Is a fair energy transition possible? Evidence from the French Low-Carbon Strategy[1]

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ABSTRACT

The distributional consequences of environmental policies are a major issue for the public acceptability of energy transitions, as the Yellow-vest demonstrations highlighted. Our objective is to assess the short and mid-term distributional impacts of policy packages on firms and households – rather than of single policy instruments - including carbon taxing, technology adoption subsidies and compensating lump-sum transfers. We offer insights on the fair transition promoted by the EU Fit-for-55 proposal with a case-study on two successive versions of the French low-carbon strategy.

To that end, we develop an innovative numerical method that combines micro-simulation and macroeconomic modelling techniques. We explicitly model the heterogeneity of households' behaviour and the role of the distribution of energy-efficient durable technologies — electric vehicles, energy-efficient housing — among consumers.

Focusing technology adoptions on the largest energy consumers to maximise emission reductions reduces the discrepancy of impacts between rural and urban households. However, it aggravates the regressivity of carbon taxation if households are not rebated their carbon tax payments. Recycling schemes favouring poorer households are powerful means to offset the regressivity of carbon taxation in the short term. In parallel, policies supporting electric vehicles and thermal renovation are effective in reducing households' tax payments at further horizons.

KEYWORDS

Distributional Effects; Environmental Taxes and Subsidies; Low-carbon strategy; Macro-micro modelling

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HIGHLIGHTS

- Raising mitigation ambition from Factor-4 to Net Zero Emissions prompts increased horizontal and vertical inequalities, thus threatening social acceptability.
- Selection of the beneficiaries of thermal renovation and electric vehicle subsidies is key.
- Addressing subsidies to the largest energy consumers reduces the rural-urban divide but aggravates vertical inequalities compared to other selections.
- Lump-sum recycling ─ targeted on low-income households or not ─ benefits the poorest but leaves unchanged horizontal inequalities.
- Measures supporting thermal renovation and electric vehicles fail to make carbon taxation progressive in the absence of recycling.
- Such measures, by significantly lowering carbon tax payments after 2030 only, are complementary to recycling, which can be directed to more than compensate the carbon tax payments of 81% of households in the bottom 3 deciles in the short term (2025).

1. INTRODUCTION

According to the United Nations, “Climate Change is the defining issue of our time and we are at a defining moment” (UN website, December 2021). Without dramatic changes in trajectories, major threats to human activity are bound to concretise. In December 2019, the European Union consequently became one of the first major economies to announce net zero emissions of greenhouse gases by 2050. In July and December 2021, it released the ‘Fit for 55’ policy package aiming at this objective. The very ambition of the transformation calls for thorough assessments of both the efficiency of transition pathways — how are they going to influence aggregate economic activity and welfare? — and their equity consequences — how are their costs and benefits going to distribute across economic agents? Our paper contributes to the latter question by assessing the distributional consequences of France's 2015 and 2020 energy transition propositions up to 2035.

Assessing the distributional impacts of climate policies has been a topic of academic interest for several years (Baumol et al., 1988; Ekins and Speck, 2011; Fleurbaey et al., 2014; Lamb et al., 2020). It has become clear that the political acceptability of environmental reforms is closely linked to fairness, whether perceived or real (Büchs et al., 2011; Maestre-Andrés et al., 2019). The Yellow vest movement in France has demonstrated how the perception of carbon taxes as unfair (Douenne and Fabre, 2020) can sparkle severe popular unrest.

Recent literature draws mixed conclusions about the regressivity of carbon taxes and other environmental policies (Dorband et al., 2019; Ohlendorf et al., 2020; Wang et al., 2016).[2] In the case of France, Italy and (to a lesser extent) Germany, a carbon tax on direct emissions would be slightly regressive relative to expenditures, but not in the case of other countries (Feindt et al., 2021; Symons et al., 2002). Berry (2019) and Douenne (2020) show that the carbon component of excise taxes on fossil fuel consumptions in France is regressive on all income deciles when measured against income. Känzig (2021) concludes from UK data and EU ETS shocks that carbon pricing is both efficient at cutting emissions and highly regressive, whether measured against income or against expenditures. A carbon tax on the full carbon footprint of households tends to be neutral relative to total consumption for European countries individually but regressive at the aggregate European level (Feindt et al., 2021). Indeed, the total carbon footprint of households tends to be proportional to expenditures, but the contribution of energy and individual transport consumptions to the carbon footprint decreases with income in developed countries (Isaksen and Narbel, 2017; Pottier et al., 2020).

Despite their contrasted findings on the partial or total regressivity of environmental policies, the above studies and several others (Carattini et al., 2019; Combet et al., 2009; Ekins and Dresner, 2004; Fremstad and Paul, 2019; Metcalf, 2019; Metcalf et al., 2010) conclude that recycling carbon tax revenues toward households can counter the regressivity of the carbon tax and can therefore increase social acceptability. Moreover, recycling can be complemented with subsidies (Baranzini et al., 2017), whose non-coercive ‘pull’ nature has higher public support (Drews and Bergh, 2016). In fact, most national low-carbon strategies consider the simultaneous implementation of several tools — taxes, subsidies, norms, regulations, etc. — whose distributional effects may amplify or offset each other (Fullerton, 2011; Vona, 2021). However, the distributive effects of such policy packages are little researched so far (Lamb et al., 2020). To the best of our knowledge, Bourgeois et al. (2021) and Giraudet et al. (2021) provide the only analyses of the cross-impacts of a carbon tax, support measures for energy efficiency technology and carbon tax recycling in a static partial-equilibrium framework.

By comparison, the contribution of our work lies in the comprehensive analysis of the distributive impacts, both vertical (across income classes) and horizontal (following other non-income dimensions), of low-carbon policy packages in a dynamic, general-equilibrium framework. To do so, we implement an original ‘macro-micro’ methodology, whose microsimulation component improves on current tools of distributive assessment of transition

[2] Following the literature, we define a carbon tax as regressive when the ratio of carbon tax payments to income or expenditures is larger for poorer households than for richer ones. See section 4.2 for more discussion on the issue of measurement against income or expenditures.

packages by (1) resting on long-term elasticities differentiated for 40 classes of households and 14 goods and services, to forecast household consumption patterns following price and income evolutions (2) modelling explicitly technical change brought by the adoption of electric vehicles and the massive thermal renovation of dwellings, which escape historical trends, and (3) providing dynamic outlooks at 2025, 2030 and 2035 temporal horizons.

Our case study bears on two successive versions of the French Low-Carbon Strategy (SNBC in its French acronym), whose level of ambition has been raised from the 'Factor 4' objective of a cut of 75% of 1990 emissions (SNBC 1, 2015) to the carbon neutrality of 'net zero emissions' (SNBC 2, 2020) by 2050. The two packages are meant as part of a coordinated global effort to limit global warming to 2°C and 1.5°C, respectively. They include carbon tax trajectories, recycling options, energy mix prescriptions, housing renovation subsidies, bonus-malus schemes for conventional and electric vehicles and various measures additionally targeting emissions in all activity sectors. Our method of analysis rests on the iterative linkage between micro-simulation on a 10,000-household database and macroeconomic modelling of the aggregate economy. Our macroeconomic modelling calibrates on input-output tables from the official macroeconomic evaluation of the two policy packages.

The rest of our paper organises as follows. In Section 2, we describe the three main drivers of the distributional impacts of carbon-control policies. In Section 3, we present the original numerical tool that we built to address the blueprint emerging from Section 2. In Section 4, we present modelling results, successively considering a brief overview of the macroscopic impacts of disaggregating households when assessing low-carbon strategies (4.1); the distributional impacts of low-carbon transition without carbon payments recycling (section 4.2); a focus on the role of housing energy efficiency and electric vehicles subsidies (section 4.3); and the complementarity of subsidies and lump-sum recycling of carbon payments (section 4.4). We summarise our results in Section 5.

2. DRIVERS OF THE DISTRIBUTIONAL IMPACTS OF CLIMATE POLICIES

We focus this section on three main determinants of the distributive effects of climate policies, which frame our methodological choices and differentiate our analysis from the literature: the heterogeneity of household behaviour, the macro-economic feedback effects and the penetration of energy-efficient technologies in households. We refer to the literature for more detail on additional drivers (Ghersi, 2014; Ohlendorf et al., 2020; Stiglitz, 2019; Wang et al., 2016). Due to lack of data, we do not take into account the heterogeneous effects of environmental policies on total employment (Ekins et al., 2011; Fullerton and Heutel, 2007) and employment of more or less skilled workers by sector (Marin and Vona, 2019; Vona, 2021). We also focus our analysis on carbon emissions and do not consider health and environmental quality incidences and benefits that can arise from the considered policies (Drupp et al., 2021).

2.1. Heterogeneity of the adaptive behaviour of households

Lower income classes have more carbon-intensive consumptions and dedicate larger income shares to energy expenses, which makes carbon taxes regressive across income classes (Cronin et al., 2019; Flues and Thomas, 2015; Pizer and Sexton, 2019). However, many factors largely independent from income shape the energy consumptions of households, hence their sensitivity to carbon-control policies, from housing characteristics (insulation, size, individual or collective) to geography (density, climate of residence area) to socio-economic variables (household composition, occupational status of household members) (Büchs and Schnepf, 2013; Douenne, 2020; Poterba, 1991). Typically, carbon taxes weigh more on the budgets of rural households living in poorly insulated individual houses and heavily dependent on personal car use irrespective of their wealth (Büchs et al., 2011). 'Horizontal' inequalities among households of the same income class may, in fact, be as large as 'vertical' inequalities across income-class averages (Cronin et al., 2019; Ekins and Dresner, 2004).

Both vertical and horizontal inequalities affect households' behavioural responses to price signals; they vary according to their adaptation or deprivation capacities. Douenne (2020), for instance, estimates the price and income elasticities of 3 goods (transport fuels, residential energy consumptions and non-energy goods) for 50 categories of French households defined by two criteria: income (10) and size of urban unit of residence (5). Nadaud (2021a) refines the method by calculating the long-term and income elasticities of 14 goods and services, including 4 energy goods, proving that low-income households have higher fuel price elasticities than richer ones, but that rural households tend to be more fuel dependent and have lower price elasticities. Accounting for households' behaviour on larger numbers of goods allows pinpointing direct and indirect carbon tax payments and ‘rebound effects’ from energy savings or compensation payments. More aggregated approaches, e.g. that of Douenne (2020), or partial equilibrium approaches, only present fragmented views of the impacts of carbon taxes. Typically, thermal renovations reduce heating consumption and thus free up income, which households can partially use to increase energy consumption again.

2.2. Policy signals and their propagations in the economic system

Carbon-control policies affect households through three distinct channels. The first is the direct effect of policies on the prices and availability of energy and energy-consuming equipment — “use-side” impacts.[3] The second channel is the set of indirect effects of price and non-price measures on the production costs of firms. Cost shifts loop from firm to firm via the input-output structure of inter-sectoral exchanges. They end up modifying the relative prices of consumer goods and services. The third channel of impact is the set of feedbacks from all markets incurring price shifts. The relative price variations from the first and second channels retroact on the consumers’ and the producers' consumption and input choices. Hence, on factor demands and payments, and finally on households’ income. These "resource-side" impacts can offset the carbon tax regressivity as social benefits rise and carbon-intensive sectors — which often are capital-intensive as well — shrink (Goulder et al., 2019; Rausch et al., 2011).

Despite their sequential presentation, the three channels occur simultaneously. This interdependency requires considering them in one unified computational framework where their interactions play up to some equilibrium. Cockburn et al. (2014) review modelling efforts to integrate the heterogeneity of microeconomic models into macroeconomic frameworks. We stress here the most important references for our model. Chen and Ravaillon (2004) were among the firsts to develop one-way linkage from macroeconomic modelling to microsimulation. Rausch et al. (2011) refined the method by directly integrating 15,000 households into their macroeconomic model to compute feedback effects. Their fully integrated approach is the theoretically soundest (Bourguignon et al., 2008) but requires simplifying households’ reaction functions to ensure consistency with macroeconomic modelling (Bourguignon and Savard, 2008). A simpler approach consists of an iterative exchange of data between macroeconomic modelling and micro-simulation. Buddelmeyer et al. (2012) and Vandyck and Van Regemorter (2014) perform such ‘soft-linking’ by adjusting the representativeness weights of survey households (see section 3.4), but do not consider retroactions from microsimulation to macroeconomic modelling.

2.3. Penetration of electric vehicles and renovation technologies

Estimating the adaptive behaviour of households conventionally rests on econometric analysis linking past consumer choices to past price and income variations. However, such statistics only describe the trends of evolution of households’ preferences and cannot convey any information on the consequences of disruptive

[3] In the case of the second SNBC (SNBC 2), this channel covers the impact of the carbon tax on the prices of natural gas and petroleum products; of the bonus/malus provision on the prices of private vehicles; and of subsidies on the investment costs of housing insulation, space-heating and water-heating equipment.

technological changes. Ambitious climate policies as the French SNBC envision two such changes: the electrification of personal cars and the dramatic increase of the thermal efficiency of buildings.

The electric vehicle technology is only gradually reaching maturity, as ranges catch up on those of conventional alternatives while prices decrease. Consequently, the income and price elasticities of vehicle fuels and electricity consumptions of past decades cannot be related by the direct substitution possibility that electric mobility only begins to embody. The case of thermal efficiency gains, which originate in the oil shocks of the 1970s, is rather of quantitative nature: the obligation of renovation at any change of occupancy, the ambition of renovations and the commitment to renovate all public-owned buildings (17% of the current housing stock in France) at unprecedented rate mark a change of regime. Accounting for these two technical disruptions requires extending numerical methods beyond econometric analysis.

Both technologies have significant distributional consequences. For example, the least energy-efficient dwellings are inhabited by poorer-than-average households, who are therefore more affected by renovation policies. Conversely, the largest consumers of vehicle fuels are rural and wealthy households, who will therefore benefit more from electric vehicle subsidies.

3. COMPUTATIONAL METHOD

The previous section provides the blueprint of our methodology. To consider the heterogeneity of households, like a growing number of studies, we rely on microsimulation, which we operate on a database of more than 10,000 households. To capture feedback effects from the economic system, we additionally mobilise macroeconomic modelling, which we combine with microsimulation through the iterative exchange of linking variables rather than one-way coupling only. Lastly, our microsimulation originally extends to the explicit modelling of electric vehicle adoption and thermal renovation consequences.

3.1. Data and scenario description

We use microeconomic data from the latest French consumer expenditure survey, *Budget des Familles* (BDF), performed in 2010-2011 by the French statistical agency INSEE. The database provides the exhaustive breakdown of income sources and expenditures of more than 15,000 French households characterised by hundreds of demographic, geographic and socio-economic series. Out of this set, we focus our analyses on the slightly more than 10,000 households of metropolitan France. We use several series of variables matched to BDF from other databases to expand BDF to physical energy consumptions and the energy performance diagnosis (EPD) of dwellings.[4]

Our macroeconomic data is not the usual Input-Output table for some statistical year. Rather, we calibrate on outlooks from the official macro-modelling of low carbon strategies by the French Agency for Ecological Transition (ADEME) using the ThreeME model (Callonnec et al., 2016, 2013). These ‘SNBC input-output tables’ are specific to each scenario and time horizon. Our macroeconomic model calibrates on them and performs comparative statics analysis while embarking aggregate household behaviour explicitly addressing dynamic adjustments from calibration year (the year of the BDF household survey) to time horizon.

We study two carbon control scenarios at three forecast horizons 2025, 2030 and 2035. The ‘Factor 4’ (F4) scenario, which corresponds to the 2015 version of the SNBC, aims at bringing net French emissions at 25% their 1990 level in 2050. The ‘Net Zero Emissions’ (NZE) scenario, which corresponds to the updated 2020 SNBC,

[4] See De Lauretis (2017) and Douenne (2017) for more detail.

targets 2050 carbon-neutrality. We derive three extra scenarios from NZE, where we contain respectively the carbon tax, thermal renovation subsidies and vehicle bonuses-maluses to their levels in the F4 scenario.[5]

In 2010, the starting point of our analysis for both scenarios, no carbon price for either firms or households was in place in France. The distributional impacts that we analyse are therefore entirely related to the measures put in place between 2010 and 2035 (Table 1). However, it should be noted that specific taxes on fuels have been in place for almost a century in France. The evolution of fuel taxes excluding carbon pricing is common to both the F4 and NZE scenarios. The carbon tax comes on top of these excise fuel taxes and exacerbates the distributive impacts of heterogeneous fuel consumptions.

Table 1: Main elements of Factor 4 and Net Zero Emissions policy packages

	Factor Four (F4)	Net Zero Emissions (NZE)
Carbon tax in 2035 (€ 2019)	€26.8/tCO_2	€246/tCO_2
Housing Renovation		
Thermal renovation (2010-2035)	500 million m^2	1 billion m^2
Renovations per year	220,000 dwellings	700,000 dwellings
Subsidies to renovation	-	11.5% of cost
Subsidies (2010-2035, € 2019)	€7 billion	€15 billion
New Buildings		
New efficient building	20.0 million m^2	19.5 million m^2
		Energy self-sufficiency from 2020 on
Electric Vehicles (EV)		
Share of car sales in 2035	24%	49%
2035 Bonus (€ 2019)	€0 /EV	€4400/EV

Source: French Agency for Ecological Transition (ADEME), and Ministry for Ecological and Inclusive Transition (MTES).[6]
See appendix C for details.

The SNBC assumes recycling of their carbon tax payments to firms and households but does not pinpoint any distribution scheme. We first explore distributional consequences in the absence of recycling (to both firms and households), then test several rebating schemes to households under the shared assumption that firms' payments are rebated as output tax credits.

To summarise, for all scenarios and at each time horizon we use official SNBC data from ADEME regarding: 24-good input-output tables at horizon; yearly level of carbon tax up to horizon; yearly volume (m^2) of housing in each energy performance diagnosis (EPD) class from A to G, up to horizon; yearly volumes of thermal renovation for each EPD transition with renovation cost per square meter and mean energy gain, up to horizon; yearly composition of vehicle fleet per fuel (conventional versus electric) up to horizon; fuel-efficiency gains of conventional vehicles, up to horizon; yearly malus-bonus per type of vehicle purchase.

[5] See Appendix C for the full descriptive of our scenarios.

[6] https://www.ecologie.gouv.fr/sites/default/files/2020-03-25_MTES_SNBC2.pdf

3.2. The IMACLIM-3ME model

Our macroeconomic model is an adaptation of the static version of the IMACLIM[7] model developed at CIRED since the 1990s (Ghersi, 2015), which is specified to approach the behaviour of the ThreeME macroeconomic model used by ADEME to produce official SNBC estimations up to 2050 (Callonnec et al., 2016, 2013). The specifications retained after ThreeME concern macroeconomic assumptions, microeconomic behaviour, and a set of accounting rules on how the secondary distribution of income affects households' gross disposable income. We only detail these adjustments here and refer to Ghersi (2020) for exhaustive algebraic equations.

We implement macroeconomic analysis in a 'comparative static' framework by operating IMACLIM-3ME independently at our three forecast horizons and for each scenario explored. Our numerical procedure gradually distorts the initial SNBC input-output tables to reflect the iterated response of our micro-simulation of households' behaviour.

Regarding macroeconomics, IMACLIM-3ME is of demand-driven neo-Keynesian inspiration. It endogenises the stock of capital and indexes its rental price on the producer price of investment goods, thereby implicitly assuming constant interest rates. It also models unemployment equilibrium through a 'wage curve' (Blanchflower and Oswald, 2005). Closure is on imported savings through adjustment of the real effective exchange rate under the constraint of investment demand proportional to the capital demand of sectors, and domestic savings proceeding from households' behaviour (see below) and endogenous public deficit. The latter deficit results from constant taxes and excise duties applying to endogenous expenses, versus horizon-specific but scenario-independent real public expenditures.[8]

Concerning microeconomics, IMACLIM-3ME only represents the substitutability of capital and labour in production, that of imports and domestic products in supplies, and the implicit trade-off between French and foreign productions on international markets. All specifications reflect those of the Three-ME model of ADEME at the source of official SNBC outlooks, and replicate their elasticities of substitution.

3.3. Micro-simulation in the *Budget de Famille* household survey

We perform survey-based micro-simulation to aggregate households' behaviour with respect to relative price and income sources forecasts from the macroeconomic model. To this end, we developed the MATISSE model — Microsimulation Assessment within the low-carbon Transition of Inequalities and Sustainable Systems of Energy. MATISSE develops three steps of microsimulation and two steps of linkage to IMACLIM-3ME (Figure 1).

Step 1 consists in projecting the disposable incomes of BDF households to explored horizons (2025, 2030 or 2035). Macroeconomic analysis by IMACLIM-3ME — initially calibrated on official SNBC outlooks by ADEME — allows computing the increases, from 2010 on, of eight components of aggregate disposable income: domestic wages and benefits from self-employed activity, capital income, unemployment benefits, other social benefits including pensions, repatriated wages, international remittances, and on the side of expenses income taxes and other direct taxes.[9] We adjust homothetically the corresponding disposable income items of all households of

[7] See http://www.centre-cired.fr/en/imaclim-network-en/.

