂ carbon budget of that year.

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

3.2 Second-best alternatives

By design, the second-best scenarios entail a higher total system cost – 11 to 16% higher than in first best, depending on the variants (Figure 3 and Table 3).¹¹ This is due to the fact that, unlike second-best alternatives, the first-best scenario ignores energy efficiency barriers that differently affect heterogeneous households. For instance, while the first-best scenario will optimally select the most cost-effective insulation measure in a given dwelling, investment in that measure will be hindered in practice by credit constraints if the occupant is from the low-income group. This barrier could not be fully overcome by alternative subsidy designs. This results in a different effort allocation between first-best and second-best scenarios, with a larger role played by insulation in the first-best scenario (Figure 4). In the first-best scenario, insulation alone achieves a 30% reduction in energy consumption, compared to the 6-20% range observed in second-best designs. Consequently, in the first-best scenario, there is a lesser need for additional capacities like peaking plants and batteries (-3 GW), as well as solar capacity (-30 GW) (Figure 5). This adjustment substantially lowers the energy system’s annual costs by 0.7-1.5 billion euros per year.

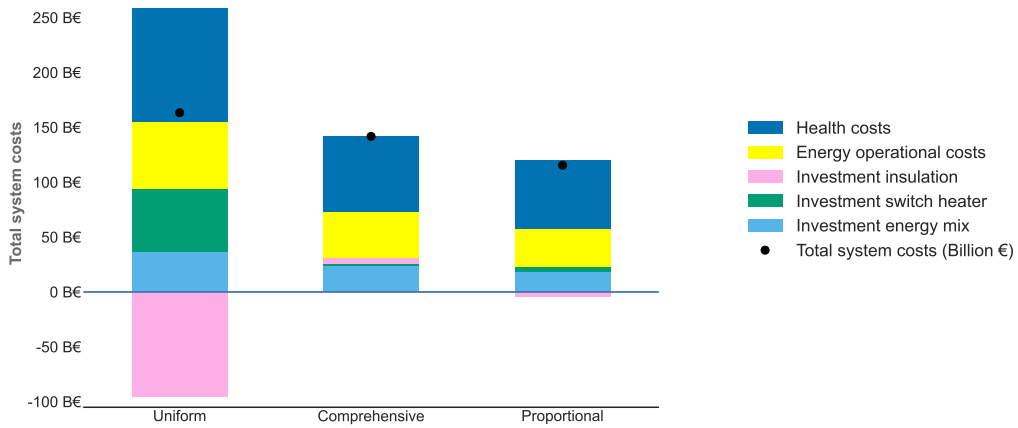


Figure 3: Difference in total annualized system costs over period 2025-2050 (Billion EUR) compared to the ‘optimal’ subsidy insulation scenario. Energy operational costs include all costs related to system operation (e.g., methanization variable cost, wood energy expenditures).

The effort allocation between insulation, fuel switch and fuel decarbonization varies greatly across subsidy designs. Compared to ‘uniform’ subsidies, ‘comprehensive’ subsidies entail a €23 billion lower total system cost (or €0.9 billion per year on average), as illustrated in Figure 3. Specifically, they involve twice as much investment in insulation (hence an extra €4.5 billion per year), less investment in both heat pump adoption (5 million fewer, hence a €3.7 billion less per year) and energy system (€0.5 billion less per year). This is achieved through endogenously-determined *ad valorem* subsidy rates of 50 to 75% for insulation and 0 to 60% for heat pumps over time horizon (Figure S5 in the Supplementary material). The ‘comprehensive’ and ‘proportional’ scenarios produce very similar results, save for more investment in insulation, and a slightly lower total system cost, in the former. Such a similarity by contrast highlights the poorer performance of the less well-targeted ‘uniform’ subsidy design, thereby revealing that energy performance is only poorly reflected in technology cost.¹²

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

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

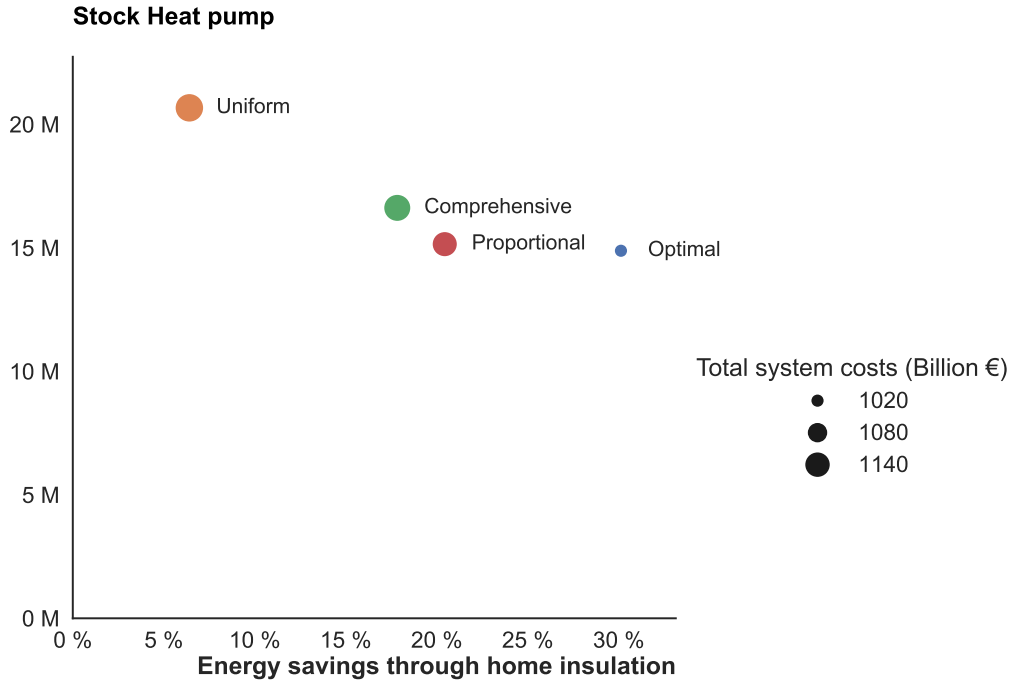


Figure 4: Trade-offs between energy savings from home insulation and switch to heat pumps in 2050 across scenarios. Home insulation is reflected through energy demand savings compared to 2020, while heat pumps is reflected through stock evolution (in reference to 39 millions dwellings in 2050).

Overall, our results highlight the key role played by subsidy specifications in determining the trade-off between insulation and fuel switch (Figure 4). Subsidy specifications are more marginal in the energy system (which again supplies all end-use sectors), and concentrated on peak-load and solar capacity and production. The main result is a 6 GW lower peak-load capacity in the ‘comprehensive’ scenario than in the ‘uniform’ one (Table 3).