[8] The assumption of constant public expenditures at any given horizon reflects their indexation on (exogenous) potential growth in official SNBC outlooks.

[9] Due to well-known issues with matching data from consumer surveys and national accounts (André et al., 2016; Rausch et al., 2011), the information on income-source variations passing from macroeconomic modelling to microsimulation households is in the form of relative evolutions rather than absolute numbers. The downward link from macroeconomic modelling to microsimulation is thus performed with 8 increase factors for income sources, 14 increase factors for prices and 2 increase factors for tax rates.

our microeconomic database. The total disposable income of each household therefore increases depending on its initial structure.

Step 2 of the micro-simulation consists in households adapting their consumption choices to their projected disposable incomes and the macroeconomic evolution of the relative prices of 14 consumption goods and services: food, electricity, gas (natural and biogas), other residential energy, construction and construction services, first-hand vehicles, vehicle fuels and lubricants, rail and air transport, road and water transport, leisure services, other services, other consumption/equipment goods, housing rents, second-hand vehicles. [10] We use disaggregated long-term price and income elasticities estimated by Nadaud (2021a) on 40 classes of households. Nadaud's study is the most comprehensive and detailed on French consumers, building on 7 consecutive surveys from 1979 to 2010. The 40 classes correspond to the crossing of ten income deciles[11] and four categories of economic vulnerability grouping households with statistically similar pre-committed expenses (see Nadaud (2021b)). The 40 classes of behaviour and the individualisation of income growth allow strong differentiation of households' consumption dynamics.

For each household, the update of good i expenditures from E_i^0 (2010) to E_i^1 (projection horizon) is summarised by the following equation (Equation 1), with $e_{E_iP_i}$ the elasticity of expenses to price P_i; e_{E_iX} the elasticity of consumption to income X; and P^* the Stone price index computed for each household[12] to deflate current prices, as price elasticities are calibrated on 2010 constant prices.

$$E_i^1 = E_i^0 \times \left(1 + e_{E_iP_i}\right) \cdot \left(\frac{P_i^1 - P_i^0}{P_i^0} \cdot \frac{1}{P^*} - 1\right) \times \left(1 + e_{E_iX}\right) \cdot \frac{X^1 - X^0}{X^0} \times \frac{P_i^1 - P_i^0}{P_i^0} \quad (1)$$

The price and income elasticities calculated with such Engel curves warrant close-to constant savings rates. However, to avoid double counting of rebound effects on residential consumptions following thermal renovations, we introduce slight variations of the saving rate (see below).

Step 3 of our microsimulation is the original methodological contribution of representing explicitly the gradual penetration of disruptive technical progress, namely the massive thermal renovation of dwellings and electrification of personal vehicles. We model these penetrations in the database as the distribution of volumes of energy-efficient investments over subsets of households summing up to the aggregated SNBC target for the particular technology adoption. We modify the budget of each household in the subsets in response to these investments in new equipment: reduction in energy/fuel consumption, investment in new vehicle/renovation, interest payments on loans backing such investment, electricity expenses of electric vehicles and allocation of induced savings. We distinguish between investments made at projection horizons, whose effects are directly visible in projected budgets, and investments made between 2010 and projected horizons, of which only the induced perennial savings and expenses are visible in budgets at the horizons.[13] We also consider trends of efficiency gains of conventional vehicles between 2010 and the horizon, as well as a homogeneous decrease of vehicle fuel consumptions from increased working from home.

[10] Price evolutions are computed for the 24 goods and services of IMACLIM-3ME then mapped to the 14 goods and services of the microsimulation. The two nomenclatures are compatible enough for the mapping to be straightforward. The latter one results from a compromise between econometric relevance and explicit coverage of the main patterns of energy-intensive lifestyles. Nadaud (2021a) provides its correspondence with level 5 of the Classification of individual consumption by purpose (COICOP) nomenclature.

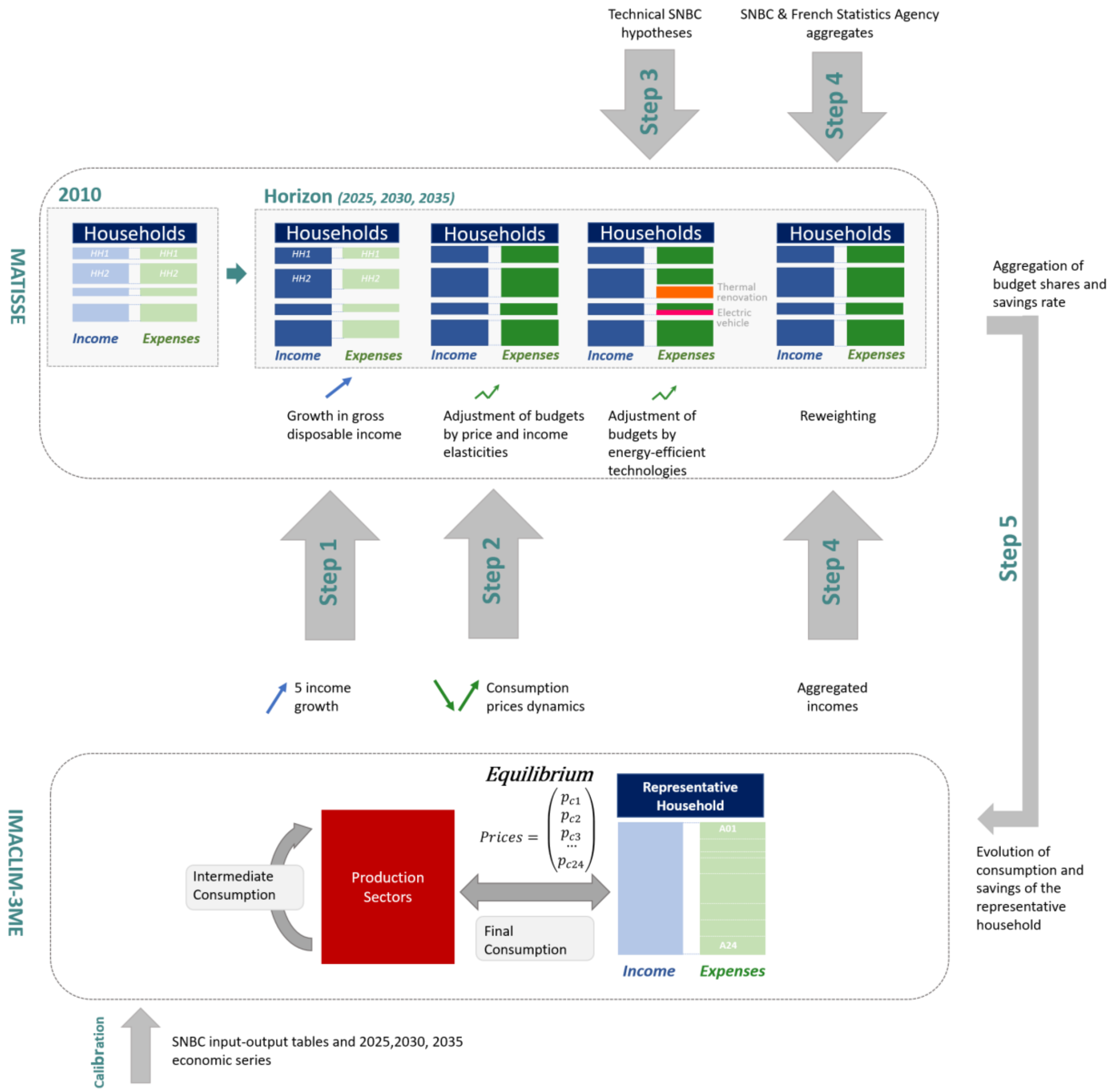
[11] By income decile we mean, here and hereafter, living-standard decile with living standard measured as income per consumption unit. The number of consumption units per household is 1 for the person of reference + 0.5 per individual 14 and above + 0.3 per individual below 14.

[12] The Stone Price index P^* of each cell is $ln(P^*) = \sum_{(i=1)}^{14} w_i \ln(P_i)$ with w_i the budget share of item i in the cell and P_i the price index of item i (Green and Alston, 1990). Microsimulation means that the structure of expenditures of each household is likely to evolve. We iterate microsimulation to ensure full consistency of Eq (1) and the resulting Stone price index.

[13] See Appendix E for detail.

Importantly, the subsets of households shifting to electric vehicles and moving from lower to higher EPD classes (the latter being specified for each possible class move) must be defined annually from 2010 to projected horizons. There are multiple possible criteria to do so, each of them with implementation issues. Typically, the economically efficient option of ordering technology shifts by net current value is hard to relate to plausible implementation policies.[14] We rather chose to frame the overall energy efficiency of the SNBC by exploring three variants of selection based on households' absolute energy consumptions. The 'maximum energy savings' variant selects each year, and for each technology shift, those households with the highest total energy consumptions. The 'median' and 'minimum' variants rather select households with median and lowest energy consumptions. Modelling such variants allows assessing the sensitivity of results to the allocation of technology incentives, and the extent to which energy savings computed on national averages hold when micro-simulated.

Figure 1: Computational method



Source: Authors.

[14] The costs of technical shifts to more efficient dwellings and electric vehicles are inputs from the official SNBC, which we apply to each selected household in proportion to housing surface and vehicle investment costs. There is therefore no a priori on the negative or positive sign of the net present value of forced shifts.

3.4. 'Macro-micro' linkage of IMACLIM-3ME and MATISSE

Step 4 of our methodology (see Figure 1) is the adjustment of the representativeness weights of households of the microeconomic database, or 'reweighting', to ensure consistency with macroscopic variables beyond those linking to IMACLIM-3ME. Challenges and current trends in macro-micro modelling are described in Bourguignon and Savard (2008) and Cockburn (2014). We follow the method introduced by Deville and Särndal (1992) and recently applied by Agénor et al. (2004), Buddelmeyer et al. (2012), Vandyck and Van Regemorter (2014) or De Lauretis (2017). We reweight under the maintained constraints of reproducing aggregate IMACLIM-3ME evolutions of total labour income, unemployment benefits, other social benefits (including pensions), capital income, the aggregate income tax, aggregate other direct tax. We expand to additional constraints concerning (1) demographic evolutions (total population, gender and age groups, active population) projected by INSEE as well as unemployment shifts computed by IMACLIM-3ME.[15] (2) Several sets of national totals maintained at survey values (shares of households' composition types, shares of collective versus individual housing, survey collect waves, distribution of households across regions and sizes of urban units). And (3) technology penetration (total housing surface by EPD class, the private vehicle fleet and the share of electric vehicles therein, the sales of thermal and electric vehicles). Among the infinite number of fitting weight adjustments, we choose the adjustment that minimises quadratic deviation from the original set of weights (Agénor et al., 2004).

Step 5 is the aggregation of microsimulation results, feedback to IMACLIM-3ME and simulation update. The 'upward' link from MATISSE to IMACLIM-3ME is embodied in four increase factors (2010 to projection horizon) of absolute energy consumptions (oil and oil products, natural gas, coal and electricity), the remaining aggregated macroeconomic consumption shares and the aggregate saving rate.[16]

We iterate this 5-step procedure using the updated income and relative-price variations of Step 5 as a new starting point of Step 1. We stop the iteration when Step-5 information has converged below a 10^{-5} tolerance threshold, i.e. has not deviated by more than 0.001% from previous iteration. Convergence warrants consistency of the microsimulation and macroeconomic modelling of our exploration.

4. MODELLING RESULTS

We start the review of our converged macro-micro modelling results by the benchmark policy case of no recycling of either the F4 or NZE carbon tax payments (sections 4.1, 4.2 and 4.3 with the exceptions of Tables 2 and 3). We first investigate the macroscopic effects of microsimulation results and hypotheses (section 4.1), then compare the distributional impacts of F4 and NZE (section 4.2) and the particular role of electric vehicle and thermal renovation support on inequality and carbon tax payment dynamics (section 4.3). We then extend the exploration to rebating options of the carbon tax payments (section 4.4).

4.1. Which households renovate and purchase electric vehicles strongly influences carbon emissions reductions

NZE additional investments into low-carbon options have a multiplier effect on activity that more than compensates the increased costs of energy services due to higher carbon prices. Indeed, NZE scores better than F4 in terms of GDP, unemployment rates and households' consumption at all projection horizons including 2035

[15] Hérault (2010) checks the robustness of the reweighting approach compared to a behavioural model for employment and proves it to be a good approximation for distributional impacts.

[16] The R code of MATISSE is fully open source, available at https://github.com/eravigne/matisse.

(Table 2). This directly reflects the demand-driven structure of IMACLIM-3ME (see Section 3.2).[17] The three variants of distribution among households of electric vehicle and dwelling renovations impact macroeconomic results through feedback effects: induced energy savings are only partially offset by rebounds of consumption and households reallocate the net benefit between non-energy spending and savings (see section 3.3). Increased household savings reduce the national debt and improve the trade balance at the cost of a slight slowdown of activity.

Table 2: Evolution of macroeconomic indicators from 2010 to 2035

F4 Scenario	SNBC evaluation	Maximum energy savings	Median energy savings	Minimum energy savings
Real GDP	+45.2%	+43.6%	+43.6%	+43.2%
Unemployment rate	+0.9 pts	+1.7 pts	+1.7 pts	+2.0 pts
Trade Balance / GDP	-1.6 pts	-1.4 pts	-1.4 pts	-1.4 pts
Real Disposable Income	+42.7%	+41.5%	+41.4%	+41.0%
Saving Rate	id.	+1.4 pts	+1.3 pts	+1.7 pts
Real Consumption	+43.8%	+40.6%	+40.6%	+39.6%
NZE Scenario	SNBC evaluation	Maximum energy savings	Median energy savings	Minimum energy savings
Real GDP	+49.9%	+47.4%	+47.1%	+47.1%
Unemployment rate	-0.9 pts	+0.3 pts	+0.6 pts	+0.7 pts
Trade Balance / GDP	-1.7 pts	-1.0 pts	-0.8 pts	-0.8 pts
Real Disposable Income	+48.3%	+46.4%	+46.1%	+46.1%
Saving Rate	id.	+2.9 pts	+3.4 pts	+3.5 pts
Real Consumption	+51.2%	+44.9%	+43.8%	+43.7%

Source: Authors' calculations. Real changes are current-price changes corrected by specific deflators. Columns correspond to the official SNBC evaluation by the ThreeME model of ADEME (column 2) and the variants focusing electric vehicle and efficient dwelling adoptions on largest, median and smallest energy consumers (columns 3 to 5). Carbon tax payments of households are rebated in proportion of income per consumption unit (see footnote 11).

The growth of real disposable income aggregates that of the different income sources of households (Table 3), whose contrasted evolutions impact income inequality. The real income gap from F4 to NZE is driven by rising capital income, at the benefit of capital owners i.e. the richer households.[18] This inequality trend is aggravated by the slight drop of social benefits, which represent 53% of income of the lower three deciles (D1-D3) against 24% for the higher three (D8-D10). The three variants of energy savings distribution marginally modify macroeconomic conditions, leading to differentiated income growth (Table 3).

[17] Macroeconomic studies in neoclassical frameworks condition such 'double dividend' (increased welfare or economic activity alongside decreased emissions) to the recycling of carbon tax proceeds into the reduction of pre-existing distortive taxations (Ekins et al., 2012; Goulder et al., 1999; Parry, 1995).

[18] Influence of the higher growth of capital income on income distribution in household surveys is limited by the under-reporting of income from capital and exceptional income common to all surveys (van Ruijven et al., 2015).

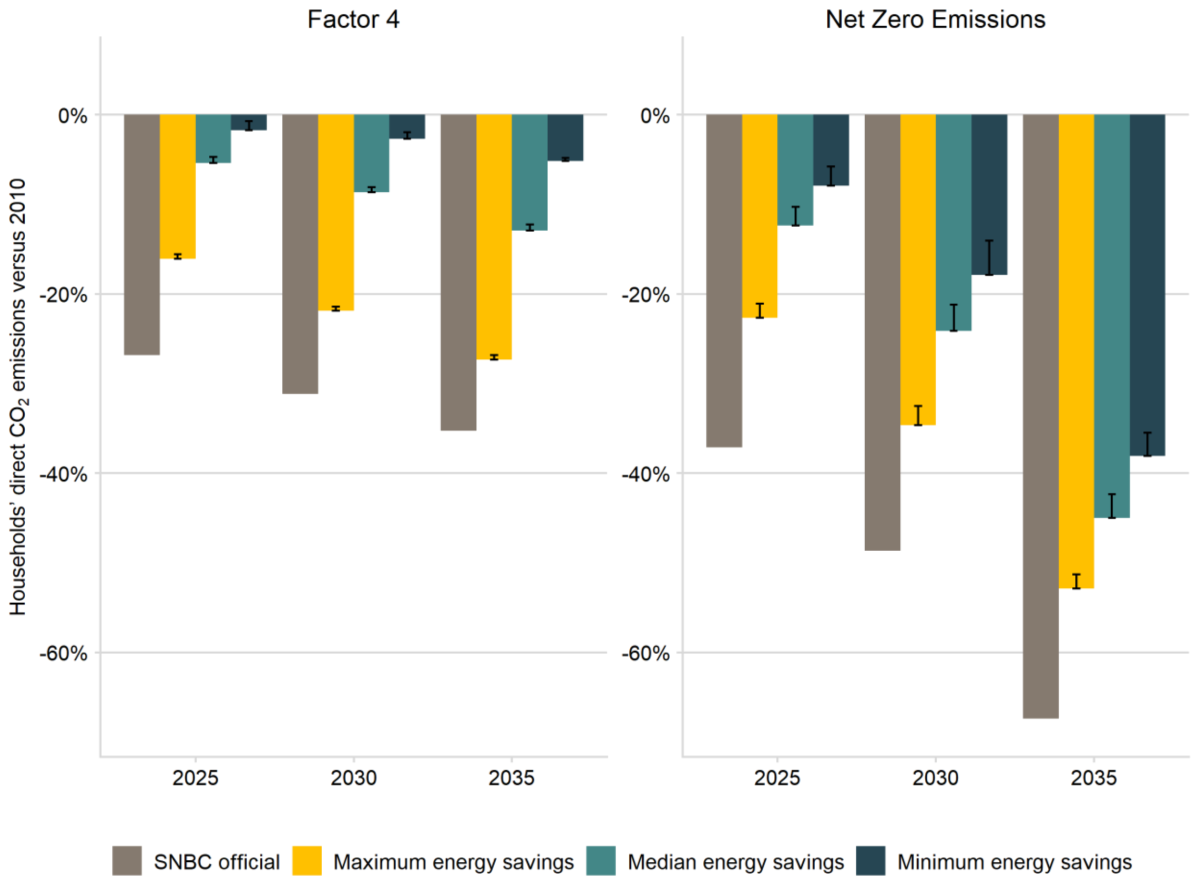
Table 3: Evolution of disposable income components from 2010 to 2035

F4 Scenario	SNBC evaluation	Maximum energy savings	Median energy savings	Minimum energy savings
Wages	+42.2%	+41.6%	+41.3%	+40.9%
Capital income	+53.8%	+51.9%	+51.5%	+50.7%
Unemployment Benefits	+42.1%	+41.3%	+41.0%	+40.5%
Other Social Benefits	+49.5%	+49.1%	+48.8%	+48.5%
Foreign transfers	+53.4%	+55.9%	+56.2%	+57.2%
NZE Scenario	SNBC evaluation	Maximum energy savings	Median energy savings	Minimum energy savings
Wages	+45.4%	+44.0%	+43.3%	+42.9%
Capital income	+60.0%	+57.0%	+56.0%	+55.5%
Unemployment Benefits	+45.3%	+43.7%	+43.0%	+42.6%
Other Social Benefits	+49.0%	+48.3%	+47.8%	+47.5%
Foreign transfers	+37.4%	+42.1%	+43.0%	+43.4%

Source: Authors' calculation. Variations are from 2010 to 2035 on aggregate volumes of income (and not per capita) to be consistent with the growth of Real Disposable Income in Table 2. Carbon tax payments of households are rebated in proportion of income per consumption unit (see footnote 11).

Results on households' direct carbon emissions highlight strong decoupling with income. Macro-micro simulation, however, re-evaluates upwards the emission trajectories of official SNBC forecasts (Figure 2). Depending on energy savings variants, it computes households' direct emissions 37.3% to 52.6% below 2010 emissions in 2035 for the NZE scenario. In comparison, the SNBC trajectory forecasts a 68% decrease. Even the maximum energy savings variant leads to a delay of 3 to 4 years in emission reductions that France would need to catch up during the 15 years separating 2035 from the 2050 carbon neutrality horizon. The higher emissions are despite the lower projected activity levels (Table 2). Analysis reveals that the resulting gap is partly caused by overestimated average energy savings in SNBC and partly by lower price and higher income elasticities in our microsimulation than in official forecasts.