The residual carbon values associated with the carbon constraint vary mildly across scenarios, within a range that is consistent with the value recommended by French authorities for public assessment (Table S11 in Supplementary material A.7).

Interestingly, our results continue to hold qualitatively when health costs are not included in the social planner’s objective function, which establishes their robustness (Figures S3 and S4 in Supplementary material A.5).

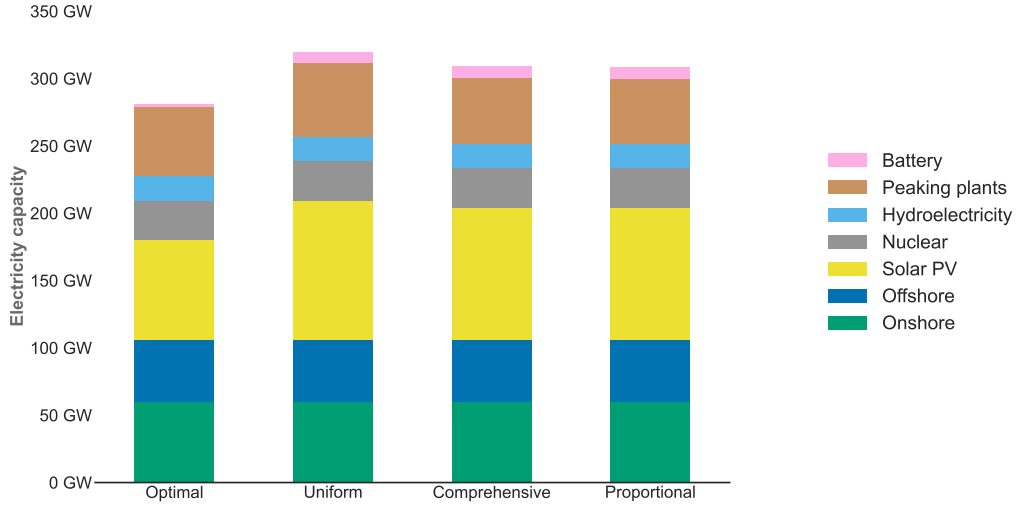


Figure 5: Comparison of electricity mix across different scenarios. All scenarios install maximal capacity of onshore and offshore capacity. First-best (‘optimal’) scenario needs less peaking plants and batteries (-3 GW), as well as solar capacity (-30 GW).

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

Table 3: Summary of results. In the table, energy consumption refers to 2050. Values in billion euros are the sum of actual invested values between 2025 and 2050. In contrast, the metric Total system costs, used to compare scenarios (e.g in Figure 3), refers to the average of annualized costs over time period 2025-2050. Comparison is done with the ‘optimal’ scenario.

3.3 Variants with restricted supply-side assumptions

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

By design, all alternatives result in a higher total system cost compared to the reference assumptions. In general, more limited potentials for fuel decarbonization imply stronger energy efficiency efforts through home insulation or heat pump adoption. Figure 6 more specifically illustrates the trade-offs between insulation and heat

pump in all four scenarios, under alternative assumptions regarding fuel decarbonization potentials.

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

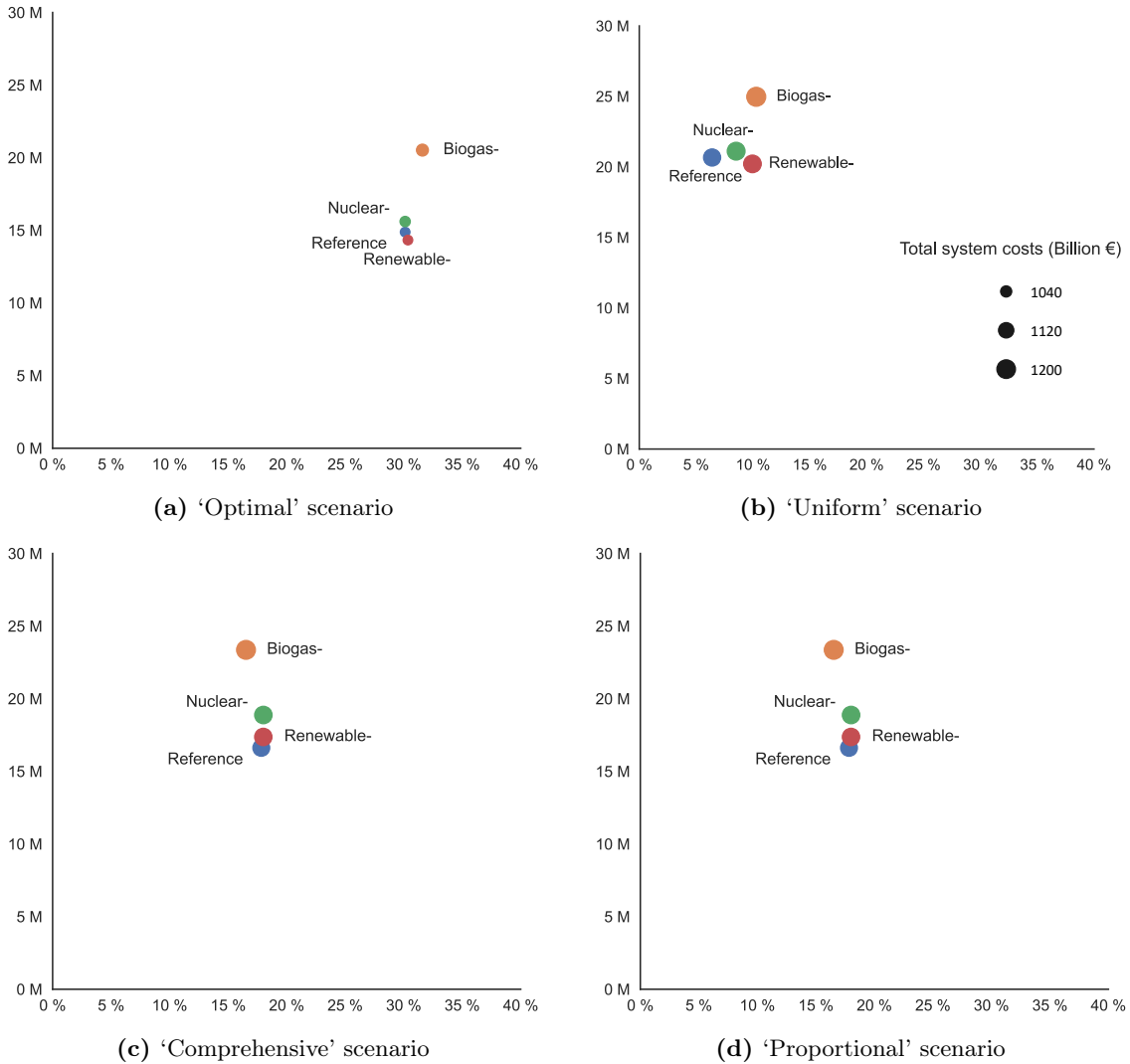


Figure 6: Evolution of demand-side mitigation strategy depending on supply-side assumptions. x-axis corresponds to energy savings through home insulation in percentage of 2020 consumption, and y-axis corresponds to stock of heat pumps in million (in reference to 39 millions dwellings in 2050). Size of points on the figure corresponds to the total system costs.