Figure 2: Evolution of households' direct CO_2 emissions



Source: Authors' calculations. The intervals indicated for all results except the official SNBC correspond to the emission reduction intervals obtained for five recycling options (see section 4.4). The central option is that of the absence of recycling. Households' direct CO_2 emissions are those from direct fuel consumptions for both residential and mobility purposes.

Lastly, we test the marginal influences of carbon taxation, EV bonuses and thermal renovation subsidies by removing them from the otherwise full NZE package — keeping them at F4 levels. This allows revealing that the 25-point additional reduction in households' 2035 direct CO_2 emissions between NZE and F4 — under maximum energy savings — is more than half due to the carbon tax increase, 25% due to additional EV bonuses and only 1% due to thermal renovation subsidies.[19] We stress that this is not a direct measure of EV and thermal renovation efficiency to decrease CO_2 emissions but the marginal impacts of the subsidies. The increase of support measures to electric vehicle adoption and thermal renovation has less impact on households' emissions — reduction of 6 points by 2035 — than the targeting of technology shifts on highest energy consumers — reduction of 14 points by 2035 compared to the median variant and of 22 points compared to the minimum variant. Carbon taxes remain the most effective tool[20] with a drop of 14.1 pts of households' emissions when raised from F4 level to NZE level (see Fig C.2 in Appendix C).

[19] The remaining 24% primary lie in the higher share of biogas and biofuel in the NZE scenario and in the partial redundancy of the policy tools.

[20] We note that ex-post studies of carbon pricing show positive but often limited impact of isolated carbon pricing on national CO_2 emissions (Green, 2021; Shmelev and Speck, 2018) as well as the significant and persistent fall of households' emissions in the UK (Känzig, 2021). In this study, we can only compare households' emissions reduction in F4 to NZE or 2010.

4.2. NZE could increase income inequalities, poverty and carbon-tax inequalities

We present the inequalities induced by NZE and F4 policy packages in several orthogonal directions, firstly income inequalities, then vertical and horizontal 'expenditure' (carbon tax payments) inequalities. This section holds constant the hypothesis of maximising energy savings by selecting the largest energy consumers as beneficiaries of electric vehicle adoptions and thermal renovations.

The investment-driven growth supplement from F4 to NZE results in higher income, especially for decile 1 (D1) and median (D5) living standards at all tested horizons (Table 4). However, when households are not rebated their carbon tax payments, NZE induces higher Gini indexes and intercentile ratios — D9/D1, D9/D5 and D5D/1 are systematically higher under NZE than F4 (Table 4) —, which means that the distribution of income is wider and more unequal under NZE than under F4. Analysis of NZE marginal variants maintaining either EV support or renovation subsidies at F4 levels under median or minimum energy savings variants, reveals second-order effects on income distribution only, mainly caused by small GDP variations.

Table 4: Evolution of income distribution indicators

F4 scenario	**2010**	**2025**	**2030**	**2035**
Gini index	0.285	0.251	0.237	0.230
D1 (€2019)	10,873	12,800	13,658	14,592
D5 (€2019)	20,824	24,143	25,764	27,560
D9 (€2019)	37,873	43,689	46,631	49,859
Poverty rate	14.96%	14.77%	14.90%	15.33%
NZE scenario	**2010**	**2025**	**2030**	**2035**
Gini index	0.285	0.256	0.247	0.240
D1 (€2019)	10,873	12,817	13,682	14,662
D5 (€2019)	20,824	24,203	25,949	27,870
D9 (€2019)	37,873	43,988	46,352	50,751
Poverty rate	14.96%	14.70%	15.01%	15.12%

Source: Authors' calculations. Results are those under the assumption of maximum energy savings variant without recycling of carbon tax payments. The Gini index aggregates the distribution of income into one single indicator. A Gini index of 0 would describe a population in which all individuals earn the same amount when an index of 1 represents the opposite extreme of the entire national income captured by one single person. In this particular table, rather than decile averages, D1, D5 and D9 designate the annual living-standard thresholds, in 2019 euros, between deciles 1 and 2, 5 and 6, 9 and 10. D5 is thus the median living standard of households. Living standard is income per consumption unit as defined in footnote 11. The poverty rate is the rate of households with living standard below 60% that of D5.

Last on the income side of inequalities, the marked favourable time trends of Gini indexes or intercentile ratios in both scenarios do not prevent rising poverty rates.[21] Considering French demographic trends, a 0.2-point increase of the rate means an 18.1% increase of the number of people living in poverty. Interestingly, despite its higher median income and thus poverty threshold, NZE exhibits a poverty rate 0.2 points lower than F4. This result moderates the concerns raised by the other income inequality indicators.

Turning to indicators of expenditure inequalities, we focus our analysis on direct carbon tax payments. Carbon taxation is significantly stronger under NZE than under F4, up to ten times higher in 2035 (see Table 1). This signal prompts energy savings that mitigate the increases of vehicle and residential fuel and gas consumptions following the rises of income. Indeed, carbon tax payments in the NZE scenario are about 6 times higher than in the F4 scenario for all income deciles. The weight of carbon payments in households' disposable income increases similarly. The distribution of direct carbon tax payments is thus similarly regressive in both scenarios, inversely proportional to household income (Figure 3). Still, the rise of carbon tax payments can only amplify acceptability

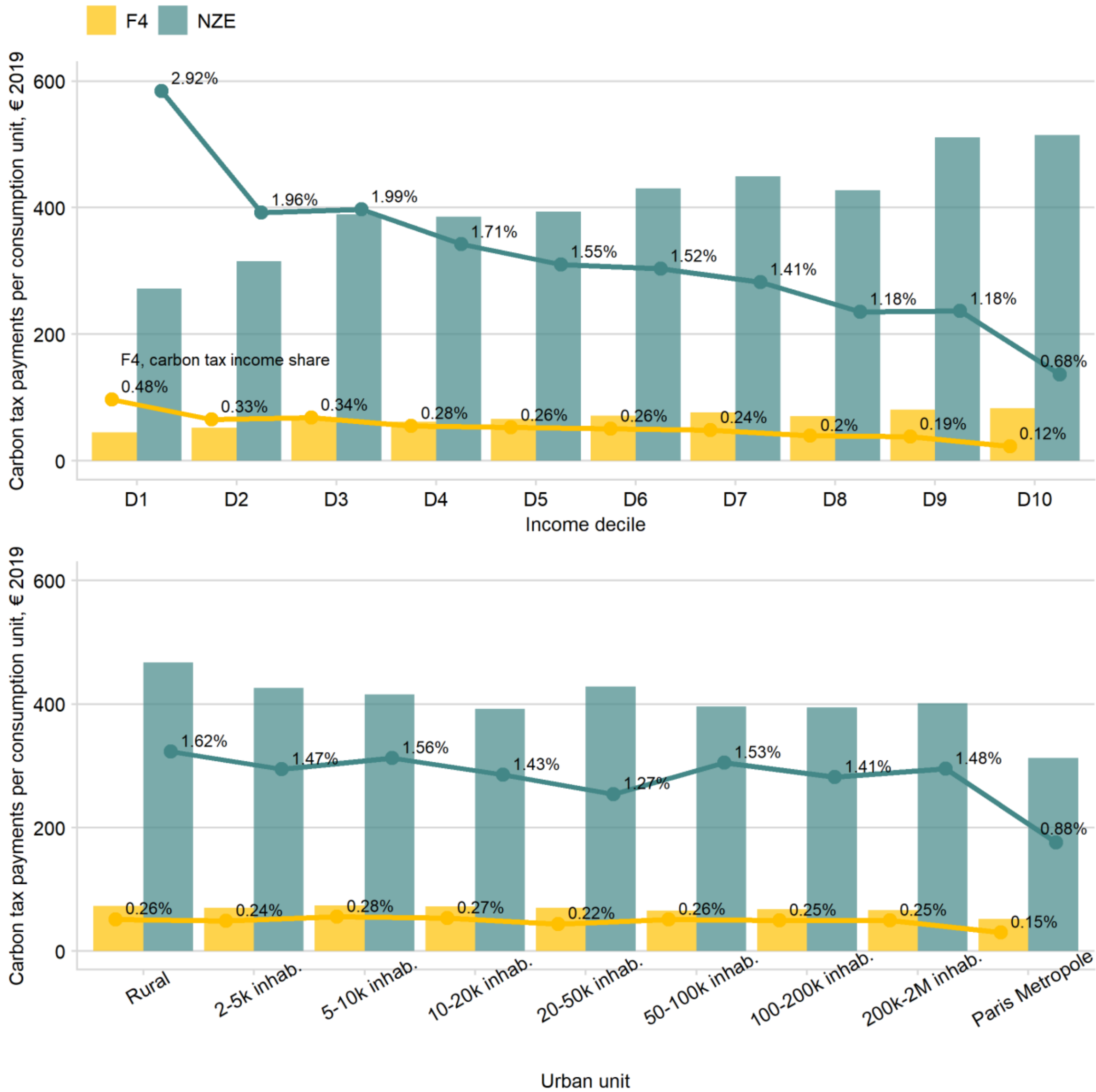
[21] The positive Gini and intercentile ratio dynamics result from favourable indexing assumptions by official SNBC evaluations, which we replicate in IMACLIM-3ME. In particular, unemployment benefits are indexed on wages and other social transfers, including pensions, on productivity growth. We will not comment upon the induced marked downward trend. Rather, we will keep our focus on its variations between the F4 and NZE scenarios.

issues. In 2035, on average, D9 households dedicate €770 or 1.2% of their disposable income to carbon tax payments, while D1 households' payments of €350 mobilise 2.9% of their disposable income.[22] Regressivity stems from two preliminary observations that poorer households dedicate larger income shares to energy and are more dependent on energy goods. For instance, D1-D3 households have lower price elasticities for domestic fuels than richer households. Middle-class households (D5-D7) are more dependent on car fuel than richer households as price elasticities are U-shaped across income (see Appendix A). Like Ohlendorf (2020) but contrary to Douenne (2020), we find that the regressivity of carbon tax payments is diminished when measured against expenditure rather than income, but persists from deciles 3 to 10 (see Appendix G). Our results are thus robust enough to the choice of income or expenditures as a measure of economic standing.

Poterba (1991) and subsequent papers (see Cronin et al. (2019) and Metcalf (2019) for instance) apply the permanent income theory (Friedman, 1957) and use expenditures as a proxy for lifetime income. Their main argument is that annual income can fluctuate and does not include the use of loans or savings for retired persons and students especially. This approach has been criticised among others by Chernick and Reschovsky (1997) and Teixidó and Verde (2017), who contest both that expenditures are a constant fraction of lifetime income, and that gasoline and energy consumption decisions are made on the basis of lifetime income. Independent of the debate over the drivers of gasoline consumption, we believe that annual income is a more accurate proxy for households' acceptability of the carbon tax, especially considering the uncertainty surrounding the low-carbon transition. Hence, we prefer income to expenditures to compute the relative burden of carbon taxation for households.

[22] €770 and €350 are average payment per households, per consumption unit payments are respectively €511 and €272 for D1 and D9.

Figure 3: 2035 carbon tax payments (bars) and their ratios to income (line) per decile



Source: Authors' calculations. Results are those under the assumption of maximum energy savings without recycling of carbon tax payments. Reading: on average, direct carbon tax payments of D1 households in 2035 are €45 per consumption unit and mobilise 0.48% of their disposable income in the F4 scenario, versus €272 per consumption unit and 2.92% of their income in the NZE scenario. Rural households dedicate 1.62% of their disposable income to carbon tax under NZE, 0.14 points more than 200k-2M city dwellers. Income deciles are defined in footnote 11.

Regarding horizontal inequalities, rural households pay more carbon tax because of longer daily journeys, mostly by private car, and larger dwellings. Carbon tax payments decrease with area density. NZE aggravates the divide between rural and urban households: profiles of payments and income shares along urban unit are more contrasted under NZE than F4. Rural households pay between 9.7% and 61.6% more than other households under NZE versus 3.9-53.4% more under F4. The effect in terms of share of disposable income and per consumption unit is less sharp, as households of the first income deciles live in denser areas and rural households are more populated (Figure 3).

The size of urban units is the main source of carbon tax payment discrepancy between households with similar income (Figure 4), which is consistent with the literature (Douenne, 2020; Fischer and Pizer, 2017; Pizer and Sexton, 2019). Intra-decile gaps exceed inter-deciles differences at least for the first 6 income deciles.

The type of housing is largely correlated with the size of urban unit, as 95% of rural dwellings are individual dwellings, while 67% of dwellings in agglomerations of more than 100,000 inhabitants are collective dwellings. Payments of households in individual housing remain higher than those of households in collective housing for all deciles. Disparities between regions are more complex. Regions with the coldest winters (East, West and North have the highest heating and hot water expenditures in 2010) do not induce systematically higher carbon tax payments. Indeed, rich households in these cold areas benefit from energy renovations under the assumption of maximum energy savings, as they are among the highest energy consumers (see section 3.3).

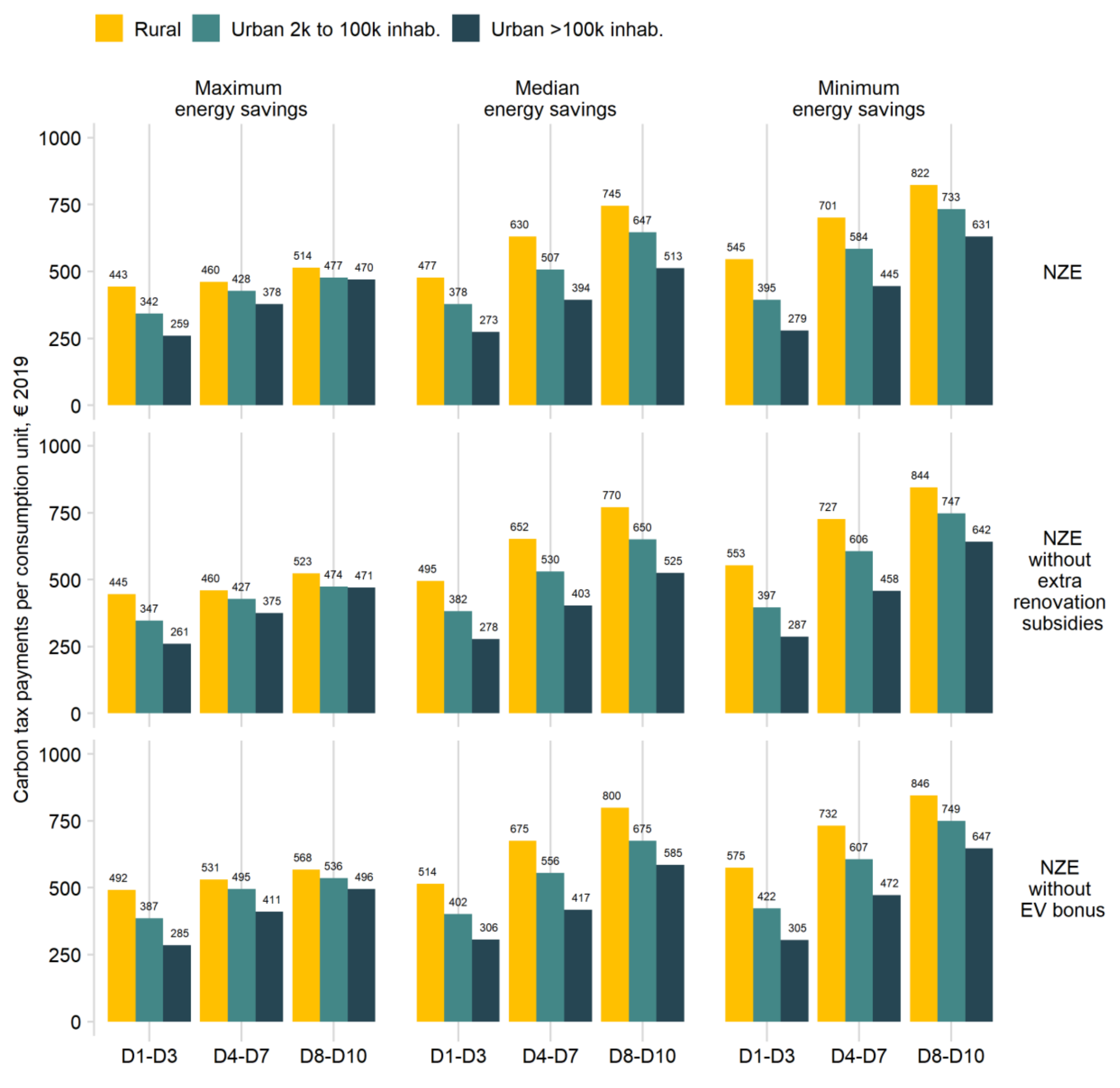
Figure 4: Horizontal inequalities in 2035 carbon tax payments under NZE scenario

Source: Authors' calculations. Results are those under the assumption of maximum energy savings without recycling of carbon tax payments. Payments are average annual payments per consumption unit (see footnote 11), in 2019 euros. For reasons of simplicity, results are aggregated on three income categories and three strata of urban unit (rural, urban in small and medium towns under 100k inhabitants and urban in cities above 100k inhabitant). Income deciles are defined in footnote 11.

4.3. Electric vehicle and renovation subsidies distribution mitigates rural-urban divide and impacts emissions dynamics

The higher renovation and electric vehicle subsidies of the NZE scenario have only second-order effects on income distribution, thus have little impact on the Gini index, intercentile ratios or the poverty rate. However, they directly impact energy expenses, hence carbon tax payments (Figure 5): EV measures lower carbon tax payments the most, up to 16% for D4-D7 households, while renovation support reduces them by 2% at most for rich households in large cities. Carbon taxation remains regressive, but households' payments relative to income increase less than the tax. This reduced burden reflects the adaptation measures taken by households, as well as the impacts of additional measures to support thermal renovation and electric vehicles.

Figure 5: Impacts of EV and renovation support measures on carbon tax payments in 2035



Source: Authors' calculations. Results are those under the assumption of maximum energy savings without recycling of carbon tax payments. Reading: Vertical comparison highlights the 'volume' effect of subsidies by reporting mean carbon tax payments of three household categories for the NZE scenario, NZE with F4 EV bonus and NZE with F4 renovation subsidies. Horizontal comparison highlights the 'selection effect' through three energy savings options. Income deciles are defined in footnote 11.

Selecting the largest energy consumers for EV adoption and thermal renovation increases vertical inequalities with or without an increase of EV and renovation support. For instance, in the full NZE scenario, D8-D10 rural households pay only 15.9% more than D1-D3 rural ones under maximum energy savings, against 50.8% under minimum energy savings (Figure 5). The more even distribution of payments across income deciles implies more unequal ratios to disposable income. This points at an efficiency-equity trade-off. Assuming that EV adoptions and thermal renovations benefit the highest energy consumers — maximising energy savings — favours rich and middle-class households while maximising emission reduction, whereas assuming that they benefit the lowest energy consumers decreases vertical inequalities but is suboptimal for emission reduction.

Conversely, assuming that EV and renovations benefit the highest energy consumers reduces horizontal inequalities. Under minimum energy savings and for the full NZE package, D4-D7 rural households pay on average 20% and 58% more carbon tax than D4-D7 urban households of respectively small and large cities. Under maximum energy savings, payment gaps are brought down to 7% and 22%.

The paradoxical effects of EV and renovation support measures are because the selection of beneficiaries has a weaker effect on poor households than on rich ones, but one more differentiated according to territory. In the full NZE scenario, maximum rather than minimum savings lower payments by 37.5% for rural D8-D10 households and 25.6% for large-city D8-D10 households, compared with respectively 18.8% and 7.1% for D1-D3 households. Importantly, the volume of subsidies is not nearly as significant as the selection. The two scenarios with limited volumes of renovations or EVs — due to lower subsidies — but well-targeted at energy-intensive households reduce more carbon tax payments and both vertical and horizontal payment inequalities than the full but poorly-targeted NZE package (Figure 5).

Average carbon tax payments across all deciles decrease from €600 in 2030 to €585 in 2035 (euros 2019) under full NZE and maximum energy savings. The curbing down is allowed by about one-third of households, who manage to decrease their payments between 2030 and 2035, by 27.0% despite the 38% increase in the carbon tax over the same period (from €178 to €246/tCO_2). 69% of these households, whose payments decrease between 2030 and 2035, have benefited from either EV adoption, thermal renovation or new efficient housing. The average payment also decreases under median energy savings but not under minimum savings, which demonstrates again the importance of adequate targeting of technology adoptions.

Reduced average payments imply more reduced average income shares dedicated to payments considering income growth. In fact, carbon payments decrease for all deciles and especially for the middle classes (Figure 6, left). The trend is explained by simultaneous decreases of households' energy efforts, especially for mobility with a drop of more than one third for the middle classes D4-D7 (Figure 6, right). This illustrates the efficiency of gradual EV penetration in reducing energy expenses, carbon payments and thus carbon emissions.

Figure 6: Weight of carbon tax and energy in income under NZE scenario

Source: Authors' calculations. Results are those under the assumption of maximum energy savings without recycling of carbon tax payments. Differences between territories, which are lesser than for absolute payments, are not reported. Mobility energy expenses include EV electricity. Income deciles are defined in footnote 11.

Low-income classes are the main beneficiaries of renovation under both maximum and minimum energy savings over time (Table 5). In 2035, the distribution of EVs among households forms an inverted U-shaped curve across income under maximum energy savings, even though richer households are better off in the short term. Minimum energy savings favour the poorest households (D1-D3). Subsidy volumes — which increase EV sales and renovations — have little effect on the evolution of this distribution. But, over time and the greater the volume, households selected by one or the other options tend to be the same, which reduces differences between energy savings variants.

Table 5: Beneficiaries of energy-efficient technologies across time in the NZE scenario

	Maximum energy savings			Minimum energy savings		
Electric Vehicles	D1-D3	D4-D7	D8-D10	D1-D3	D4-D7	D8-D10
2025	13%	38%	49%	42%	32%	26%
2030	15%	42%	43%	40%	35%	26%
2035	21%	47%	32%	39%	40%	21%
Thermal renovations	D1-D3	D4-D7	D8-D10	D1-D3	D4-D7	D8-D10
2025	31%	40%	29%	39%	39%	22%
2030	33%	41%	26%	38%	40%	22%
2035	35%	41%	24%	37%	41%	22%

Source: Authors' calculations. Reading: in 2025 and under maximised energy savings, (1) households owning electric vehicles are for 13% D1-D3 households, for 38% D4-D7 households and for 49% D8-D10 households; (2) households living in thermally renovated dwellings are for 31% D1-D3 households, for 40% D4-D7 households and for 29% D8-D10 households. Percentages may not sum to 100% due to rounding. Income deciles are defined in footnote 11.

Social acceptability of the NZE transition is called into question, particularly because of the rapid increase of carbon payments in the NZE scenario, which hits all households. Energy-efficient technologies prove efficient in reducing territorial inequalities for middle classes in the long run, but leave unprotected the poorest households, especially in urban areas. Consequently, investing in a greater volume of subsidies for EVs and renovation does not appear to be a short-term solution to policy impact mitigation, as it only allows for significant decreases of energy expenses between 2030 and 2035. The transition period 2025-2030 is therefore critical for the acceptability of a more ambitious strategy. EV and renovation subsidies need to be paired with some short-term policy targeting the burden of low-income households to ensure the acceptability of the tax.

4.4. Carbon payment recycling is complementary to subsidies in the short term

Social acceptability of environmental policies hangs on a sense of justice, i.e. the fair distribution of the burden among actors and the adequacy of means and ends (Douenne and Fabre, 2020). Recycling of carbon tax payments as a short-term solution addressing vertical inequalities has already been investigated and proven effective (Baranzini et al., 2017; Cronin et al., 2019). Direct transfers have been proven more equitable than, for instance, labour tax cuts (Fremstad and Paul, 2019; Klenert et al., 2018), especially when directed to poor people (Vogt-Schilb et al., 2019).

We test four direct compensatory policy options through rebates of carbon tax payments: [23, 24]

- Per-capita rebate: each household receives an identical fraction per consumption unit (CU) of the collected tax. Because total energy expenditures increase with living-standard deciles, households in the lower deciles receive more rebate than they pay taxes.
- Poverty-targeted rebate: the rebate per CU is identical for households of the same decile, but higher for low deciles than for high ones. It is calibrated to at-least compensate 95% of decile 1 households prior to any adaptation behaviour, and is degressive at constant rate for the following deciles up to decile 9. Decile 10 households are excluded from compensation.
- Rural-targeted rebate: following on section 4.2 results that urban size is a better indicator of carbon payments than income, the rebate per CU is identical for households of same urban-density strata and skewed in favour of rural households. It is designed to at-least compensate 95% of rural households prior to adaptation, which leads to massive overcompensation for most of them due to the wide dispersion of energy consumptions of rural households.
- Living-standard rebate: each household receives an amount proportional to its living standard (disposable income per CU). This scheme neutralises the impact of rebating on income distribution.

Following the official low-carbon strategy, we assume full recycling of firms' carbon tax payments into tax credits.[25] Likewise, we fully rebate to households their own payments levied on direct fossil fuel consumptions. We focus our exposition on the NZE scenario for the maximum energy savings variant, where the higher carbon tax induces more direct inequalities but also more compensation possibilities.

[23] Our recycling terms are deliberately schematic and based on easily observable variables. We acknowledge the fact that any policy aimed at households supposes implementation costs that can potentially determine its efficiency. That is why we only consider variables simple enough to be the conditions of public policies: income, number of persons in the household and density of place of living.

[24] We choose to address inequalities by means of a social transfer additional to existing transfers, an option that is both likely to win the support of households for the necessary reforms, and easier to implement and less harmful to the carbon price signal than some targeted pricing options.

[25] Additionally recycling part of households' payments to firms could increase economic activity with indirect benefits to households of higher deciles, while rebates to households could be focused on lower ones (Combet et al., 2009).

Table 6: Impacts of four carbon tax recycling schemes on growth and income distribution under NZE

Variable	Horizon	Poverty-targeted rebate	Per capita rebate	Living-standard rebate	Rural-targeted rebate	No recycling
Macroscopic variables						
GDP vs 2010	2035	+48.14%	+47.44%	+47.44%	+47.41%	+46.73%
Unemployment rate vs 2010	2035	-0.01 pts	+0.31 pts	+0.30 pts	+0.32 pts	+0.63 pts
Household CO_2 vs 2010	2035	-51.8%	-52.5%	-53.2%	-52.4%	-53.7%
Income distribution						
Gini Index	2025	0.249	0.253	0.257	0.253	0.256
Gini Index	2030	0.237	0.242	0.246	0.243	0.247
Gini Index	2035	0.232	0.236	0.240	0.236	0.240
D1 (€2019)	2035	15,495	15,122	14,875	15,066	14,662
D5 (€2019)	2035	28,278	28,380	28,239	28,319	27,870
D9 (€2019)	2035	51,102	51,516	51,545	51,275	50,751
Poverty rate	2035	13.9%	14.7%	15.0%	15.1%	15.1%

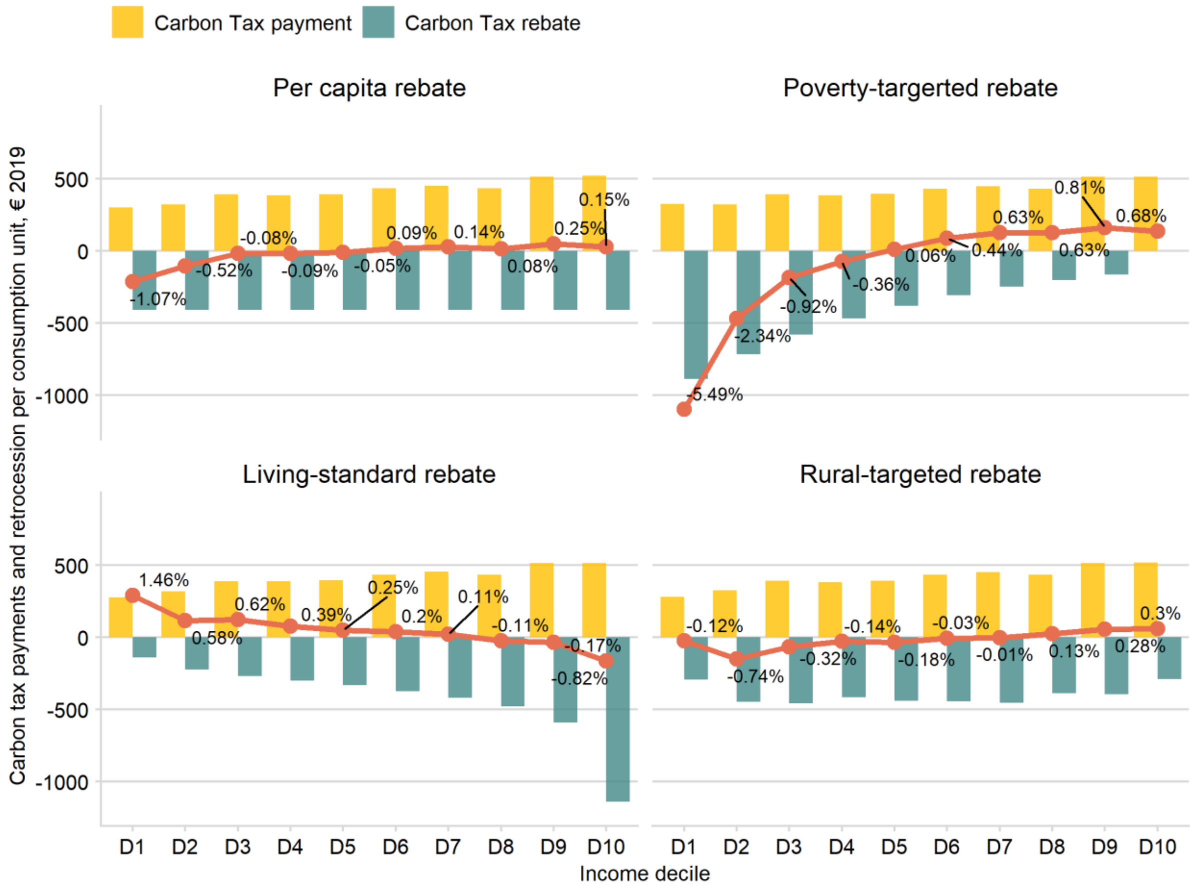
Source: Authors' calculations. Gini index, deciles and the poverty rate are defined as in Table 4.

In 2035, the rebating of nearly 31 billion euros (€2019) to households boosts consumption and GDP growth (Table 6).[26] Per the loop architecture of our method, the targeting of recycling has significant macroscopic consequences. The poverty-targeted rebate maximises GDP growth, one percentage point ahead of per-capita rebate, at the cost of a 3.2% rebound in direct households' emissions compared to no recycling. Poorer households have higher income-elasticities in labour and carbon-intensive goods, thus sustaining both activity and emissions. Nevertheless, rebound effects due to rebating have much less influence on emissions than the selection of EV and renovation beneficiaries (see Figure 2).

Per-capita and poverty-targeted rebates are the only options making the net carbon tax progressive (Figure 7), with respectively 81% and 69% of D1-D3 households being at least compensated. Income distribution indicators are expectedly improved by the rebates favouring the poorest. By construction, the rebate proportionally to living standard leaves the Gini index and inter-decile ratios almost unchanged compared to the absence of recycling. The poverty-targeted rebate allows NZE to have a Gini comparable to that of F4 (0.232 compared to 0.230), lower intercentile ratios and a poverty rate that is almost one point lower than in 2010. This confirms that it is possible to have a more ambitious yet fairer transition through the poverty-targeted recycling of carbon tax revenues.

[26] Rebating options do not have as much influence in F4 due to the lower tax payments (4.7 billion 2019 euros in 2035 under maximum energy savings).

Figure 7: 2035 carbon tax payments and rebates under NZE for four rebating schemes



Source: Authors' calculations. Results are those under the assumption of maximum energy savings. Reading: For each decile, the average 2035 carbon tax payments (yellow) and rebates (green) are plotted under four recycling schemes for the NZE scenario. The red line marks the ratio of net carbon tax (payment minus rebate) to income for each decile. Income deciles are defined in footnote 11.

The rural-targeted rebate largely reduces the territorial divide between rural and urban dwellers. Still, it concentrates overcompensation on a smaller number of households, with less than half (49.4%) of D1-D3 households compensated beyond their carbon tax payments. It disproportionately benefits rural people with an annual 2035 carbon tax rebate of more than €2000 per household when the payment differential between rural and large-city dwellers is only €150-300 without recycling. Induced income inequalities are comparable to those induced by per-capita rebate: inequalities are reduced compared to the absence of recycling, but are increased compared to poverty-targeted rebate and therefore worse than in the F4 scenario. The rural-targeted rebate should not be used to limit inequalities but can easily be coupled with another recycling scheme if warranted by the concentration of opposition to the low-carbon transition in rural areas.

The poverty-targeted rebate is complementary to EV and renovation support measures as it cuts carbon tax payments in the short term. Following Farrel (2017) or Douenne (2020), to further interpret results we regress net-of-rebate carbon tax payments for three schemes and the no-recycling option for NZE in 2025 (Table 7). 2025 is the short-term interest horizon where we seek to establish the complementarity of the policy tools to ensure social acceptability. Poverty-targeted recycling considerably increases the weight of disposable income in the payment, thus making it more progressive. It also reduces territorial inequalities: the "rural" dummy variable is no longer significant and lower than without recycling, at the cost of a slight increase in the gap between small and large cities.

EV adoption for rural dwellers means a drop of around €400 under maximum energy savings compared to €650 under minimum energy savings. EV influence is roughly similar for no-recycling, and income-related recycling.

Renovations reduce carbon payments (negative coefficients), but their influence is not significant enough to compare scenarios under maximum energy savings. We conclude that recycling and EV and renovation support measures are complementary in the short term since supported technologies contribute to lowering carbon payments in similar proportions regardless of the recycling scheme. Poverty-targeted rebates effectively compensate the first deciles to the point of making the carbon tax progressive, decreasing poverty and income inequalities without increasing territorial disparities.

Table 7: Regression of net carbon tax payment per household in 2025

	Dependent variable: Net carbon tax payment							
	No rebate		Poverty-targeted rebate		Per-capita rebate		Rural-targeted rebate	
Energy savings	Max	Min	Max	Min	Max	Min	Max	Min
Intercept	-1,077.49***	-1,563.38***	-6,041.20***	-7,502.50***	-842.84***	-1,156.83***	-588.49***	-793.66***
Log(income)	126.55***	160.60***	653.03***	790.53***	102.32***	119.26***	130.10***	145.34***
Consumption units	137.07***	186.35***	-660.74***	-762.09***	-245.10***	-259.43***	-256.58***	-270.95***
Rural (dummy)	119.25***	164.57***	72.65***	116.02***	109.80***	157.40***	-1,969.50***	-2,356.72***
Small city (dummy)	82.36***	96.09***	63.02***	70.96***	77.57***	91.31***	-315.42***	-373.78***
Age	-2.76***	-0.33	-4.23***	-2.15***	-2.79***	-0.34	-1.15**	2.00***
Region	7.02***	1.40	4.84*	-1.22	6.21***	0.33	5.53**	-1.15
Surface	2.13***	3.58***	3.33***	5.03***	2.37***	3.79***	1.97***	3.45***
Electric Vehicle (EV)	30.37	-368.20***	152.29*	-393.17***	21.73	-401.09***	222.27***	-327.64***
Rural: EV	-408.86***	-267.01**	-460.45***	-244.25	-416.51***	-248.05**	-937.20***	-261.39*
Small city: EV	-197.38**	-90.77	-274.28**	-153.41	-198.86*	-75.03	-482.15***	-56.69
Thermal renovation (TR)	8.46	-222.42***	-7.35	-263.37***	23.05	-237.57***	27.24	-287.75***
Rural: TR	-21.28	-18.29	-26.80	-10.90	-37.14	-7.80	28.86	145.07***
Small city: TR	-57.34	-46.68	-92.23**	-71.35	-66.73*	-43.13	-62.36	-75.82
New Housing (NH)	75.17**	-252.82***	112.75***	-215.04***	67.41*	-255.67***	132.51***	-321.21***
Rural: NH	72.05	-20.37	17.56	-107.38	75.63	-24.82	8.05	88.30
Small city: NH	-31.62	-45.37	-53.73	-77.08	-31.33	-48.89	-36.03	-112.30
Adjusted R-squared	0.12	0.19	0.26	0.29	0.06	0.11	0.57	0.57
Observations	10,251	10,251	10,262	10,262	10,256	10,257	10,254	10,255

** p < 0.1; ** p < 0.05; *** p < 0.01. Source: Authors' calculations. The baseline of the size of urban unit is Large cities of more than 100,000 inhabitants. Some households have been withdrawn due to negative or zero disposable income. We observe likewise trends in NZE 2035 with no rebate, per capita rebate and rural-targeted rebate; redistribution effects under poverty-targeted rebate override most of the effects of EV and renovation support measures (see Appendix H). Under minimum energy savings without rebate, adoption of an EV means a €635.21 decrease in carbon tax (-368.20+-267.01). The decrease is €408.86 under maximum energy savings.*

5. CONCLUSION & POLICY IMPLICATIONS

We have assessed the distributive effects of two environmental policy packages of incremental ambition: The French *Stratégie Nationale Bas Carbone* (SNBC) 2015 and 2020 editions aiming respectively at cutting 1990 emissions by 75% (Factor Four, F4) and reaching Net Zero Emissions (NZE) by 2050. We linked macroeconomic modelling to microsimulation through iterative exchange of shared variables to represent macro- and microeconomic effects of disaggregated household behaviour and explicit penetration of electric vehicles and thermal renovations.

Our first conclusion is that low-carbon strategies — either F4 or NZE — induce regressive carbon tax payments and income impacts if they do not consider recycling of the carbon tax revenues. Our modelling method integrates all effects pointed out as progressive by the literature: income effects (Rausch et al., 2011), indexation of social income on prices (Metcalf, 2019), use of multisector macroeconomic modelling (Ohlendorf et al., 2020), subsidies for low-carbon technologies and the crossed effect with a carbon tax (Lamb et al., 2020). Contrary to Goulder

(2018), we conclude univocally that all these effects are not enough to offset the regressive impact of the carbon tax and the induced increase of poverty.

Our second conclusion is that targeting electric vehicle adoption, new efficient dwellings and thermal renovations on the largest energy consumers is essential to limit horizontal, especially territorial, inequalities, and to approach mitigation objectives. But such targeting advantages middle classes and richer households and thus widens vertical inequalities and carbon tax regressivity.

Thirdly, electric vehicles are particularly effective in both cutting down long-term carbon tax payments and reducing the rural-urban divide when benefiting the largest fuel consumers, thereby maximising energy savings. The progressive penetration of electric vehicles allows the average carbon tax payment to decrease after 2030.

Fourthly, recycling carbon tax payments through poverty-targeted or per-capita rebates reduces income inequalities and poverty and makes the carbon tax progressive in the very short term. However, both these direct “lump-sum” recycling options do not tackle horizontal inequalities and trigger rebound effects of about 3% of GHG emissions.

Fifthly, carbon tax recycling and electric vehicle and renovation support measures are highly complementary on the short term and are both needed for a successful energy transition. Rebating carbon tax payments to households does not limit the efficiency of subsidies but warrants that 81% of the three lowest income deciles are better off with the policy. Our study suggests that recycling could only be a temporary compensation until 2035, when household adaptation and diffusion of EV and thermal renovations have sufficiently lowered carbon tax payments.

We could refine our methodology in several directions: the growth of the six different income sources could be differentiated across sectors of activity and skill levels of workers to differentiate the labour income variations benefitting micro-simulated households. Additionally, we could better harmonise between our different data sources by, e.g., introducing hybrid accounting of economic and energy flows (Ghersi, 2015) or correcting the (under-reported) capital income of database households. Notwithstanding, the present analyses are clearly far from exhausting the potential of our numerical tool. The wealth of information of our household database calls for further investigation of the French energy transition, including beyond what the French government's official strategy proposes.