4 Discussion

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

One important added value of our framework is to compare first-best and second-best strategies in a detailed bottom-up modeling framework. This allows us to identify a 11% to 16% higher total-system cost under second-best policy, as illustrated in Figure 3 and Table 3. In contrast, related works tend to rely on a first-best approach, implicitly assuming the policy considered to be optimal (e.g., Zeyen *et al.*, 2021; Mandel *et al.*, 2023). Our more comprehensive approach delivers a more cautionary message: granted, significant demand reductions can in theory be achieved in the residential sector, but only two thirds of it is attainable with realistic subsidy programs.

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

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

5 Conclusion

Taking a whole-system demand-supply approach to the decarbonization of residential space heating, we show how a politically-constrained social planner can implement energy efficiency subsidies so as to mitigate the GHG externality while overcoming en-

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

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

Code availability

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

Data availability statement

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

CRedit authorship contribution statement

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

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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References

1. ADEME. *Transition(s) 2050* tech. rep. (2022).
2. Allcott, H., Mullainathan, S. & Taubinsky, D. Energy policy with externalities and internalities. en. *Journal of Public Economics* **112**, 72–88 (Apr. 2014).
3. Ang, B. W. & Zhang, F. Q. A survey of index decomposition analysis in energy and environmental studies. *Energy* **25**, 1149–1176 (Dec. 2000).
4. Berrill, P., Wilson, E. J. H., Reyna, J. L., Fontanini, A. D. & Hertwich, E. G. Decarbonization pathways for the residential sector in the United States. en. *Nature Climate Change* **12**. Number: 8 Publisher: Nature Publishing Group, 712–718 (Aug. 2022).
5. Bourgeois, C., Giraudet, L.-G. & Quirion, P. Lump-sum vs. energy-efficiency subsidy recycling of carbon tax revenue in the residential sector: A French assessment. en. *Ecological Economics* **184**, 107006 (June 2021).
6. Brown, T., Schlachtberger, D., Kies, A., Schramm, S. & Greiner, M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. en. *Energy* **160**, 720–739 (Oct. 2018).
7. Cabeza, L. F. *et al.* in *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022).
8. Chan, N. W. & Globus-Harris, I. On consumer incentives for energy-efficient durables. en. *Journal of Environmental Economics and Management* **119**, 102813 (May 2023).
9. Christensen, P., Francisco, P., Myers, E. & Souza, M. Decomposing the Wedge between Projected and Realized Returns in Energy Efficiency Programs. *The Review of Economics and Statistics*, 1–46 (Aug. 2021).
10. Dervaux, B. & Rochaix, L. *Socio-Economic Evaluation of the Health Effects of Public Investment Projects* tech. rep. (France Stratégie, Mar. 2022).
11. Douenne, T. & Fabre, A. Yellow Vests, Pessimistic Beliefs, and Carbon Tax Aversion. en. *American Economic Journal: Economic Policy* **14**, 81–110 (Feb. 2022).
12. Elnagar, E. *et al.* Framework to assess climate change impact on heating and cooling energy demands in building stock: A case study of Belgium in 2050 and 2100. *Energy and Buildings* **298**, 113547 (Nov. 2023).
13. Fallahnejad, M. *et al.* District heating potential in the EU-27: Evaluating the impacts of heat demand reduction and market share growth. *Applied Energy* **353**, 122154 (Jan. 2024).
14. Gerarden, T. D., Newell, R. G. & Stavins, R. N. Assessing the Energy-Efficiency Gap. en. *Journal of Economic Literature* **55**, 1486–1525 (Dec. 2017).
15. Giraudet, L.-G., Bourgeois, C. & Quirion, P. Policies for low-carbon and affordable home heating: A French outlook. en. *Energy Policy* **151**, 112140 (Apr. 2021).
16. Hirth, L., Ruhnau, O. & Sgarlato, R. *The European Electricity Market Model EMMA - Model Description* eng. Working Paper (Kiel, Hamburg: ZBW - Leibniz Information Centre for Economics, 2021).
17. IEA. *World Energy Outlook 2023* en-GB. Tech. rep. (IEA, 2023).
18. Krey, V. *et al.* Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models. *Energy* **172**, 1254–1267 (Apr. 2019).
19. Levesque, A., Pietzcker, R. C., Baumstark, L. & Luderer, G. Deep decarbonisation of buildings energy services through demand and supply transformations in a 1.5°C scenario. en. *Environmental Research Letters* **16**. Publisher: IOP Publishing, 054071 (May 2021).
20. Mandel, T. *et al.* Investigating pathways to a net-zero emissions building sector in the European Union: what role for the energy efficiency first principle? en. *Energy Efficiency* **16**, 22 (Mar. 2023).
21. Mastrucci, A., van Ruijven, B., Byers, E., Poblete-Cazenave, M. & Pachauri, S. Global scenarios of residential heating and cooling energy demand and CO₂ emissions. en. *Climatic Change* **168**, 14 (Oct. 2021).
22. Maxim, A. & Grubert, E. Highly energy efficient housing can reduce peak load and increase safety under beneficial electrification. en. *Environmental Research Letters* **19**. Publisher: IOP Publishing, 014036 (Dec. 2023).