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APPENDICES

Appendix A. Price and income elasticities of French households

Table A.1: Long-term price elasticities of French households

Income Decile	Vulnerability class	A01 Food	A02 Electricity	A03 Natural Gas	A04 Other Residential Energy	A05 Construction	A06 First-hand vehicle	A07 Vehicle fuel	A08 Rail and Air transport	A09 Road and water transport	A10 Leisure services	A11 Other services	A12 Other goods	A13 Housing rent	A14 Second-hand vehicles
D01	1	-0.179*** (-3.43)	-0.708*** (-12.53)	-0.193*** (-3.42)	-0.423 (-1.47)	-0.65** (-2.29)	-2.153*** (-3.33)	-0.362*** (-4.61)	-0.14 (-1.51)	-0.671 (-1.39)	-0.204** (-2.32)	-0.238*** (-7.49)	-0.419*** (-4.97)	-0.745* (-1.92)	-0.412* (-1.79)
D01	2	-0.12*** (-2.83)	-0.566*** (-12.48)	-0.159*** (-3.51)	-0.423 (-1.47)	-0.802** (-2.28)	-2.153*** (-3.33)	-0.361*** (-4.61)	-0.171 (-1.49)	-0.774 (-1.39)	-0.26** (-2.15)	-0.237*** (-7.49)	-0.467*** (-4.89)	-0.745* (-1.92)	-0.434* (-1.77)
D01	3	-0.106*** (-2.66)	-0.506*** (-12.45)	-0.251*** (-6.17)	-0.423 (-1.47)	-0.205** (-2.4)	-2.153*** (-3.33)	-0.21*** (-4.53)	-0.196 (-1.48)	-0.934 (-1.39)	-0.188** (-2.39)	-0.215*** (-7.6)	-0.403*** (-5)	-0.745* (-1.92)	-0.892 (-1.6)
D01	4	-0.079** (-2.22)	-0.424*** (-12.39)	-0.151*** (-4.41)	-0.423 (-1.47)	-0.211** (-2.4)	-2.153*** (-3.33)	-0.271*** (-4.57)	-0.251 (-1.47)	-0.977 (-1.39)	-0.259** (-2.16)	-0.201*** (-7.69)	-0.462*** (-4.9)	-0.745* (-1.92)	-0.774 (-1.63)
D02	1	-0.178*** (-3.42)	-0.73*** (-12.53)	-0.175*** (-3.01)	-0.382 (-1.47)	-0.42** (-2.32)	-1.926*** (-3.34)	-0.254*** (-4.56)	-0.2 (-1.48)	-0.865 (-1.39)	-0.195** (-2.36)	-0.246*** (-7.45)	-0.398*** (-5.01)	-0.771* (-1.93)	-0.426* (-1.77)
D02	2	-0.104*** (-2.63)	-0.536*** (-12.46)	-0.139*** (-3.22)	-0.382 (-1.47)	-0.427** (-2.32)	-1.926*** (-3.34)	-0.344*** (-4.6)	-0.248 (-1.47)	-1.093 (-1.39)	-0.278** (-2.12)	-0.233*** (-7.51)	-0.472*** (-4.89)	-0.771* (-1.93)	-0.569* (-1.69)
D02	3	-0.133*** (-2.99)	-0.589*** (-12.49)	-0.183*** (-3.87)	-0.382 (-1.47)	-0.265** (-2.36)	-1.926*** (-3.34)	-0.21*** (-4.53)	-0.238 (-1.47)	-1.047 (-1.39)	-0.189** (-2.39)	-0.233*** (-7.51)	-0.389*** (-5.03)	-0.771* (-1.93)	-0.503* (-1.72)
D02	4	-0.062* (-1.9)	-0.387*** (-12.36)	-0.124*** (-3.95)	-0.382 (-1.47)	-0.179** (-2.42)	-1.926*** (-3.34)	-0.253*** (-4.56)	-0.607 (-1.45)	-1.365 (-1.39)	-0.324** (-2.05)	-0.196*** (-7.72)	-0.491*** (-4.86)	-0.771* (-1.93)	-1.161 (-1.57)
D03	1	-0.19*** (-3.51)	-0.783*** (-12.55)	-0.166*** (-2.66)	-0.367 (-1.47)	-0.465** (-2.31)	-1.682*** (-3.35)	-0.249*** (-4.56)	-0.22 (-1.48)	-0.929 (-1.39)	-0.194** (-2.36)	-0.255*** (-7.42)	-0.393*** (-5.02)	-0.813* (-1.93)	-0.41* (-1.79)
D03	2	-0.103*** (-2.61)	-0.513*** (-12.45)	-0.115*** (-2.79)	-0.367 (-1.47)	-0.319** (-2.34)	-1.682*** (-3.35)	-0.365*** (-4.61)	-0.334 (-1.46)	-1.274 (-1.39)	-0.292** (-2.09)	-0.222*** (-7.57)	-0.463*** (-4.9)	-0.813* (-1.93)	-0.525* (-1.71)
D03	3	-0.124*** (-2.88)	-0.574*** (-12.48)	-0.182*** (-3.96)	-0.367 (-1.47)	-0.23** (-2.38)	-1.682*** (-3.35)	-0.193*** (-4.51)	-0.304 (-1.46)	-1.298 (-1.39)	-0.187** (-2.4)	-0.233*** (-7.51)	-0.386*** (-5.03)	-0.813* (-1.93)	-0.598* (-1.68)
D03	4	-0.073** (-2.13)	-0.401*** (-12.37)	-0.12*** (-3.69)	-0.367 (-1.47)	-0.152** (-2.46)	-1.682*** (-3.35)	-0.229*** (-4.55)	-1.289 (-1.44)	-1.389 (-1.39)	-0.291** (-2.1)	-0.191*** (-7.76)	-0.47*** (-4.89)	-0.813* (-1.93)	-1.335 (-1.56)
D04	1	-0.201*** (-3.59)	-0.796*** (-12.55)	-0.166*** (-2.62)	-0.435 (-1.47)	-0.417** (-2.32)	-1.475*** (-3.36)	-0.257*** (-4.56)	-0.214 (-1.48)	-0.926 (-1.39)	-0.189** (-2.38)	-0.251*** (-7.43)	-0.387*** (-5.03)	-0.861* (-1.93)	-0.419* (-1.78)
D04	2	-0.12*** (-2.83)	-0.551*** (-12.47)	-0.12*** (-2.72)	-0.435 (-1.47)	-0.268** (-2.36)	-1.475*** (-3.36)	-0.376*** (-4.61)	-0.31 (-1.46)	-1.299 (-1.39)	-0.254** (-2.17)	-0.219*** (-7.58)	-0.438*** (-4.94)	-0.861* (-1.93)	-0.609* (-1.67)
D04	3	-0.139*** (-3.05)	-0.594*** (-12.49)	-0.196*** (-4.13)	-0.435 (-1.47)	-0.197** (-2.41)	-1.475*** (-3.36)	-0.181*** (-4.5)	-0.311 (-1.46)	-1.199 (-1.39)	-0.177** (-2.45)	-0.227*** (-7.54)	-0.375*** (-5.06)	-0.861* (-1.93)	-0.661* (-1.65)
D04	4	-0.083** (-2.3)	-0.429*** (-12.4)	-0.124*** (-3.59)	-0.435 (-1.47)	-0.155** (-2.45)	-1.475*** (-3.36)	-0.248*** (-4.56)	-0.757 (-1.44)	-1.494 (-1.39)	-0.261** (-2.15)	-0.194*** (-7.73)	-0.45*** (-4.92)	-0.861* (-1.93)	-1.533 (-1.55)
D05	1	-0.2*** (-3.58)	-0.79*** (-12.55)	-0.177*** (-2.81)	-0.471 (-1.47)	-0.325** (-2.34)	-1.364*** (-3.36)	-0.236*** (-4.55)	-0.224 (-1.48)	-0.965 (-1.39)	-0.182** (-2.42)	-0.246*** (-7.45)	-0.379*** (-5.05)	-0.897* (-1.94)	-0.457* (-1.75)
D05	2	-0.131*** (-2.96)	-0.563*** (-12.48)	-0.123*** (-2.73)	-0.471 (-1.47)	-0.234** (-2.38)	-1.364*** (-3.36)	-0.39*** (-4.62)	-0.295 (-1.46)	-1.182 (-1.39)	-0.244** (-2.19)	-0.212*** (-7.62)	-0.436*** (-4.94)	-0.897* (-1.94)	-0.69 (-1.65)
D05	3	-0.137*** (-3.03)	-0.578*** (-12.48)	-0.178*** (-3.83)	-0.471 (-1.47)	-0.188** (-2.42)	-1.364*** (-3.36)	-0.181*** (-4.5)	-0.34 (-1.46)	-1.258 (-1.39)	-0.177** (-2.45)	-0.223*** (-7.56)	-0.369*** (-5.07)	-0.897* (-1.94)	-0.595* (-1.68)
D05	4	-0.086** (-2.35)	-0.431*** (-12.4)	-0.119*** (-3.41)	-0.471 (-1.47)	-0.153** (-2.46)	-1.364*** (-3.36)	-0.241*** (-4.55)	-0.94 (-1.44)	-1.579 (-1.39)	-0.254** (-2.17)	-0.194*** (-7.74)	-0.437*** (-4.94)	-0.897* (-1.94)	-1.109 (-1.58)
D06	1	-0.218*** (-3.7)	-0.832*** (-12.56)	-0.171*** (-2.58)	-0.567 (-1.48)	-0.317** (-2.34)	-1.247*** (-3.37)	-0.251*** (-4.56)	-0.214 (-1.48)	-0.94 (-1.39)	-0.179** (-2.44)	-0.243*** (-7.46)	-0.374*** (-5.06)	-0.947* (-1.94)	-0.445* (-1.76)
D06	2	-0.149*** (-3.15)	-0.611*** (-12.5)	-0.118** (-2.41)	-0.567 (-1.48)	-0.249** (-2.37)	-1.247*** (-3.37)	-0.478*** (-4.64)	-0.265 (-1.47)	-1.246 (-1.39)	-0.232** (-2.22)	-0.215*** (-7.6)	-0.418*** (-4.97)	-0.947* (-1.94)	-0.606* (-1.67)
D06	3	-0.145*** (-3.11)	-0.603*** (-12.49)	-0.184*** (-3.8)	-0.567 (-1.48)	-0.182** (-2.42)	-1.247*** (-3.37)	-0.186*** (-4.51)	-0.315 (-1.46)	-1.388 (-1.39)	-0.17** (-2.5)	-0.223*** (-7.56)	-0.359*** (-5.09)	-0.947* (-1.94)	-0.645* (-1.66)
D06	4	-0.097** (-2.52)	-0.447*** (-12.41)	-0.12*** (-3.33)	-0.567 (-1.48)	-0.145** (-2.47)	-1.247*** (-3.37)	-0.244*** (-4.56)	-0.802 (-1.44)	-1.518 (-1.39)	-0.235** (-2.22)	-0.191*** (-7.76)	-0.423*** (-4.96)	-0.947* (-1.94)	-1.155 (-1.57)
D07	1	-0.216*** (-3.69)	-0.84*** (-12.56)	-0.186*** (-2.78)	-0.689 (-1.48)	-0.266** (-2.36)	-1.148*** (-3.38)	-0.255*** (-4.56)	-0.217 (-1.48)	-1.073 (-1.39)	-0.173** (-2.48)	-0.241*** (-7.47)	-0.368*** (-5.07)	-1.003* (-1.94)	-0.57* (-1.69)
D07	2	-0.165*** (-3.31)	-0.636*** (-12.51)	-0.123** (-2.42)	-0.689 (-1.48)	-0.227** (-2.38)	-1.148*** (-3.38)	-0.468*** (-4.64)	-0.247 (-1.47)	-1.168 (-1.39)	-0.216** (-2.27)	-0.212*** (-7.62)	-0.407*** (-4.99)	-1.003* (-1.94)	-0.643* (-1.66)

D07	3	-0.165*** (-3.31)	-0.652*** (-12.51)	-0.182*** (-3.48)	-0.689 (-1.48)	-0.185** (-2.42)	-1.148*** (-3.38)	-0.194*** (-4.51)	-0.292 (-1.47)	-1.346 (-1.39)	-0.165** (-2.53)	-0.224*** (-7.55)	-0.352*** (-5.11)	-1.003* (-1.94)	-0.602* (-1.67)
D07	4	-0.122*** (-2.86)	-0.49*** (-12.44)	-0.12*** (-3.04)	-0.689 (-1.48)	-0.142** (-2.48)	-1.148*** (-3.38)	-0.264*** (-4.57)	-0.516 (-1.45)	-1.466 (-1.39)	-0.207** (-2.31)	-0.191*** (-7.76)	-0.392*** (-5.02)	-1.003* (-1.94)	-0.894 (-1.6)
D08	1	-0.253*** (-3.91)	-0.948*** (-12.58)	-0.195*** (-2.58)	-0.842 (-1.48)	-0.256** (-2.37)	-1.059*** (-3.39)	-0.277*** (-4.58)	-0.192 (-1.48)	-1.055 (-1.39)	-0.164** (-2.54)	-0.24*** (-7.48)	-0.355*** (-5.1)	-1.072* (-1.95)	-0.579* (-1.68)
D08	2	-0.203*** (-3.61)	-0.688*** (-12.52)	-0.125** (-2.27)	-0.842 (-1.48)	-0.194** (-2.41)	-1.059*** (-3.39)	-0.399*** (-4.62)	-0.248 (-1.47)	-1.063 (-1.39)	-0.194** (-2.36)	-0.206*** (-7.66)	-0.383*** (-5.04)	-1.072* (-1.95)	-0.582* (-1.68)
D08	3	-0.185*** (-3.47)	-0.698*** (-12.53)	-0.189*** (-3.39)	-0.842 (-1.48)	-0.174** (-2.43)	-1.059*** (-3.39)	-0.205*** (-4.52)	-0.264 (-1.47)	-1.393 (-1.39)	-0.158*** (-2.58)	-0.222*** (-7.56)	-0.342*** (-5.14)	-1.072* (-1.95)	-0.682 (-1.65)
D08	4	-0.129*** (-2.94)	-0.505*** (-12.45)	-0.112*** (-2.75)	-0.842 (-1.48)	-0.148** (-2.47)	-1.059*** (-3.39)	-0.292*** (-4.58)	-0.511 (-1.45)	-1.586 (-1.39)	-0.207** (-2.31)	-0.192*** (-7.75)	-0.386*** (-5.03)	-1.072* (-1.95)	-0.726 (-1.64)
D09	1	-0.289*** (-4.08)	-1.025*** (-12.59)	-0.205** (-2.52)	-0.776 (-1.48)	-0.218** (-2.39)	-0.988*** (-3.39)	-0.279*** (-4.58)	-0.184 (-1.49)	-1.084 (-1.39)	-0.154*** (-2.62)	-0.234*** (-7.51)	-0.34*** (-5.14)	-1.149* (-1.95)	-0.641* (-1.66)
D09	2	-0.239*** (-3.83)	-0.748*** (-12.54)	-0.125** (-2.09)	-0.776 (-1.48)	-0.174** (-2.43)	-0.988*** (-3.39)	-0.437*** (-4.63)	-0.234 (-1.47)	-1.13 (-1.39)	-0.178** (-2.44)	-0.203*** (-7.68)	-0.36*** (-5.09)	-1.149* (-1.95)	-0.612* (-1.67)
D09	3	-0.193*** (-3.53)	-0.699*** (-12.53)	-0.191*** (-3.42)	-0.776 (-1.48)	-0.159** (-2.45)	-0.988*** (-3.39)	-0.206*** (-4.53)	-0.269 (-1.47)	-1.401 (-1.39)	-0.156*** (-2.61)	-0.216*** (-7.6)	-0.338*** (-5.15)	-1.149* (-1.95)	-0.785 (-1.62)
D09	4	-0.176*** (-3.4)	-0.576*** (-12.48)	-0.118** (-2.56)	-0.776 (-1.48)	-0.145** (-2.47)	-0.988*** (-3.39)	-0.302*** (-4.59)	-0.356 (-1.46)	-1.167 (-1.39)	-0.189** (-2.39)	-0.19*** (-7.76)	-0.37*** (-5.07)	-1.149* (-1.95)	-0.645* (-1.66)
D10	1	-0.486*** (-4.68)	-1.503*** (-12.64)	-0.263** (-2.21)	-1.254 (-1.48)	-0.167** (-2.44)	-0.832*** (-3.42)	-0.317*** (-4.59)	-0.156 (-1.5)	-1.014 (-1.39)	-0.138*** (-2.8)	-0.221*** (-7.57)	-0.314*** (-5.23)	-1.426** (-1.96)	-1.083 (-1.58)
D10	2	-0.45*** (-4.6)	-0.996*** (-12.59)	-0.133* (-1.68)	-1.254 (-1.48)	-0.145** (-2.47)	-0.832*** (-3.42)	-0.431*** (-4.63)	-0.195 (-1.48)	-0.874 (-1.39)	-0.154*** (-2.63)	-0.192*** (-7.75)	-0.327*** (-5.18)	-1.426** (-1.96)	-0.554* (-1.69)
D10	3	-0.27*** (-3.99)	-0.87*** (-12.57)	-0.205*** (-2.96)	-1.254 (-1.48)	-0.149** (-2.46)	-0.832*** (-3.42)	-0.244*** (-4.56)	-0.205 (-1.48)	-1.403 (-1.39)	-0.143*** (-2.74)	-0.213*** (-7.61)	-0.315*** (-5.22)	-1.426** (-1.96)	-0.889 (-1.6)
D10	4	-0.257*** (-3.93)	-0.685*** (-12.52)	-0.118** (-2.16)	-1.254 (-1.48)	-0.135** (-2.49)	-0.832*** (-3.42)	-0.326*** (-4.6)	-0.286 (-1.47)	-1.113 (-1.39)	-0.165** (-2.53)	-0.187*** (-7.79)	-0.337*** (-5.15)	-1.426** (-1.96)	-0.557* (-1.69)

*Reproduced from Nadaud (2021a). Economic vulnerability classes are defined on socio-economic characteristics. Standard errors in parentheses. *** significant to < 0.01, ** significant to < 0.05, * significant to < 0.1. Households in decile 1, class 1, have price elasticities of -0.18 for agricultural products; -0.70 for electricity; etc. The shaded elasticities were estimated without distinction of class.*

Table A.2: Long-term income elasticities of French households

Income Decile	Vulnerability class	A01 Food	A02 Electricity	A03 Natural Gas	A04 Other Residential Energy	A05 Construction	A06 First-hand vehicle	A07 Vehicle fuel	A08 Rail and Air transport	A09 Road and water transport	A10 Leisure services	A11 Other services	A12 Other goods	A13 Housing rent	A14 Second-hand vehicles
D01	1	0.279*** (3.86)	0.46*** (8.1)	1.354*** (23.82)	0.863** (2.39)	1.861** (1.99)	2.486*** (9.25)	0.692*** (3.66)	1.307*** (9.21)	1.388*** (5.89)	1.581*** (38.8)	1.147*** (40.84)	1.385*** (34.32)	0.563*** (2.79)	1.926*** (4.54)
D01	2	0.417*** (7.14)	0.567*** (12.44)	1.29*** (28.3)	0.863** (2.39)	2.067* (1.79)	2.486*** (9.25)	0.692*** (3.66)	1.377*** (7.9)	1.448*** (5.32)	1.796*** (32.16)	1.147*** (40.94)	1.436*** (31.42)	0.563*** (2.79)	1.985*** (4.39)
D01	3	0.448*** (8.1)	0.612*** (14.97)	1.462*** (35.76)	0.863** (2.39)	1.26*** (4.47)	2.486*** (9.25)	0.818*** (7.32)	1.435*** (7.13)	1.541*** (4.69)	1.518*** (41.78)	1.131*** (45.24)	1.368*** (35.46)	0.563*** (2.79)	3.232*** (3.16)
D01	4	0.513*** (10.48)	0.674*** (19.58)	1.274*** (37.05)	0.863** (2.39)	1.268*** (4.37)	2.486*** (9.25)	0.767*** (5.37)	1.562*** (6.01)	1.566*** (4.55)	1.79*** (32.3)	1.121*** (48.44)	1.431*** (31.7)	0.563*** (2.79)	2.909*** (3.32)
D02	1	0.282*** (3.91)	0.444*** (7.58)	1.32*** (22.54)	0.876*** (2.68)	1.55*** (2.6)	2.327*** (9.7)	0.781*** (5.81)	1.445*** (7.02)	1.501*** (4.93)	1.544*** (40.46)	1.153*** (39.47)	1.363*** (35.8)	0.548*** (2.63)	1.963*** (4.44)
D02	2	0.453*** (8.27)	0.589*** (13.62)	1.252*** (28.94)	0.876*** (2.68)	1.559** (2.57)	2.327*** (9.7)	0.707*** (3.93)	1.555*** (6.06)	1.633*** (4.25)	1.862*** (30.79)	1.144*** (41.67)	1.442*** (31.13)	0.548*** (2.63)	2.352*** (3.79)
D02	3	0.386*** (6.27)	0.549*** (11.58)	1.335*** (28.12)	0.876*** (2.68)	1.341*** (3.63)	2.327*** (9.7)	0.818*** (7.33)	1.533*** (6.22)	1.607*** (4.36)	1.521*** (41.62)	1.143*** (41.76)	1.354*** (36.53)	0.548*** (2.63)	2.173*** (4.04)
D02	4	0.551*** (12.25)	0.701*** (22.23)	1.224*** (38.82)	0.876*** (2.68)	1.224*** (5.04)	2.327*** (9.7)	0.782*** (5.85)	2.384*** (3.73)	1.791*** (3.73)	2.04*** (27.96)	1.118*** (49.68)	1.461*** (30.22)	0.548*** (2.63)	3.964*** (2.92)
D03	1	0.256*** (3.42)	0.404*** (6.43)	1.304*** (20.76)	0.881*** (2.81)	1.611** (2.43)	2.156*** (10.32)	0.786*** (5.96)	1.49*** (6.57)	1.538*** (4.71)	1.541*** (40.59)	1.159*** (38.12)	1.358*** (36.16)	0.524** (2.39)	1.92*** (4.55)
D03	2	0.456*** (8.35)	0.607*** (14.65)	1.207*** (29.14)	0.881*** (2.81)	1.414*** (3.15)	2.156*** (10.32)	0.689*** (3.6)	1.754*** (5.03)	1.738*** (3.87)	1.919*** (29.76)	1.136*** (43.81)	1.432*** (31.61)	0.524** (2.39)	2.234*** (3.95)
D03	3	0.409*** (6.88)	0.561*** (12.11)	1.334*** (28.81)	0.881*** (2.81)	1.294*** (4.07)	2.156*** (10.32)	0.832*** (8.08)	1.683*** (5.33)	1.753*** (3.83)	1.514*** (41.99)	1.144*** (41.67)	1.351*** (36.72)	0.524** (2.39)	2.431*** (3.7)
D03	4	0.525*** (11)	0.691*** (21.18)	1.217*** (37.32)	0.881*** (2.81)	1.188*** (5.83)	2.156*** (10.32)	0.802*** (6.59)	3.954*** (2.9)	1.805*** (3.69)	1.912*** (29.88)	1.114*** (51.11)	1.439*** (31.28)	0.524** (2.39)	4.436*** (2.82)