23. Mundaca, L., Neij, L., Worrell, E. & McNeil, M. Evaluating Energy Efficiency Policies with Energy-Economy Models. *Annual Review of Environment and Resources* **35**. [_eprint: https://doi.org/10.1146/annurev-environ-052810-164840](https://doi.org/10.1146/annurev-environ-052810-164840), 305–344 (2010).
24. Ni, J. & Maurice, J. *Révision du taux d'actualisation [Revision of the discount rate]* tech. rep. (France Stratégie, Oct. 2021).
25. Palzer, A. & Henning, H.-M. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies – Part II: Results. en. *Renewable and Sustainable Energy Reviews* **30**, 1019–1034 (Feb. 2014).
26. Panos, E. *et al.* Deep decarbonisation pathways of the energy system in times of unprecedented uncertainty in the energy sector. *Energy Policy* **180**, 113642 (Sept. 2023).
27. Pfenninger, S. & Staffell, I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. en. *Energy* **114**, 1251–1265 (Nov. 2016).
28. Pye, S., Sabio, N. & Strachan, N. An integrated systematic analysis of uncertainties in UK energy transition pathways. en. *Energy Policy* **87**, 673–684 (Dec. 2015).
29. RTE. *Futurs énergétiques 2050* fr. Tech. rep. (2022).
30. Shirzadeh, B., Perrier, Q. & Quirion, P. How Sensitive are Optimal Fully Renewable Power Systems to Technology Cost Uncertainty? en. *The Energy Journal* **43**, 43–75 (Jan. 2022).
31. Shirzadeh, B. & Quirion, P. Low-carbon options for the French power sector: What role for renewables, nuclear energy and carbon capture and storage? en. *Energy Economics* **95**, 105004 (Mar. 2021).
32. Shirzadeh, B. & Quirion, P. The importance of renewable gas in achieving carbon-neutrality: Insights from an energy system optimization model. en. *Energy* **255**, 124503 (Sept. 2022).
33. Unnewehr, J. F., Weidlich, A., Gfüllner, L. & Schäfer, M. Open-data based carbon emission intensity signals for electricity generation in European countries – top down vs. bottom up approach. *Cleaner Energy Systems* **3**, 100018 (Dec. 2022).
34. Vazquez, E. & Bect, J. Convergence properties of the expected improvement algorithm with fixed mean and covariance functions. en. *Journal of Statistical Planning and Inference* **140**, 3088–3095 (Nov. 2010).
35. Victoria, M., Zhu, K., Brown, T., Andresen, G. B. & Greiner, M. Early decarbonisation of the European energy system pays off. en. *Nature Communications* **11**. Number: 1 Publisher: Nature Publishing Group, 6223 (Dec. 2020).
36. Vivier, L. & Giraudet, L.-G. *Is France on track for decarbonizing its residential sector? Assessing recent policy changes and the way forward*. Jan. 2024.
37. Zeyen, E., Hagenmeyer, V. & Brown, T. Mitigating heat demand peaks in buildings in a highly renewable European energy system. en. *Energy* **231**, 120784 (Sept. 2021).
38. Ürge Vorsatz, D., Herrero, S. T., Dubash, N. K. & Lecocq, F. Measuring the Co-Benefits of Climate Change Mitigation. *Annual Review of Environment and Resources* **39**. [_eprint: https://doi.org/10.1146/annurev-environ-031312-125456](https://doi.org/10.1146/annurev-environ-031312-125456), 549–582 (2014).

A Supplementary Materials

A.1 Description of Res-IRF

A.1.1 Modeling hypotheses

In a nutshell, the Res-IRF model is a well-established dynamic microsimulation model of energy consumption and long-term energy efficiency improvement of the French residential building sector.¹⁴ It focuses on space heating as the main usage. The model integrates a detailed description of the energy performance of the dwelling stock with a rich description of household energy-efficiency investment behavior (Table S1). Specifically, the energy performance of the dwelling stock is described through buildings archetypes, each characterized by their type (single or multi family), the insulation level of the main components of the envelope (walls, floor, roof, windows) and the heating system (electrical heating, heat pumps, gas boilers, fuel oil boilers, wood furnaces). Households, in turn, are characterized by their occupancy status (owner-occupier, renter in the private sector, renter in social housing) and income class.

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

Table S1: Res-IRF model dimension. Total number of dwelling-households pair is therefore around 180,000.

The structure of the dwelling stock evolves through decentralized household energy efficiency investment in home insulation and heating system (Figure S1). Investment decisions are influenced by key economic costs and benefits, namely investment and financing costs, energy bill savings, subsidy amounts and by market-barriers (hidden cost, landlord-tenant dilemma, collective decision in multi-family dwelling) and behavioral anomalies (myopic expectation). Mathematically, these decisions are represented by discrete choice models. First, a homeowner decides to install a new heating system, triggered by the end of the service life of his heating system, subject to the constraint that heat pumps cannot be installed in the least efficient homes (energy performance certificate F and G).¹⁵ In a second stage, the homeowner decide whether to renovate, and if so, what kind of insulation to take. Note that the model incorporates a baseline stream of renovation even without subsidies, reflecting natural stock turnover.

Lastly, the model incorporates a wedge between predicted and realized energy consumption to capture the much-discussed energy performance gap (Christensen *et al.*, 2021). This wedge varies endogenously in response to energy efficiency upgrades, energy prices and household income. Parameterized with engineering data (Cayla *et al.*, 2013), these adjustments together capture rebound effects.

We adapt the original Res-IRF method as our integrated framework requires an hourly demand profile using daily profile for outdoor temperature and solar irradiance.

¹⁴The development of Res-IRF has produced six peer-reviewed articles to this day

¹⁵This constraint is meant to reflect heat pumps' inability to heat water above 55°C, the minimum temperature needed to heat dwellings, considering France's climate and standard radiator size.

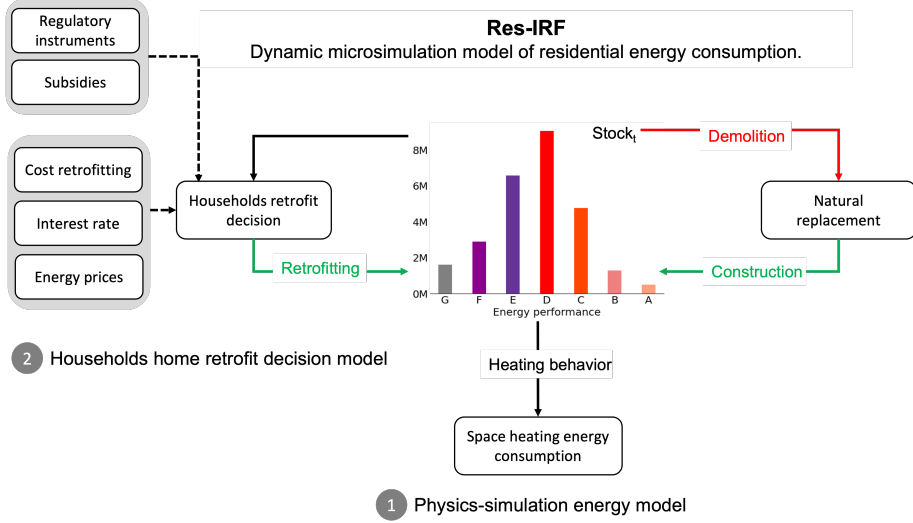


Figure S1: Schema Res-IRF 4.0.

We then fit the same hourly space heating demand profile (Moreau *et al.*, 2022) for every day. Finally, we calculate the final energy demand by considering an hourly profile of the efficiency of heat-pumps. Indeed, the efficiency of the heat pump depends on the difference between indoor and outdoor temperatures (Staffell *et al.*, 2012). We consider the same indoor temperatures between water and air source heat pumps of 55°C.

A.1.2 Data

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

Table S2: Cost analysis from Observatoire BBC field study (Effnergie *et al.*, 2021). The costs for the wall insulation correspond to exterior insulation. For the roof, the costs correspond to an average value for the insulation costs of converted attics, lost attics and crawl spaces. Model excludes ventilation costs, audit and accompanying expenses, and non-energy related renovation costs

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

Table S3: Data derived from RTE *et al.* (2020). It includes costs related to domestic hot water systems as part of heating system costs, but do not consider other costs, such as those associated with heat emitters (radiators). We also integrate an exogenous technical progress that reduces the costs of the heat pump by 20% by 2035.

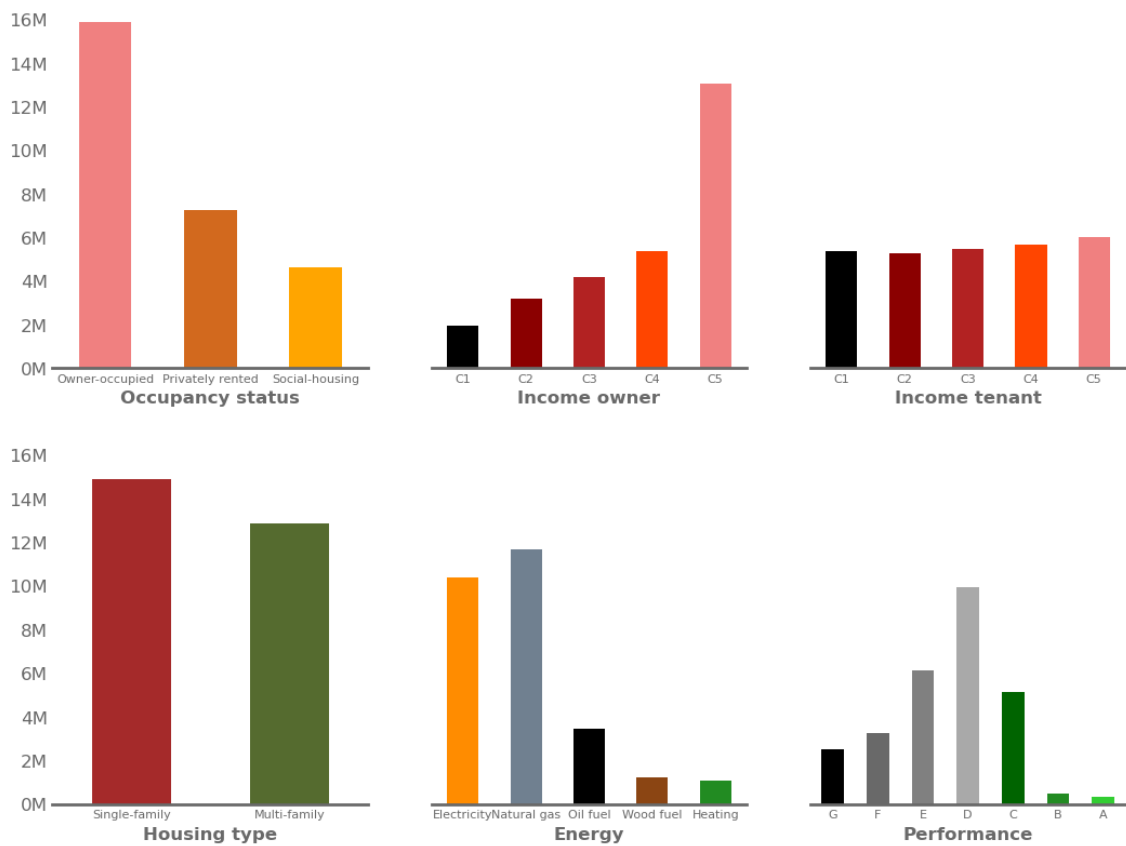


Figure S2: Description of the building stock in France in 2018 (MTE, 2020). To simplify the presentation, the energy performance levels are described with EPC, but Res-IRF 4.0 uses the level of insulation for each component of the building envelope.

A.2 Description of EOLES

A.2.1 Modeling hypotheses

The hourly capacity factors for variable renewable energy (VRE) (offshore and onshore wind and solar PV) are specified at the French departmental level, based on historical records for the 2000-2018 period.¹⁶ Most of the technological cost parameters are taken from the French Transmission System Operator (TSO)'s latest long-term assessment (RTE, 2022), supplemented with inputs from ADEME (2018) and Zeyen *et al.* (2021) when nonavailable.

The central scenario considered for the energy mix partly relies on exogenous assumptions. First, the residual electricity demand that is not endogenously determined in Res-IRF – namely, all uses other than heating – is based on the TSO's central scenario, projecting a 595 TWh demand in 2050. This projection takes into account the increased penetration of electric vehicles. In addition, a 40 TWh hydrogen demand is considered in 2050. Second, maximal capacities are imposed on VRE and nuclear technologies, based on the TSO's central production scenario. Third, the potential for biogas production (through methanization and pyrogazification) is taken from ADEME,¹⁷ adjusted to the scope of the energy sector and the residential sector.

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

- Power system of the studied country follows the copper plate assumption, which means that the electricity produced at each point of the country can be transmitted to the consumption point instantaneously. This assumption entails the representation of the studied country (here, continental France) in a single node.
- Electricity, methane and hydrogen demand are considered inelastic. Nevertheless, thanks to sector coupling between electricity, methane and hydrogen networks, electricity demand for hydrogen production and gas demand for electricity production are elastic and calculated endogenously.
- This model uses only linear optimization: while non-linear constraints such as studying unit commitment, they entail a large increase in computation time. According to Palmintier (2014), linear programming provides an interesting trade-off, which speeds up processing by up to 1500 times.

¹⁶This is achieved using data from the renewables.ninja website (<https://www.renewables.ninja/>), following the methods proposed by Pfenninger *et al.* (2016).

¹⁷We specifically consider the S3 scenario.

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

Table S4: Evolution of CAPEX (€/kWe). New nuclear power can only be installed starting in 2035. Methanation is calculated as the sum of electrolysis CAPEX and Sabatier reaction CAPEX.

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

Table S5: Evolution of fOM (€/kWe/yr).

A.2.2 Data

We display cost projections of the main electricity supply technologies used in our simulations, which are mainly from RTE, 2022. When RTE only provides some but not all intermediate values between 2025 and 2050, we rely on linear extrapolation to estimate missing values. The annuities calculated, taking into account the interest incurred during construction, assuming a single discount rate of 3.2% per year. Evolution of CAPEX is displayed in Table S6, evolution of fixed operation costs is displayed in Table S5.