D04	1	0.229*** (2.96)	0.394*** (6.18)	1.304*** (20.43)	0.859** (2.31)	1.546*** (2.61)	2.01*** (11.01)	0.779*** (5.72)	1.476*** (6.71)	1.536*** (4.71)	1.522*** (41.53)	1.156*** (38.67)	1.351*** (36.71)	0.498** (2.14)	1.943*** (4.49)
D04	2	0.417*** (7.13)	0.578*** (13.02)	1.218*** (27.41)	0.859** (2.31)	1.344*** (3.61)	2.01*** (11.01)	0.68*** (3.45)	1.698*** (5.26)	1.753*** (3.83)	1.772*** (32.71)	1.134*** (44.37)	1.406*** (33.07)	0.498** (2.14)	2.462*** (3.67)
D04	3	0.373*** (5.93)	0.546*** (11.41)	1.36*** (28.42)	0.859** (2.31)	1.248*** (4.64)	2.01*** (11.01)	0.842*** (8.66)	1.699*** (5.26)	1.695*** (4.01)	1.475*** (44.27)	1.139*** (42.87)	1.339*** (37.69)	0.498** (2.14)	2.601*** (3.54)
D04	4	0.502*** (10.03)	0.67*** (19.25)	1.225*** (35.21)	0.859** (2.31)	1.192*** (5.73)	2.01*** (11.01)	0.787*** (6)	2.727*** (3.42)	1.866*** (3.55)	1.797*** (32.13)	1.116*** (50.21)	1.418*** (32.38)	0.498** (2.14)	4.974*** (2.73)
D05	1	0.232*** (3.01)	0.399*** (6.3)	1.323*** (20.89)	0.847** (2.11)	1.421*** (3.11)	1.933*** (11.46)	0.796*** (6.36)	1.5*** (6.49)	1.559*** (4.59)	1.493*** (43.17)	1.153*** (39.44)	1.343*** (37.32)	0.477** (1.97)	2.048*** (4.26)
D05	2	0.391*** (6.41)	0.569*** (12.54)	1.223*** (26.95)	0.847** (2.11)	1.299*** (4.01)	1.933*** (11.46)	0.669*** (3.29)	1.662*** (5.43)	1.685*** (4.05)	1.734*** (33.67)	1.129*** (45.83)	1.404*** (33.17)	0.477** (1.97)	2.682*** (3.48)
D05	3	0.377*** (6.02)	0.558*** (11.97)	1.325*** (28.43)	0.847** (2.11)	1.236*** (4.84)	1.933*** (11.46)	0.842*** (8.69)	1.768*** (4.98)	1.729*** (3.9)	1.473*** (44.38)	1.136*** (43.65)	1.333*** (38.21)	0.477** (1.97)	2.423*** (3.71)
D05	4	0.496*** (9.79)	0.668*** (19.07)	1.214*** (34.69)	0.847** (2.11)	1.19*** (5.79)	1.933*** (11.46)	0.792*** (6.19)	3.151*** (3.17)	1.916*** (3.44)	1.771*** (32.74)	1.116*** (50.29)	1.405*** (33.12)	0.477** (1.97)	3.822*** (2.95)
D06	1	0.19** (2.34)	0.368*** (5.52)	1.313*** (19.71)	0.816* (1.69)	1.411*** (3.17)	1.851*** (12.03)	0.784*** (5.89)	1.477*** (6.7)	1.545*** (4.67)	1.483*** (43.77)	1.151*** (39.89)	1.338*** (37.75)	0.449* (1.76)	2.015*** (4.33)
D06	2	0.35*** (5.37)	0.533*** (10.85)	1.213*** (24.68)	0.816* (1.69)	1.319*** (3.82)	1.851*** (12.03)	0.596** (2.4)	1.594*** (5.81)	1.722*** (3.92)	1.686*** (35.03)	1.131*** (45.28)	1.385*** (34.33)	0.449* (1.76)	2.454*** (3.68)
D06	3	0.359*** (5.58)	0.539*** (11.09)	1.336*** (27.49)	0.816* (1.69)	1.229*** (4.96)	1.851*** (12.03)	0.838*** (8.4)	1.709*** (5.21)	1.805*** (3.69)	1.446*** (46.2)	1.137*** (43.51)	1.322*** (39.13)	0.449* (1.76)	2.559*** (3.58)
D06	4	0.47*** (8.83)	0.656*** (18.13)	1.217*** (33.62)	0.816* (1.69)	1.178*** (6.1)	1.851*** (12.03)	0.79*** (6.1)	2.832*** (3.34)	1.88*** (3.52)	1.697*** (34.69)	1.114*** (51.08)	1.389*** (34.05)	0.449* (1.76)	3.946*** (2.92)
D07	1	0.195** (2.42)	0.361*** (5.37)	1.34*** (19.92)	0.777 (1.32)	1.342*** (3.62)	1.782*** (12.61)	0.781*** (5.8)	1.482*** (6.65)	1.622*** (4.29)	1.458*** (45.36)	1.149*** (40.27)	1.331*** (38.33)	0.417 (1.55)	2.356*** (3.79)
D07	2	0.312*** (4.52)	0.514*** (10.04)	1.223*** (23.89)	0.777 (1.32)	1.29*** (4.11)	1.782*** (12.61)	0.604** (2.48)	1.554*** (6.07)	1.677*** (4.08)	1.626*** (37.02)	1.129*** (45.92)	1.372*** (35.17)	0.417 (1.55)	2.554*** (3.58)
D07	3	0.312*** (4.52)	0.502*** (9.59)	1.332*** (25.41)	0.777 (1.32)	1.232*** (4.9)	1.782*** (12.61)	0.832*** (8.03)	1.657*** (5.46)	1.78*** (3.75)	1.429*** (47.45)	1.138*** (43.27)	1.314*** (39.89)	0.417 (1.55)	2.443*** (3.69)
D07	4	0.412*** (6.99)	0.624*** (15.74)	1.217*** (30.71)	0.777 (1.32)	1.175*** (6.2)	1.782*** (12.61)	0.773*** (5.55)	2.172*** (4.01)	1.85*** (3.58)	1.589*** (38.47)	1.114*** (51.17)	1.357*** (36.29)	0.417 (1.55)	3.238*** (3.15)
D08	1	0.108 (1.21)	0.28*** (3.7)	1.357*** (17.9)	0.727 (1.01)	1.328*** (3.74)	1.719*** (13.23)	0.763*** (5.22)	1.425*** (7.25)	1.611*** (4.34)	1.423*** (47.95)	1.148*** (40.52)	1.318*** (39.55)	0.378 (1.32)	2.38*** (3.76)
D08	2	0.224*** (2.88)	0.475*** (8.6)	1.226*** (22.19)	0.727 (1.01)	1.244*** (4.7)	1.719*** (13.23)	0.661*** (3.17)	1.555*** (6.06)	1.616*** (4.32)	1.54*** (40.67)	1.124*** (47.26)	1.348*** (36.99)	0.378 (1.32)	2.388*** (3.75)
D08	3	0.265*** (3.6)	0.468*** (8.34)	1.346*** (24)	0.727 (1.01)	1.217*** (5.17)	1.719*** (13.23)	0.822*** (7.52)	1.592*** (5.82)	1.807*** (3.68)	1.403*** (49.61)	1.136*** (43.77)	1.304*** (40.91)	0.378 (1.32)	2.659*** (3.5)
D08	4	0.396*** (6.53)	0.613*** (15.01)	1.201*** (29.43)	0.727 (1.01)	1.182*** (6)	1.719*** (13.23)	0.75*** (4.88)	2.162*** (4.02)	1.92*** (3.43)	1.59*** (38.42)	1.115*** (50.88)	1.351*** (36.72)	0.378 (1.32)	2.779*** (3.41)
D09	1	0.026 (0.26)	0.222*** (2.71)	1.376*** (16.8)	0.749 (1.13)	1.277*** (4.25)	1.669*** (13.8)	0.761*** (5.17)	1.408*** (7.46)	1.628*** (4.27)	1.388*** (50.96)	1.144*** (41.51)	1.302*** (41.14)	0.335 (1.09)	2.548*** (3.59)
D09	2	0.141 (1.64)	0.43*** (7.17)	1.226*** (20.43)	0.749 (1.13)	1.218*** (5.16)	1.669*** (13.8)	0.629*** (2.76)	1.522*** (6.31)	1.655*** (4.16)	1.48*** (43.94)	1.122*** (48.08)	1.323*** (39.08)	0.335 (1.09)	2.469*** (3.67)
D09	3	0.248*** (3.29)	0.467*** (8.31)	1.349*** (24.02)	0.749 (1.13)	1.197*** (5.61)	1.669*** (13.8)	0.822*** (7.5)	1.604*** (5.75)	1.812*** (3.67)	1.392*** (50.57)	1.132*** (44.95)	1.3*** (41.37)	0.335 (1.09)	2.94*** (3.3)
D09	4	0.286*** (4)	0.56*** (12.06)	1.213*** (26.15)	0.749 (1.13)	1.179*** (6.09)	1.669*** (13.8)	0.742*** (4.67)	1.804*** (4.85)	1.676*** (4.08)	1.52*** (41.63)	1.114*** (51.31)	1.334*** (38.09)	0.335 (1.09)	2.559*** (3.58)
D10	1	-0.431*** (-3)	-0.136 (-1.14)	1.484*** (12.4)	0.594 (0.56)	1.208*** (5.37)	1.56*** (15.42)	0.729*** (4.37)	1.342*** (8.49)	1.588*** (4.45)	1.324*** (58.2)	1.135*** (43.88)	1.274*** (44.34)	0.179 (0.47)	3.75*** (2.97)
D10	2	-0.348** (-2.57)	0.245*** (3.08)	1.241*** (15.6)	0.594 (0.56)	1.178*** (6.1)	1.56*** (15.42)	0.634*** (2.82)	1.433*** (7.16)	1.506*** (4.9)	1.385*** (51.26)	1.115*** (50.81)	1.288*** (42.63)	0.179 (0.47)	2.311*** (3.84)
D10	3	0.07 (0.75)	0.339*** (4.87)	1.376*** (19.75)	0.594 (0.56)	1.184*** (5.95)	1.56*** (15.42)	0.789*** (6.1)	1.457*** (6.9)	1.813*** (3.67)	1.343*** (55.8)	1.129*** (45.66)	1.276*** (44.11)	0.179 (0.47)	3.222*** (3.16)
D10	4	0.099 (1.09)	0.478*** (8.68)	1.214*** (22.05)	0.594 (0.56)	1.164*** (6.54)	1.56*** (15.42)	0.722*** (4.23)	1.642*** (5.53)	1.645*** (4.2)	1.428*** (47.52)	1.111*** (52.23)	1.298*** (41.51)	0.179 (0.47)	2.321*** (3.83)

*Reproduced from Nadaud (2021a). Economic vulnerability classes are defined on socio-economic characteristics. Standard errors in parentheses. *** significant to < 0.01, ** significant to < 0.05, * significant to < 0.1. Households in decile 1, class 1, have income elasticities of 0.290 for agricultural products; 0.46 for electricity; etc. The shaded elasticities were estimated without distinction of class.*

Appendix B. Economic vulnerability classes

The procedure for establishing the typology of economic vulnerability is taken from Nadaud (2021b). The first step is the principal component analysis (PCA) of the French Expenditures Survey (‘*Budget des Familles*’, BDF) data for 2010, which is our reference year. We carry out the PCA (Lebart et al., 2006) on the more than 10,000 metropolitan households in the 2010 BDF survey. We characterise each household by the distributions of its pre-committed (also known as constrained) expenditures and sources of income. Both income and pre-committed expenditures are described as shares (i.e. as percentages of total income and total constrained expenditure, respectively). Following Quinet and Ferrari (2008), pre-committed expenditures include energy and non-energy housing expenditures, telecommunications, television subscriptions, school canteen fees, insurance fees and financial services. Income sources are aggregated into labour income (employed and self-employed), social income (including pensions), property income, direct assistance from third parties and other miscellaneous income. We carry out the PCA on these twelve active variables, to which we add several dozen quantitative and qualitative socio-economic variables as illustrative variables (variables correlated with the results produced by the active variables for interpretation purposes).

The results of the PCA can be summarised as follows. On the first axis, labour income, associated with constrained housing expenditure excluding domestic energy and school canteen expenditure, is opposed to social income, correlated with expenditure on domestic energy and insurance. On the second axis, the opposition between labour income and social income is still present. Labour income is associated with expenditures on school canteens, telecommunications, financial services and insurance, and social income with expenditures on housing excluding domestic energy.

PCA results allow computing the input data for the household typology stage, which consists of household coordinates on the first two axes of the PCA. The first two axes are retained alone because they return 40% of the information contained in the table of correlations between sources of income and constrained expenditures, while the following axes only marginally increase the percentage of information returned. On the basis of the coordinates of households in the PCA, the typology stage consists of applying an automatic classification algorithm known as 'hierarchical ascending' (Lebart et al., 2006), which results in the definition of four classes. Detailed analysis of the socio-economic characteristics of classes produces the following dominant profiles:

- **Class 1: young active tenants in large cities.**
- **Class 2: retired, poor, single-person households tenants in large cities.**
- **Class 3: well-off working people in access to property (with repayment of property loans).**
- **Class 4: retired, modest, rural and small town owner-occupiers.**

The typology is one of economic vulnerability because it segments the population of households into homogenous groups according to their dependence on social income or assistance associated with the burden of constrained expenditures, two factors that influence households' flexibility to face changes of economic context. The examination of expenditures and income structures shows that classes 2 and 4, mostly composed of retired urban tenants and owner-occupiers, are the most economically vulnerable.

Appendix C. Policy packages: Factor 4 versus NZE

The *Stratégie Nationale Bas Carbone* (SNBC) is France's roadmap for reducing its greenhouse gas emissions. The first edition of the SNBC was presented in 2015 and aimed at the fourfold reduction of greenhouse gas emissions by 2050, compared to 1990 (Factor 4). The second SNBC, published in April 2020, raises the country’s mitigation objective to carbon neutrality (Net Zero Emission) by 2050. The SNBC presents the country's carbon budgets by 4-year period and details sectoral efforts necessary to abide by them.

Our study examines the distributional impacts of two climate policy packages as estimated by the ThreeME model in an official evaluation of the Low Carbon Strategy. For readers familiar with French low carbon policy, we specify that the NZE scenario (Net Zero Emission) corresponds to the official scenario known as "With Additional Measures" (*Avec Mesures Supplémentaires*, AMS), which targets carbon neutrality in 2050 as contribution to the global effort to limit global warming to 1.5°C. The Factor-4 scenario (F4) is known in French nomenclature as "With Existing Measures" scenario (*Avec Mesures Existantes*, AME). F4 aimed to reduce 1990 emissions by a factor of four by 2050, as part of a global mitigation effort limiting global warming to 2°C.

The two ThreeME forecasts of each scenario build on shared assumptions concerning demography and exogenous technical progress (labour productivity), which jointly define potential growth in the economy (see supplementary documents with IOT tables). Moreover, the ThreeME simulations include numerous scenario elements, which exogenously constrain both energy supply and demand trajectories in order to match the hypotheses of the French low carbon strategy (SNBC). In other words, the NZE scenario achieves carbon neutrality by construction in 2050. It only aims to evaluate the macroeconomic impact of the revised SNBC and not to validate the capacity of the Strategy's measures to achieve carbon neutrality.

The following sections summarise how the main assumptions underpinning the SNBC are translated in ThreeME forecasts (be they exogenous constraints or actual modelling results). We structure them according to four dimensions of decarbonisation: energy supply and carbon taxation, industry, transport and housing.

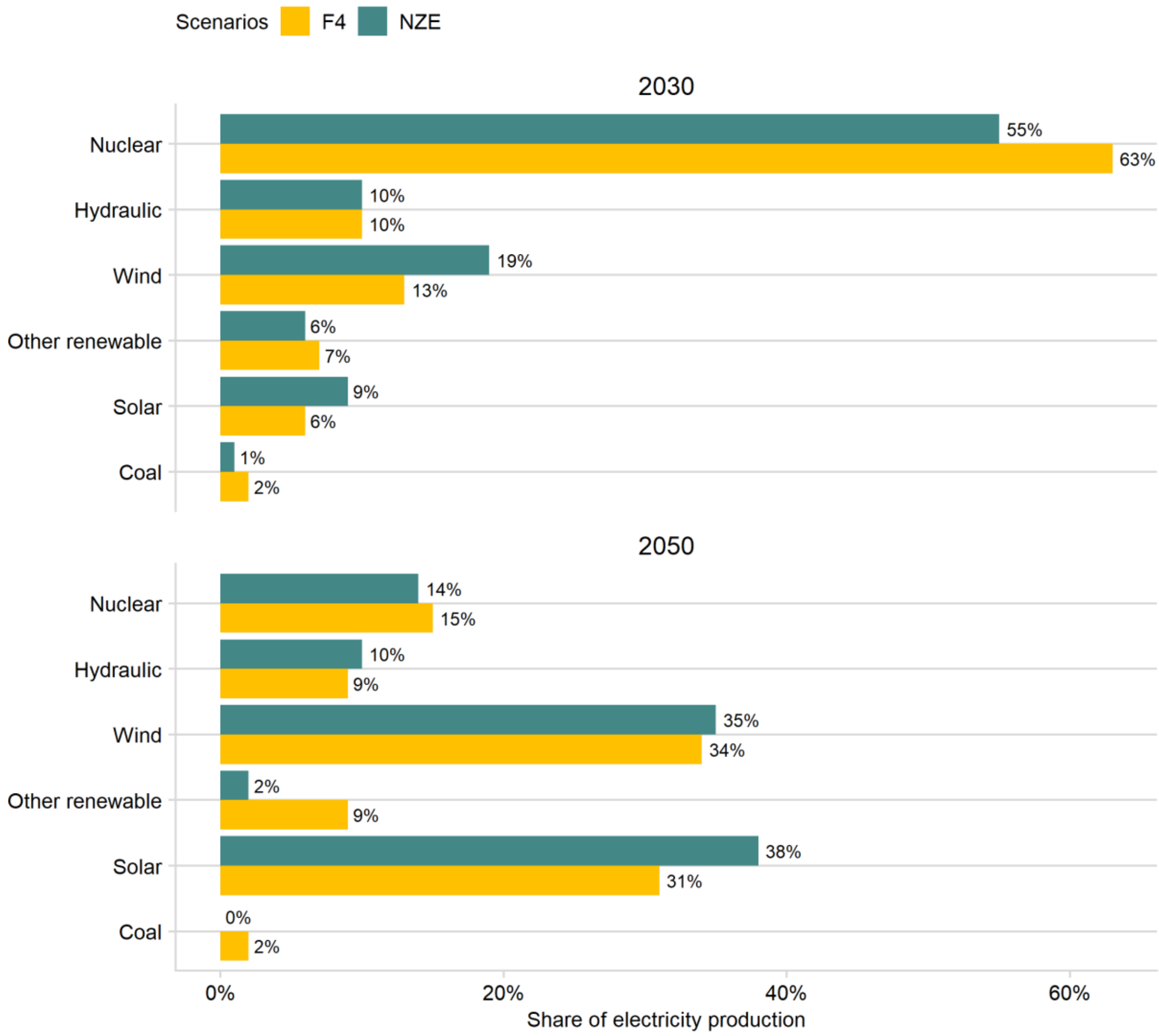
Energy mix and carbon taxation

The SNBC forecasts the evolution of energy supply and must therefore be compatible with the national plan for energy (PPE, '*Programmation Pluriannuelle de l'Energie'*), revised in 2018, which sets the trajectory of the French energy mix. In particular, the costs of renewable energies and the energy consumptions of the production sectors and households align on the successive PPEs.