The energy system strongly relies on available potential for different technologies, namely biogas (Table S8 and low-carbon technologies (Table S7).

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

Table S6: Other constant electricity generation technology parameters.

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

Table S7: Low-carbon technologies potential in 2050 (GW).

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

Table S8: Evolution of biogas potential (TWh).

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

Table S9: Evolution of storage CAPEX (€/kWh).

A.3 Additional data

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

Table S10: Evolution of carbon budget.

A.4 Decomposition analysis

We can write CO₂ emissions as follows:

$$CO2 = \sum_i \text{Surface} \times \frac{\text{Surface}_i}{\text{Surface}} \times \frac{FE_{conv,i}}{\text{Surface}_i} \times \frac{FE_i}{FE_{conv,i}} \times \frac{C_i}{FE_i} \quad (1)$$

$$= \text{Surface} \times \sum_i sh_i \times I_i \times HI_i \times C_i, \quad (2)$$

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

$$\Delta^i = \frac{\Delta CO2}{\Delta \ln CO2} \ln\left(\frac{X_i^F}{X_i^0}\right) \quad (3)$$

Therefore, we can decompose variations in CO₂ emissions as follows:

$$\Delta CO2 = \sum_i \frac{\Delta CO2_i}{\Delta \ln CO2_i} \left(\ln\left(\frac{m_2^F}{m_2^0}\right) + \ln\left(\frac{sh_i^F}{sh_i^0}\right) + \ln\left(\frac{I_i^F}{I_i^0}\right) + \ln\left(\frac{HI_i^F}{HI_i^0}\right) + \ln\left(\frac{C_i^F}{C_i^0}\right) \right) \quad (4)$$

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

$$\Delta CO2 = \Delta \text{Surface} + \Delta SH + \Delta I + \Delta HI + \Delta C \quad (5)$$

where:

$$\Delta \text{Surface} = \ln\left(\frac{\text{Surface}^F}{\text{Surface}^0}\right) \sum_i \frac{\Delta CO2_i}{\Delta \ln CO2_i}, \quad (6)$$

$$\Delta SH = \sum_i \frac{\Delta CO2_i}{\Delta \ln CO2_i} \ln\left(\frac{sh_i^F}{sh_i^0}\right), \quad (7)$$

$$\Delta I = \sum_i \frac{\Delta CO2_i}{\Delta \ln CO2_i} \ln\left(\frac{I_i^F}{I_i^0}\right), \quad (8)$$

$$\Delta HI = \sum_i \frac{\Delta CO2_i}{\Delta \ln CO2_i} \ln\left(\frac{HI_i^F}{HI_i^0}\right), \quad (9)$$

$$\Delta C = \sum_i \frac{\Delta CO2_i}{\Delta \ln CO2_i} \ln\left(\frac{C_i^F}{C_i^0}\right) \quad (10)$$

A.5 Simulations without health costs

We ran the same simulations as in Section 3 without the health costs (Figures S3 and S4). We observed the same ranking of the scenarios, and the same variation in terms of optimal strategy, as displayed in the following figures.

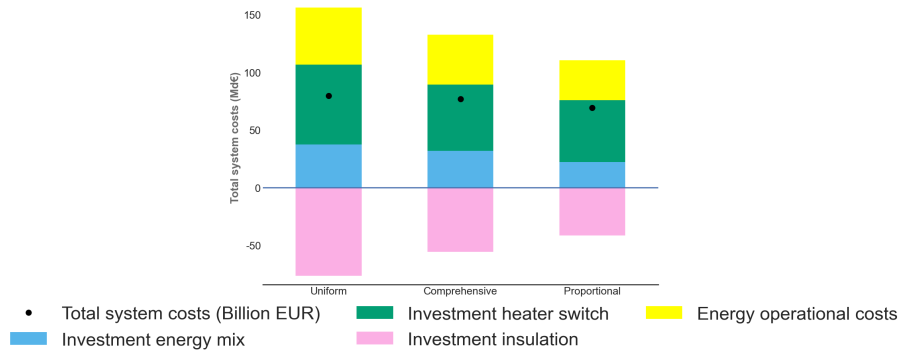


Figure S3: Difference of total system costs.

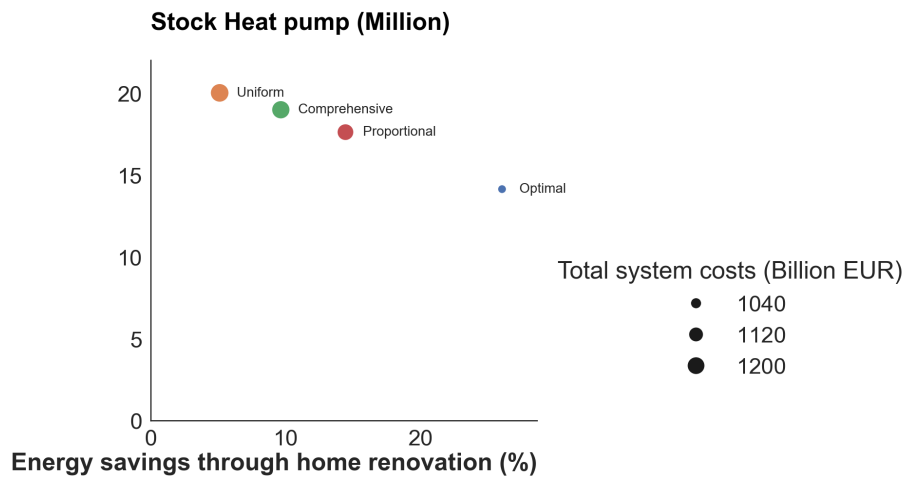


Figure S4: Evolution of demand-side strategy.

A.6 Additional figures

We display additional figures corresponding to simulations in Section 3, including evolution of subsidies (Figure S5), evolution of heat pumps stock (Figure S6), evolution of buildings stock by performance (Figure S7). We also display electricity dispatch for two representative weeks, for the ‘optimal’ scenario (Figure S8).