The NZE scenario thus plans to develop wind and solar power production. The share of nuclear power in electricity production is to drop from 75% in 2018 to 14% in 2050. NZE also projects the complete phasing out of coal from the electricity mix (Figure C.1). NZE plans to replace fossil fuels using renewable sources. The objective is that 79% of fuels and 92% of network gas are from non-fossil sources (biofuels, biogas) in 2050. Under the F4 scenario, we assume a constant contribution of 2% of coal. The F4 scenario focuses on the electricity mix and maintains the input of non-fossil sources at current levels until 2050, i.e. 6% for biofuels and 0% for biogas.

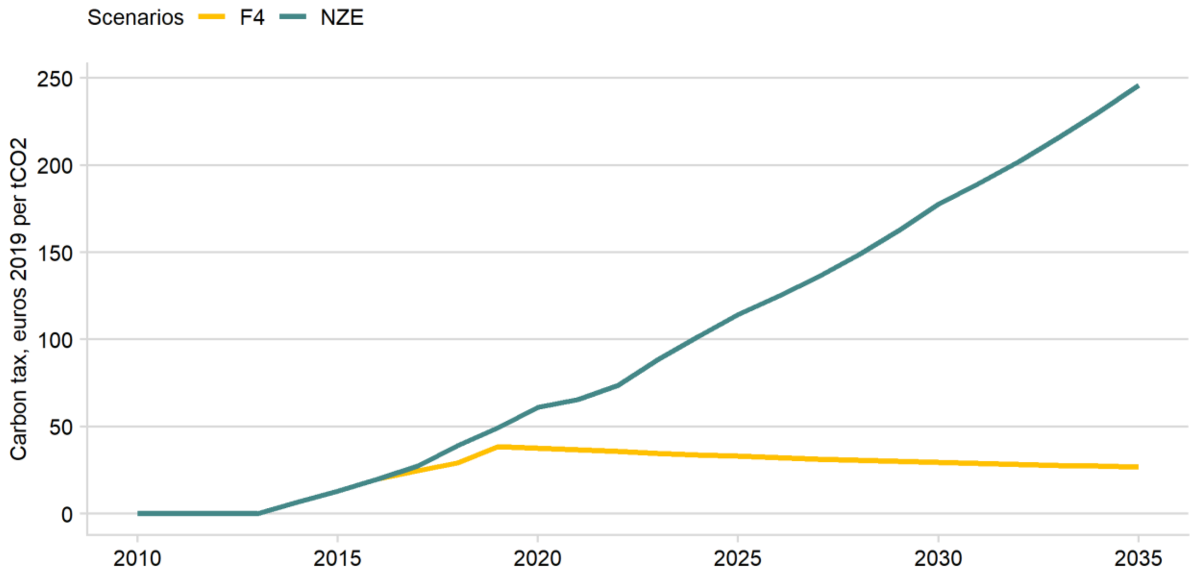
Concerning energy demand, the SNBC plans increased carbon taxation to incentivise economic agents to reduce their emissions (Figure C.2). The ThreeME simulations of both NZE and F4 scenarios assume that carbon tax proceeds are rebated to firms in the form of tax credits in proportion to turnover, and to households as lump-sum transfers. The NZE scenario foresees the gradual increase of the carbon tax: 114 €/tCO_2 in 2025 (in constant euros 2019), 177 €/tCO_2 in 2030, 246 €/tCO_2 in 2035 and up to 604 €/tCO_2 in 2050 (still in euros 2019). In comparison, the F4 scenario freezes the carbon tax at its 2019 level of 44.6 €/tCO_2, which translates into 27 €2019/tCO_2 in 2035 and 18 €2019/tCO_2 in 2050.

Figure C.1: Electricity production mix under F4 and NZE scenarios in 2030 and 2050



Source: ThreeME, ADEME.

Figure C.2: Carbon tax trajectory under F4 and NZE scenarios

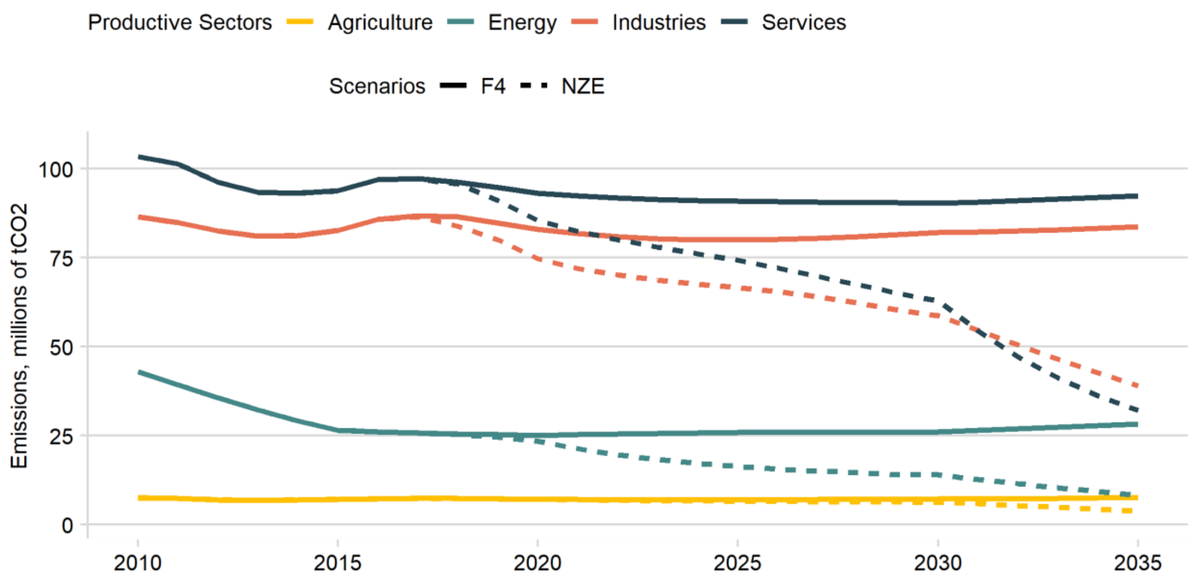


Source: ThreeME, ADEME.

Industry

Decarbonisation of the productive sector comes from improving the energy efficiency of production and substituting electricity to fossil fuels. ThreeME models decarbonisation by taxing emissions, which both encourages the substitution of capital for energy and penalises the consumption of fossil fuels. Emissions result from the intermediate consumption of fossil fuels by each sector (Figure C.3). The ratios of energy consumptions to outputs define the energy intensities of the 24 productions disaggregated by ThreeME. These intensities — also known as technical or Leontief coefficients — are also defined for non-energy inputs. We keep them constant at ThreeME levels for each scenario and each time horizon.

Figure C.3: Emissions from productive sectors under F4 and NZE scenarios



Source: ThreeME, ADEME.

Transports

The SNBC aims to reduce transport emissions of both households and commercial activities for freight and passengers. It considers multiple levers: improvement of the energy efficiency of thermal engines in buses, trucks, ships and aircrafts; the substitution of electricity and gas for oil products in freight transport; and increased capacity investment in the rail sector, which should increase demand and encourage modal shift to rail for passengers and goods. Emissions from transportation sectors (air, rail, road and water) drop by 42.6% between 2010 and 2035 under the NZE scenario.

Concerning households, SNBC measures target private transport emissions through the combination of demand reduction, efficiency improvements and electrification. Demand reduction stems from increased working from home and infrastructure management (urban tolls, reduction of traffic lanes through the development of specific sites for public transport and non-motorised modes). It leads to a 22% drop of the average annual mileage of vehicles over 25 years, in both scenarios. Efficiency improvements reduce the fuel consumptions per km of conventional car by 32.0% between 2010 and 2035 in the NZE scenario, compared with 11.3% in the F4 scenario.

Finally, ThreeME projects that electric vehicles (EVs) will account for 49% of total vehicle sales in the NZE scenario in 2035, which will induce a 17% drop in sales of internal combustion vehicles compared to 2010. In comparison, the F4 scenario only projects EV sales to account for 24% of new vehicle sales in 2035 and a 9% drop in sales of internal combustion vehicles compared to 2010. EV penetration is incentivised by a bonus/malus policy in favour of less polluting vehicles (Table C.1). On top of EV penetration, the policy encourages improvement of the efficiency of conventional alternatives. The F4 scenario relies on measures decided prior to July 1st, 2017. It encourages EV purchase with a bonus until 2023, then considers the progressive increase of the malus applying to the most polluting fossil-fuelled vehicles (class G) and the decrease of the bonus on efficient combustion vehicles (class A) (Table C.1).

The strong penetration of EV under NZE is explained by the extension of this bonus policy to 2040. The long-term attractiveness of electric vehicles is ensured by a strong bonus/malus differential between the purchase of a fossil-fuelled vehicle and an electric vehicle: between €4,400 and €10,840 (2019 euros) difference for the purchase of a highly efficient fossil-fuelled vehicle (class A) and a highly polluting vehicle (class G), respectively. Indeed, NZE plans the end of all bonuses to fossil-fuelled vehicles - even the most efficient ones - in 2024 and increasing maluses over time.

Table C.1: Bonus and malus applied to vehicle purchases under F4 and NZE scenarios

2019 euros	2010	2025	2030	2035
F4 scenario				
EV Bonus	5,251	-	-	-
Bonus/malus to class-A fossil-fuelled vehicle	985	553	494	450
Bonus/malus to class-G fossil-fuelled vehicle	- 2,561	- 5,901	- 5,273	- 4,800
NZE scenario				
EV Bonus	5,251	5,729	4,955	4,393
Bonus/malus to class-A fossil-fuelled vehicle	985	- 144	- 1,263	- 2,572
Bonus/malus to class-G fossil-fuelled vehicle	-2,561	- 6,437	- 6,706	- 7,398

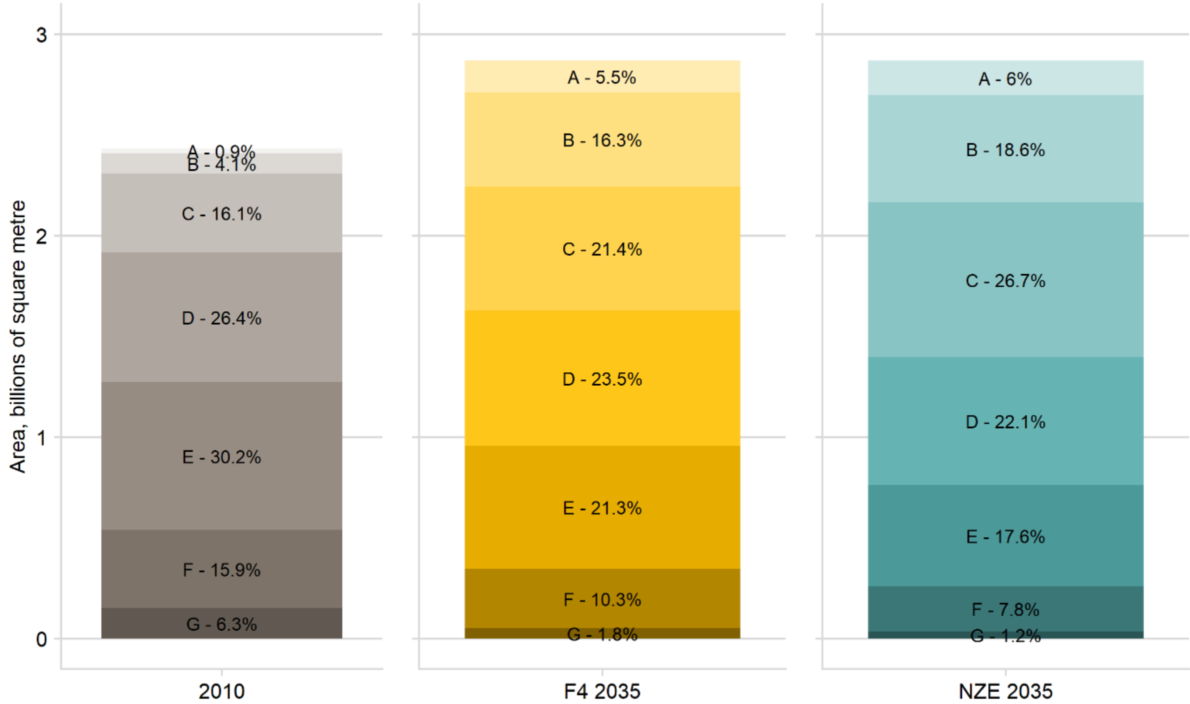
Source: ThreeME, ADEME.

Housing

The SNBC applies different policy instruments to tertiary and residential buildings. For the tertiary sector, it enforces renovation obligations, which ThreeME translates into investments to reduce consumptions and emissions. For residential buildings, the SNBC supports the construction of new efficient housing and renovation of existing dwellings. On the one hand, dwellings built after 2019 must meet the requirements of energy performance diagnosis classes (EPD) A or B. On the other hand, renovations are subsidised through the Tax Credit for Energy Transition (CITE) up to 11.5% of the actual renovation costs (the official announcement of 30% tax credits relates to expenses net of labour costs). The F4 scenario ends this scheme in 2019, while NZE extends it to 2050.

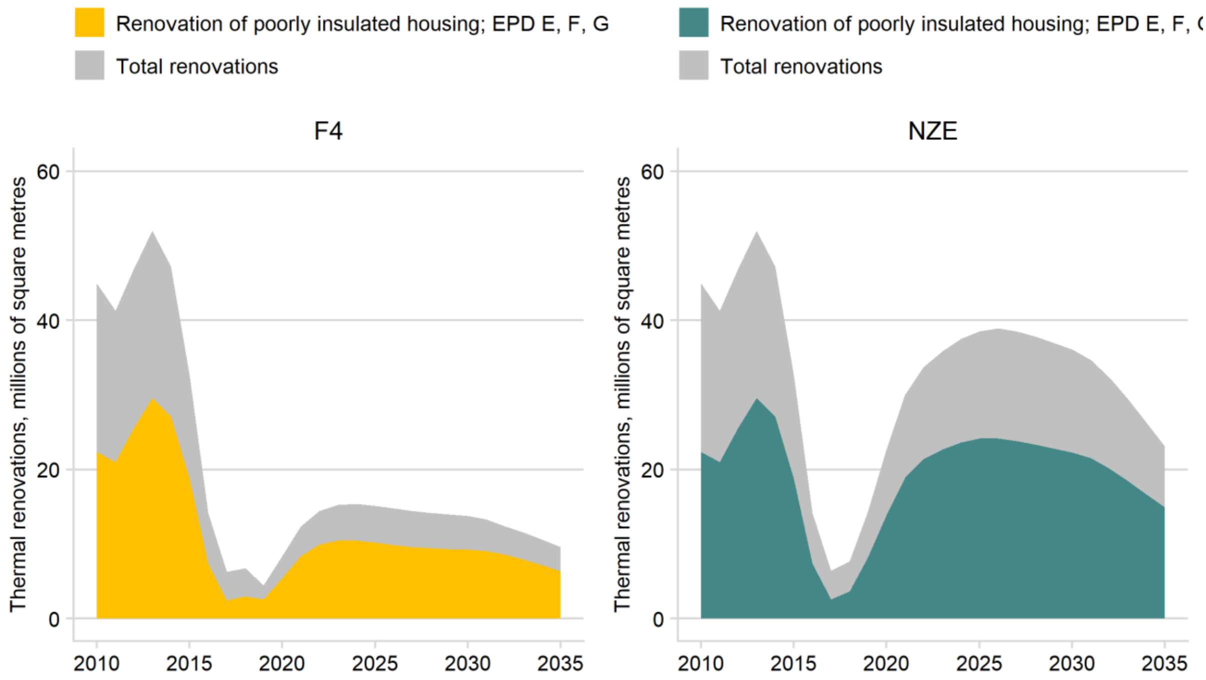
The core of the low-carbon housing strategy is to eventually replace ‘poorly efficient’ dwellings (EPD E, F and G) by 'efficient' (EPD A and B) dwellings (Figure C.4). The volume of efficient dwellings is multiplied by 6.4 under NZE (compared with 5.1 under F4) between 2010 and 2035. The volume increase proceeds from new housing for 58% and from housing renovation for 42%. The share of poorly-efficient dwellings in the stock falls by half from 52% to 24% under NZE (33% under F4) by 2035. As the destruction of housing remains marginal, the eradication of poorly-efficient dwellings is mainly based on sustained rates of renovations (Figure C.5).

Figure C.4: Structure of the housing stock by energy performance diagnosis in 2010 and 2035



Source: ThreeME simulation of SNBC, ADEME.

Figure C.5: Renovated housing surfaces under F4 and NZE scenarios



Source: ThreeME simulation of SNBC, ADEME.

The technical assumptions underlying housing construction and renovation operations are identical in both scenarios. The ThreeME model indexes renovation costs per square metre to construction prices. Similarly, new housing prices follow construction prices without explicitly accounting for the additional costs generated by new energy efficiency regulations from 2019 onwards. Energy efficiency gains offset the investment costs of renovation for households. For example, on average over 2010-2035, class B dwellings consume about 91% less than class F dwellings of the same size.

The difference between the two scenarios NZE and F4 lies in the ambition of the volume of renovation. A little over one billion square metres are treated between 2010 and 2035 under NZE (the total stock is 2.5 billion square metres in 2020). The budget devoted to subsidies is substantial: 45 billion euros (2019 euros) over 25 years, with around 30 billion concentrated on later 2026-2035 efforts and only 16.5 billion paid over the sixteen years of 2010-2025. Under F4, renovation benefits about 500 million m^2 despite the end of renovation subsidies in 2019. The renovated surface is thus only half that of NZE despite a 6-time lower subsidy total (7.6 billion over 2010-2035). The evolution of relative prices, including the effects of the relatively low carbon tax, therefore provides incentives for renovation, which the additional subsidies in the NZE scenario only reinforce.

Contrary to the phenomenon at play for conventional vehicles (lower mileage), the reduction in residential emissions through thermal renovation is counteracted by a 6% increase of housing surface per inhabitant (from 37.7 m^2 per inhabitant to 40 m^2 per inhabitant) between 2010 and 2035, in both scenarios.

Appendix D. Macro-micro consistency

The starting points of our numerical explorations are datasets of the French economy at a 2010 base year and for 3 projection horizons 2025, 2030 and 2035, for F4 and NZE scenarios. The source of these datasets are authoritative numerical simulations of the macro-economic model ThreeME maintained at the French environmental agency ADEME (see Appendix C).

For each scenario and at each horizon, ThreeME results encompass the input-output table (IOT) of annual economic flows disaggregating the input structures and markets of 24 goods and services, among which 4 energy goods: coal products, oil products, gas (natural and biogas) and electricity. The input structures of branches account for the adaptation of firms to the price and non-price measures of scenarios, as well as for feedback effects from all factor markets.

The ThreeME model uses a Stone-Geary utility function for non-energy consumption: the residual consumption budget distributes across goods and services according to constant shares beyond the satisfaction of 'basic needs'. Our modelling framework replaces this specification with microsimulation. The economy-wide final consumption of energy goods by households follows exactly the dynamics derived from the microsimulation. These dynamics come from two mechanisms: the interplay of price and income elasticities and energy savings from renovations, new buildings and electric vehicles.

The main difficulty of linking macroeconomic and microeconomic models lies in the consistency of the two visions of the economy. Households tend to under-report income, especially capital income. Besides, consumption is noticeably lower in survey data than in national accounts (van Ruijven et al., 2015). Surveys do not include expenditures by other agents (public administrations, firms) that macroeconomic models attribute to households because of national accounting conventions, such as consumption of public education and health services or consumption of self-produced goods (André et al., 2016). Conversely, surveyed budgets detail transactions and transfers between households that the aggregation of households evens out in the consumption matrices of national accounts. We adapt our numerical method to these discrepancies. Aggregate consumption of BDF accounts for only 74% of national accounts. We calibrate the breakdown of the remaining 26% between non-energy consumptions to ensure consistency between ThreeME 2010 data and BDF aggregate consumption. We then assume that this gap is structural and that this breakdown is constant across time and scenarios. Energy shares are excluded from this deficit to allow the microsimulation dynamics of energy expenditures to pass on to IMACLIM-3ME without any transformation. The corrected non-energy shares forced in IMACLIM-3ME are the weighted averages of the micro-simulated shares and the shares in the national account residual. For instance, if microsimulation computes the aggregate budget share of food at 17.1%, while food consumption accounts for 14.1% of the 26% gap between BDF and national accounts, the corrected food share forced in IMACLIM-3ME is $(1 - 26\%) \times 17.1\% + 26\% \times 14.1\% = 16.34\%$.

Appendix E. Microsimulation

Thermal renovations induce decreases in energy consumptions for heating, water heating and air conditioning purposes. Energy savings depend on the original and final EPD of dwellings. Each EPD transition at each year from 2010 to the forecast horizon is characterised by a coefficient of reduction of consumption, given by the ratio of the average heating — space and water — and air conditioning energy consumptions for the two EPD classes at the considered year in ThreeME forecasts.

To account for landlord-tenant dilemmas, we prioritise owner-occupiers and social housing for EPD shifts. Owner-occupiers are incentivised to renovate their dwellings as they bear the costs and reap the benefits of the investment. Social housing is to be renovated as part of the SNBC plan. We do not exclude tenants from the selection but only select them if the two former categories of occupiers do not allow covering the volume of renovations prescribed by ThreeME at any given year. In the latter case, we distribute the investment costs of tenants among landlords (households with income from housing rentals) and we increase each tenant's rent to exactly compensate annual investment costs in the dwelling. The selection procedure strikes an admittedly reasonable balance between the three household categories (Figure E.1).

Each of these categories is classified according to the energy efficiency variants used for housing construction. The classification is dynamic and evolves in line with annual renovations. Any given household can carry out several successive renovations that gradually improve its EPD class, as long as the financing of these renovations does not violate the solvency condition: loan repayments and interest payments must not exceed 33% of annual income.

For households carrying out a renovation between 2010 and the forecast horizon, the budgetary consequences concern several items. First of all, energy bills are reduced by the energy savings achieved thanks to the jump in EDP class. These energy savings correspond to a savings factor that applies only to expenditure on heating, water heating and air conditioning, whether it be electricity, gas, fuel oil, wood or district heating. Social housing tenants are supposed to benefit from the energy savings without any increase in rent. Their renovation costs are duly allocated to public budgets in IMACLIM-3ME. In the case of owner-occupiers, the financial costs and the repayment of the loan used for the renovation are added to their budgets. In the case of tenants, the financial costs are borne by the owner-renter households (identified in the database by the presence of rental income), who pass them on in rent increases that exactly compensate for the renovation costs in the long run.

For renovations taking place at projection horizons, the renovation costs appear in household expenditure while the loan increases income by a similar amount. Induced energy savings only apply to half the concerned expenses to account for different timelines.

The same rule applies to new construction: we select households building new housing among those who already have 'housing purchase' expenditures in their budgets.

For households engaging into renovations, we assume strict equivalence between loan-financed and self-financed investment using savings. Indeed, we assume that paying back a loan is equivalent to building back savings (the latter inducing cuts of the returns on owned capital equivalent to loan interest payment). Loan-financed investments induce payback payments during a period of 25 years — without impact on any of the 14 consumption goods — and interests — which increase the consumptions of "other goods and services" (see section 3.3).

We allocate the net financial savings from renovation (EPD shift) on all consumption items except energy goods, using the estimated income elasticities (Appendix A). Energy goods are left out of the allocation to acknowledge the fact that the energy saving coefficients derived from ThreeME forecasts are already net of rebound effects.

Similarly, we explicitly consider replacing conventional vehicles by electric vehicles (EVs) for each household of our database. For each year before the horizon of the simulation, households are ranked according to fuel consumption used for trips shorter than EV range without recharge (set at 300 km) in a way similar to thermal renovation.

The adoption of an electric vehicle leads to a decrease in fuel expenditure proportional to the share of private vehicle travel eligible for electromobility (that is the share of trips below the range of EV), and an increase in electrical energy expenditure. Electricity consumption associated with each EV is calculated by applying a cost per kilometre of electricity expenditure, deduced from ThreeME forecasts for each year, to the annual distance eligible for the EV. Only the fuel bill corresponding to the share of eligible trip is converted to electricity. Any remainder holds if the household owns more than one vehicle; it is allocated to other expenses along with net financial savings using income elasticities if the household only owns one single vehicle.

For selected EV buyers, the fuel consumption of eligible trips is switched to electric, using the average EV consumption per km from ThreeME. For households buying an EV before the forecast horizon, costs include investment costs for an average vehicle-loan repayment term of 6 years following purchase as in thermal renovation. We assume, following ADEME, that 13-year old EVs are systematically replaced by new ones.

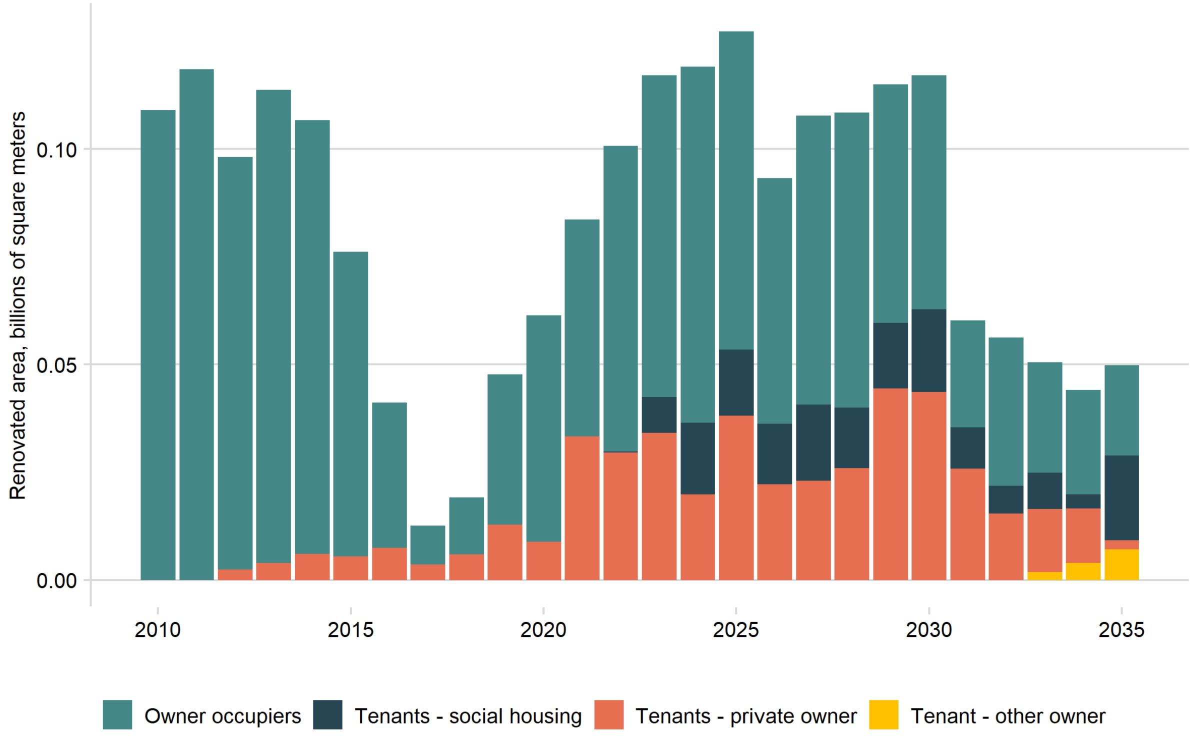
We select EV buyers at forecast horizons (2025, 2030 or 2035) among households purchasing new vehicles in the original BDF survey and adjust their consumption budgets accordingly. This warrants that we do not distort too much the concerned budgets because they do already cover the purchase of a new vehicle. We increase the purchasing prices of vehicles by coefficients reflecting both the additional cost of an EV and the bonus/malus applying to the EV and conventional counterpart, as reported by ThreeME. For households buying an EV at the forecast horizon, only half of the vehicle fuel bill is actually transformed into electricity payment.

This modelling choice minimises spurious distributional impacts: we minimise disruption to household budgets, as large investments in durable goods were already present among households with the exception of renovations. We do not expect households building new houses and/or buying new cars to be very different sociologically in 2010 and 2035. By contrast, we do not impose conditions on households renovating before or at the horizon.

We select EV buyers on their absolute gasoline consumption, to bound the potential carbon emissions savings from electric vehicles within the three energy savings scenarios. Other selection criteria such as the age of cars, correlated with particulate matter emissions on top of CO_2, would require unavailable data for a large share of households and would lower emissions reductions compared to the maximum energy savings variant.

We adopt absolute energy consumption as the criteria for thermal renovation to draw a parallel with vehicles. We have tested the alternative option of ranking households based on energy efficiency measured in kWh/m². It does not alter our results significantly (see Table E.1).

Figure E.1: Occupational status of renovated dwellings



Source: Authors' calculation. Results are for the NZE scenario with maximum energy savings and poverty-targeted rebates.

Table E.1 Macro-economic aggregates, energy, carbon tax and emissions change in 2035 vs 2010 for NZE under maximum energy savings criteria for absolute (Abs.) and relative (Rel.) energy consumption

	Abs.	Rel.	
Macroeconomy			
Real GDP	+46.7%	+46.4%	-0.3 pts
Unemployment rate	+0.6 pts	+0.8 pts	+0.1 pts
Trade Balance / GDP	-0.7 pts	-0.7 pts	+0.1 pts
Real Disposable Income	+44.6%	+44.3%	-0.3 pts
Saving Rate	+2.9 pts	+3.3 pts	+0.3 pts
Real Consumption	+43.0%	+42.2%	-0.8 pts
Energy Consumption			
Coal & lignite	-61.5%	-61.5%	id.
Oil	-39.1%	-39.1%	+0.001 pts
Electricity	+39.0%	+39.0%	-0.001 pts
Gas & heat	-19.0%	-24.7%	-5.679 pts
CO_2 direct emissions	-53.3%	-53.9%	-0.005 pts

	Abs.	Rel.	
Average Household carbon tax (€2019)			
D1	349	352	+0.9%
D5	585	574	-1.9%
D9	766	771	+0.7%
Average per c.u. carbon tax (€2019)			
D1	272	274	+0.7%
D5	394	387	-1.8%
D9	511	515	+0.8%
Average carbon tax share of income			
D1	2.92%	2.93%	+0.01 pts
D5	1.55%	1.53%	-0.02 pts
D9	1.18%	1.19%	+0.01 pts

Appendix F. Rebating options

The living-standard rebate has, by construction, neutral distributive impacts. Each household receives an amount proportional to their disposable income deflated by their number of consumption units (CU). The option is especially useful as a "neutral" counterfactual for assessing the impact of micro-simulation on IMACLIM-3ME results. Since the rebating options only affect macroeconomic aggregates by feedback, any change in the macroeconomy between rebating options would show the influence of the macro-micro linkage. Because the upper deciles spend lower proportions of their expenditures on energy, the living-standard rebate leads to a share of the carbon tax levied on lower deciles being returned to upper deciles. It is therefore proposed only as a counterpoint to politically realistic scenarios that envisage the opposite of such a transfer — the use of part of the payments from the upper deciles to compensate the lower deciles for the taxes they bear.

The per capita rebate is a lump-sum rebate that returns to all households an identical fraction per CU of the tax collected. Since energy expenditures increase with income, at least at certain levels of aggregation (notably the decile level), households in the lower deciles would receive on average more rebate than they pay taxes.

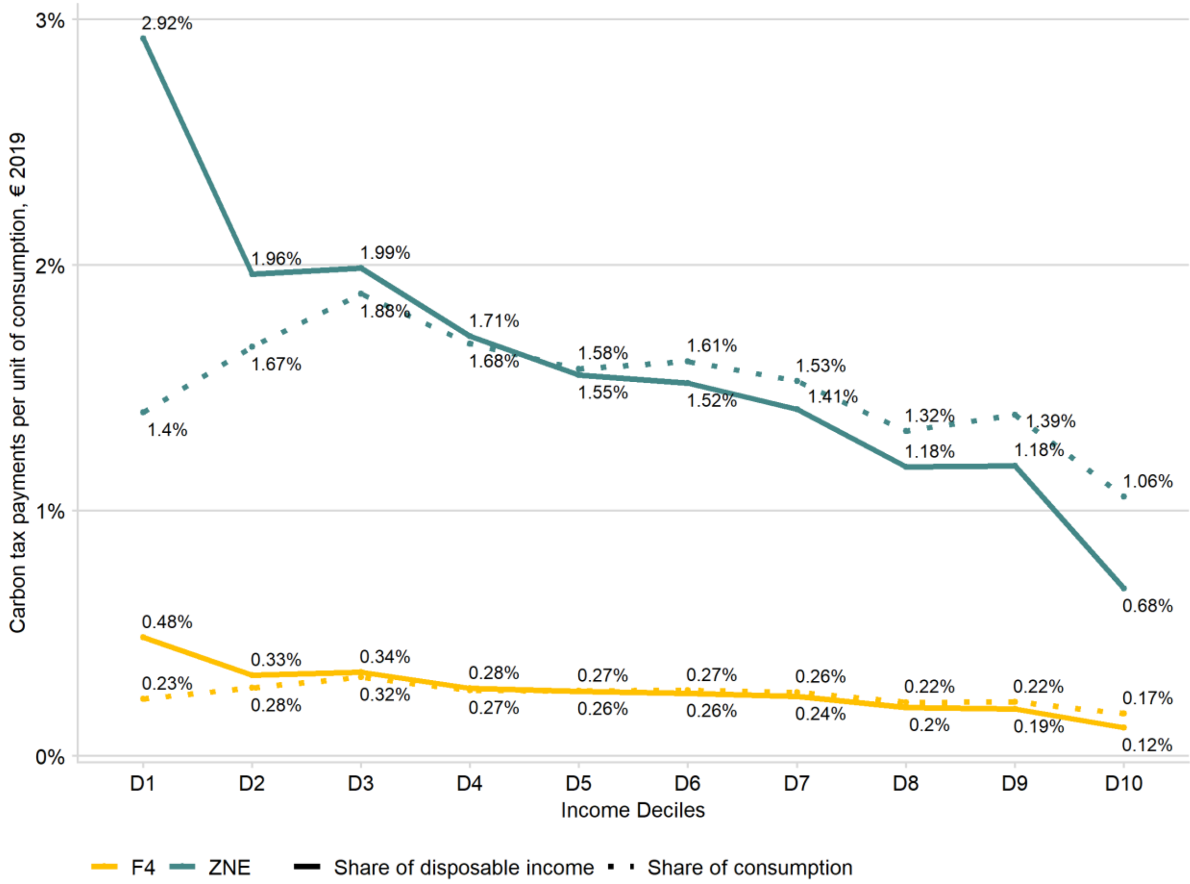
The poverty-targeted rebate is decreasing gradually, acknowledging that energy expenditures are poorly correlated with income at finer levels of disaggregation. The option therefore modulates the amount rebated per unit of consumption according to deciles, with lower amounts for the higher deciles. The precise rule is that the rebate to the first decile reflects the difference, calculated in 2010, between the average direct carbon emissions per CU for all households and the 95th percentile of the same emissions per CU for decile 1. The rebate is thus calibrated on the latest available statistics to fully compensate 95% of decile-1 households for their direct carbon tax payments calculated ex ante, i.e. without taking account of adaptation strategies. The difference in question, of 2.2, corresponds by construction to the ratio of this rebate and the sum rebated to decile-1 households in the above per capita rebate (they receive 2.2 times more). The rebates of deciles 2 to 9 are then calculated for each scenario and at each horizon under the assumption that each decile receives per CU an identical lower-than-one fraction of what the decile immediately lower receives per CU, under constraint that total rebates equal total tax payments. By hypothesis, decile 10 is not granted any rebate.

The geographical rebate reproduces the principle of the poverty-targeted rebate but according to the urban unit sizes (UUS) of households' places of residence. The rebate is calibrated to fully compensate 95% of the households residing in rural areas (UUS 0) from ex-ante direct tax payments. In 2010, the gap between the average direct carbon emissions per CU for all households and the 95th percentile of the same emissions for households in rural areas is 3.33. The fact that it is higher than the gap observed for deciles clearly shows that UUS are better indicators of the carbon tax burden than income deciles. However, the rule concentrates rebates on UUS 0 so much that the rebates accruing to households in UUS over 100,000 inhabitants are negligible compared to their tax payments. Moreover, the wide dispersion of fossil energy consumptions among rural households, for all the deciles of living standards, means that the amount rebated, given its size, massively overcompensates a large number of rural households.

Appendix G. Ratio of carbon tax payment to income and expenditures

Total expenditures are a better proxy for lifetime income than current income (Friedman, 1957), as testifies the canonical example of the medical student. However, it is debatable whether they allow computing better indicators of the acceptability of reforms. To document that debate, we compute the expenditure shares of 2035 carbon tax payments in two F4 and NZE scenarios (Figure G.1). The regressivity of carbon tax payments is diminished when measured in terms of expenditure shares rather than income shares, but persists from deciles 3 to 10.

Figure G.1: Income versus expenditure shares of carbon tax payments in 2035



Source: Authors' calculations. Scenario F4 and NZE, under maximum energy savings without any rebate.

Appendix H. Regression of net carbon tax payment per household

Table H.1: Regression of net carbon tax payment per household in 2025

	Dependent variable: Net carbon tax payment	
	Living-standard rebate	
Energy savings	Max	Min
Intercept	4,004.96***	4,711.30***
log(income)	-471.49***	-573.33***
Consumption units	562.65***	698.68***
Rural (dummy)	204.97***	275.62***
Small city (dummy)	132.13***	153.72***
Age	-1.38***	1.40**
Region	11.57***	7.04**
Surface	1.06***	2.31***
Electric Vehicle (EV)	0.12	-402.31***
Rural: EV	-415.13***	-234.56*
Small city: EV	-202.29*	-58.12
Thermal renovation (TR)	6.05	-273.42***
Rural: TR	-22.88	1.59
Small city: TR	-52.68	-22.61
New Housing (NH)	43.44	-282.05***
Rural: NH	89.11	-40.87
Small city: NH	3.08	-23.43
Adjusted R-squared	0.1743	0.1968
Observations	10,252	10,252

** p < 0.1; ** p < 0.05; *** p < 0.01. The baseline of the size of urban unit is Large cities of more than 100,000 inhabitants. Some households have been withdrawn due to negative or zero disposable income.*

Table H.2: Regression of net carbon tax payment per household in 2035

	Dependent variable: Net carbon tax payment							
	No rebate		Poverty-targeted rebate		Per-capita rebate		Rural-targeted rebate	
Energy savings	Max	Min	Max	Min	Max	Min	Max	Min
Intercept	-1,367.61***	-3,375.61***	76,693.40***	174,742.50***	-832.93***	-2,467.01***	-389.92	-1,691.47***
Log(income)	170.59***	332.59***	-7,963.51***	-18,324.10***	121.12***	246.38***	159.20***	285.39***
Consumption units	214.01***	412.37***	5,018.62***	13,669.11***	-402.46***	-412.77***	-418.31***	-432.43***
Rural (dummy)	389.05***	629.87***	-1,225.03	-3,147.96	362.47***	617.45***	-3,006.35***	-4,139.84***
Small city (dummy)	194.52***	278.49***	1,136.55	-1,094.08	166.83***	254.30***	-462.88***	-629.25***
Age	-4.47***	-3.67***	32.13	44.67	-4.50***	-4.04***	-1.58*	0.26
Region	7.24*	9.39	44.25	241.06	5.97	7.35	3.91	3.75
Surface	3.46***	7.44***	31.86***	66.14**	3.81***	8.00***	3.24***	7.30***
Electric Vehicle (EV)	-214.31***	-807.29***	574.12	-1,469.82	-221.95***	-839.53***	-24.61	-731.91***
Rural: EV	-384.85***	-568.60***	-341.65	-541.47	-377.77***	-581.23***	-945.30***	-607.06***
Small city: EV	-255.43***	-163.41	10,367.70***	-3,717.14	-245.56***	-168.53	-502.64***	-223.63*
Thermal renovation (TR)	-214.63***	-320.48***	-2,387.51	-4,324.79	-268.14***	-370.28***	-284.47***	-474.63***
Rural: TR	-229.03***	-155.23*	1,246.62	3,212.49	-183.68***	-131.12	-15.03	195.96*
Small city: TR	-121.53**	-113.79	-2,923.01	1,134.33	-67.87	-70.45	-75.94	-64.54
New Housing (NH)	33.33	-368.44***	128.71	-265.13	4.30	-382.72***	83.39	-502.72***
Rural: NH	-88.01	-250.24**	-1,060.47	-1,022.43	-63.86	-257.85**	-134.75	-20.45
Small city: NH	-104.05	-180.41*	-4,308.22	24,153.22***	-88.35	-175.54	-147.77*	-320.79***
Adjusted R-squared	0.11343	0.21736	0.00880	0.00580	0.07445	0.13675	0.52646	0.48357
Observations	10,251	10,251	10,261	10,263	10,257	10,259	10,254	10,254

** p < 0.1; ** p < 0.05; *** p < 0.01. The baseline of the size of urban unit is Large cities of more than 100,000 inhabitants. Some households have been withdrawn due to negative or zero disposable income.*

Appendix I. Time series from official low carbon strategy dataset

We provide in supplementary material all time-series from the official SNBC dataset that we used to calibrate the macroeconomic model IMACLIM-3ME and to constrain the microsimulation from base year 2010 to 2035.