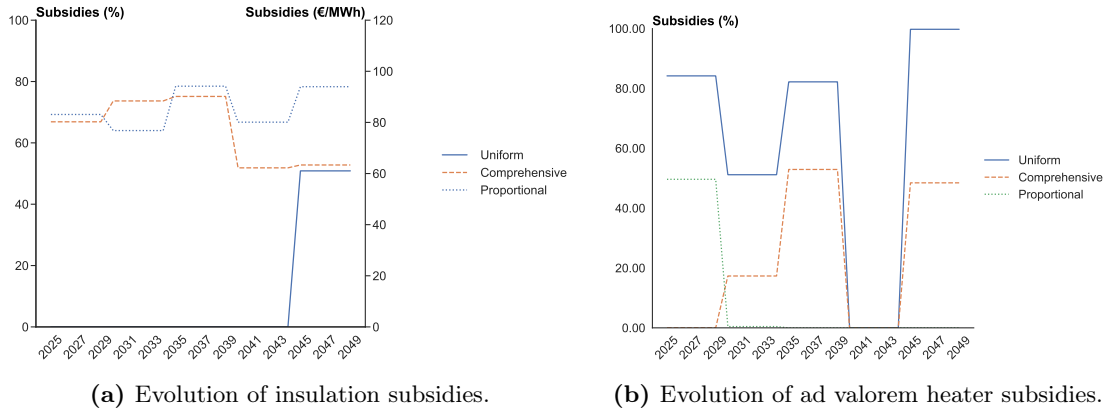


Figure S5: Evolution of subsidies for the scenarios ‘uniform’, ‘comprehensive’ and ‘proportional’. For ad valorem subsidy, the left y-axis depicts the level of the percentage of capex that is eligible for the rebate. For the ‘proportional’ insulation subsidy design, the right y-axis depicts the optimal price in €/MWh for the insulation subsidy. Similarly, heat pumps subsidies increase across all the time horizon (except for time period 2030-2035, since required investments were made during preceding time step).

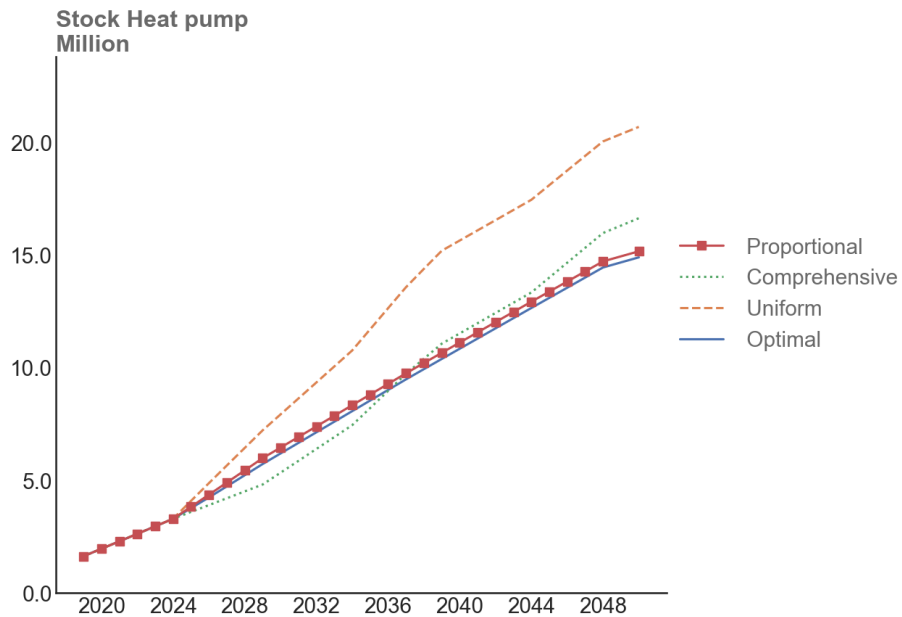


Figure S6: Development of the stock of heat pumps in all scenarios. The more the scenario relies on insulation, the fewer heat pumps are needed to meet the carbon budget. In 2050, there are between 15 and 20 billion homes equipped with heat pumps.

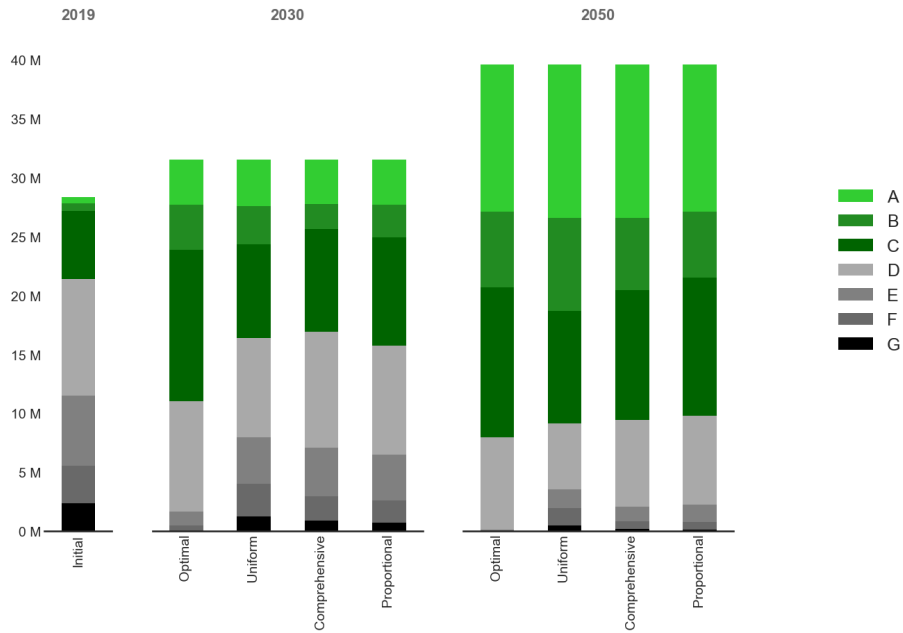
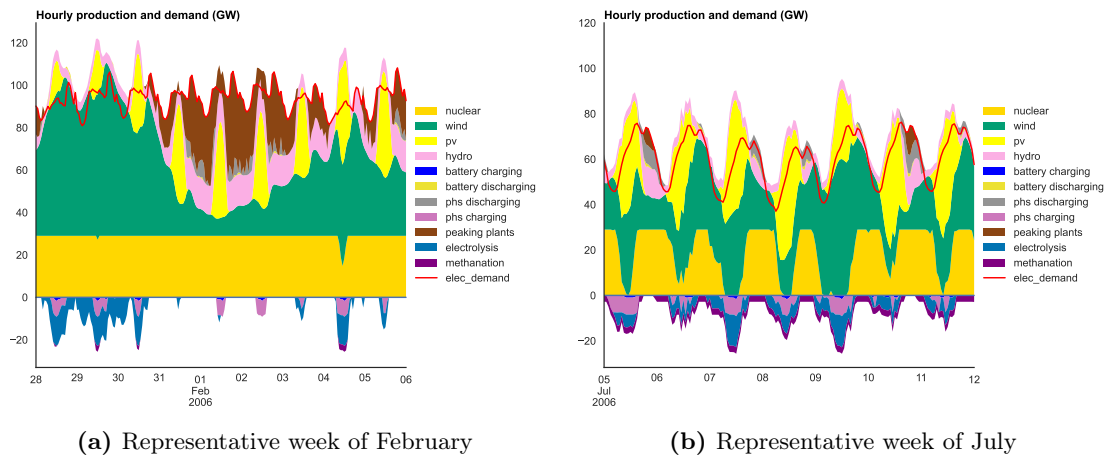


Figure S7: Development of the housing stock (millions of dwellings) according to energy performance certificates (G to A). ‘Optimal’ scenario eliminates the least efficient dwellings (G and F) by 2030, while they still exist in a ‘uniform’ scenario.



(a) Representative week of February

(b) Representative week of July

Figure S8: Hourly generation for two representative weeks in winter and summer, for the ‘optimal’ scenario. The hourly demand profile is different in February and July due to the strong seasonality of heating demand.

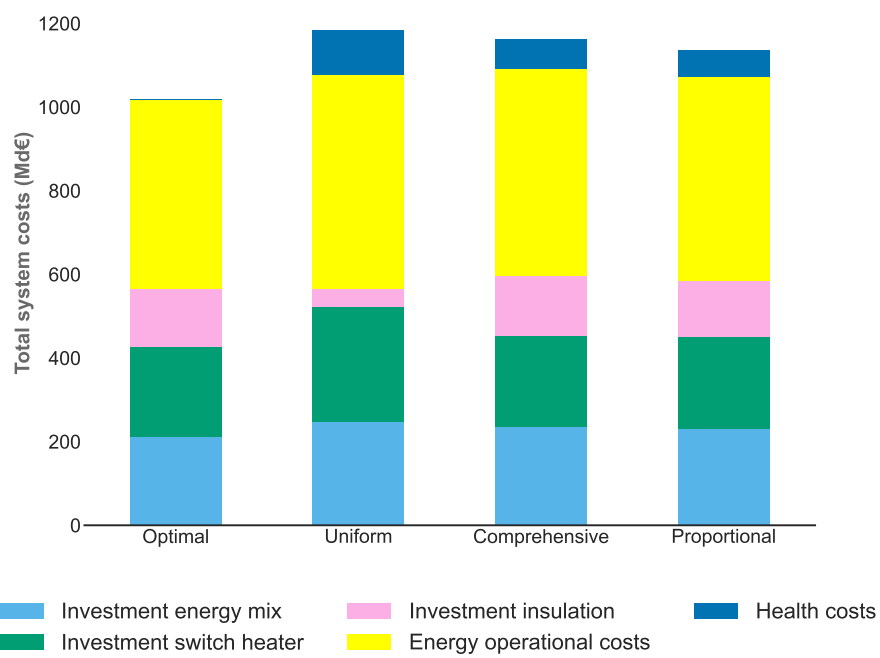


Figure S9: Breakdown of total system costs.

A.7 Implicit carbon value for scenarios in Section 3.2

Table S11 displays the implicit carbon value obtained for the different subsidy design scenarios in Section 3.2. This carbon value corresponds to the dual multiplier associated with the carbon budget constraint.

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

Table S11: Evolution of implicit carbon values in €/tCO₂ for each subsidy scenario.

A.8 Bayesian Optimization

As was emphasized in the Section 2, we use a bayesian optimization framework to find the optimal strategy of the social planner. This framework allows to find the minimum of a function without any assumptions on the function. Indeed, classical optimization algorithms rely on an analytical expression for the objective function f , and often some information on its first or second derivative. In a setting where it is only possible to evaluate the function on a given point - which is our case, due to the Res-IRF model which is a simulation model without an analytical expression - such classical optimization algorithms can no longer be used. In the case where it is cheap to evaluate the function f , one could just sample many points via grid search for example, or perform numeric gradient estimation. However, in our case, function evaluation is expensive (it takes several minutes for each time step of 5 years). In that case, it is important to minimize the number of samples drawn in order to perform the optimization. The bayesian optimization framework combines a surrogate model of the objective function (relying on gaussian processes in our case) and an acquisition function that directs sampling to areas where an improvement over the current best observation is likely. The acquisition function used in our setting is the Expected Improvement acquisition function which finds a trade-off between exploration (sampling in areas where the surrogate model is more uncertain) and exploitation (refining the value of the optimum). The problem is solved with the GpyOPT package.¹⁸

¹⁸<https://pypi.org/project/GPyOpt/>

Supplementary References

1. ADEME. *Mix de gaz 100% renouvelable en 2050 ? [A 100% renewable gas mix in 2050?]* tech. rep. (2018).
2. Ang, B. W. & Zhang, F. Q. A survey of index decomposition analysis in energy and environmental studies. *Energy* **25**, 1149–1176 (Dec. 2000).
3. Cayla, J.-M. & Osso, D. Does energy efficiency reduce inequalities? Impact of policies in residential sector on household budgets. en. *Proceedings of the ECEEE Summer Study*, 11 (2013).
4. Christensen, P., Francisco, P., Myers, E. & Souza, M. Decomposing the Wedge between Projected and Realized Returns in Energy Efficiency Programs. *The Review of Economics and Statistics*, 1–46 (Aug. 2021).
5. Effnergie & ADEME. *Les maisons renovés à basse consommation [Low-energy renovated homes]* tech. rep. (Observatoire BBC, Apr. 2021).
6. Moreau, V., Laurent, M.-H., Berthou, T. & Duplessis, B. *Household energy usage behaviour - is it mightier than energy efficiency? Accounting for the impact of behaviour diversity on household space heating hourly national power demand in ECEEE 2022 Proceedings* (2022).
7. MTE. *Le parc de logements par classe de consommation énergétique [Housing stock by energy consumption class]* fr. Sept. 2020.
8. Pfenninger, S. & Staffell, I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. en. *Energy* **114**, 1251–1265 (Nov. 2016).
9. RTE. *Futurs énergétiques 2050* fr. Tech. rep. (2022).
10. RTE & ADEME. *Réduction des émissions de CO₂, impact sur le système électrique : quelle contribution du chauffage dans les bâtiments à l'horizon 2035 ? [Reducing CO₂ emissions, impact on the electricity system: what contribution will heating make to buildings by 2035?]* tech. rep. (Dec. 2020).
11. Staffell, I., Brett, D., Brandon, N. & Hawkes, A. A review of domestic heat pumps. en. *Energy & Environmental Science* **5**, 9291 (2012).
12. Zeyen, E., Hagenmeyer, V. & Brown, T. Mitigating heat demand peaks in buildings in a highly renewable European energy system. en. *Energy* **231**, 120784 (Sept. 2021).