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The Impact of Climate Risks on Social Inequality

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Abstract

Reducing social inequality and protecting the environment are two distinct objectives that can both complement and contradict each other. Throughout this study, we examine the consequences of climate risks on social inequality and seek evidence of a potential trade-off between environmental and social improvements. In the first part, we review the macroeconomic model of Dennig et al. (2015), an Integrated Assessment Model (IAM), to theoretically determine the interactions between physical risks, transition risks and social inequality at the regional level. By substituting the representative agent with income quintiles, the model illustrates the critical need to consider inequality in calculating the social cost of carbon, both within and between countries. Without considering these disparities, current IAMs are incompatible with an inclusive pathway toward decarbonization. While developed countries will benefit from a low carbon tax, emerging countries, such as China and African countries, will bear the brunt of the impact of climate change, not only due to physical damages but also social inequality. Furthermore, the model is used to understand the optimal social transfers, either between or within regions, required to decrease the vulnerability of highly exposed population to climate damages. Results suggest that such policies alone may have limited effect to completely reverse the vulnerability aspect.

In the second part of the paper, we empirically study the social risk of the environmental transition in France. Using input-output tables and the household budget survey from 2017, we disentangle the distribution of the domestic carbon footprint. We found that, on average, the richest households emit 2.6 times more than the poorest households. The carbon footprint elasticity to expenditure is more sensitive to indirect than direct emissions, meaning that carbon intensive consumption is more rapidly saturated as income grows. Therefore, a big spender has the choice to not be a big emitter. Then, we analyze the distribution of the tax burden across income groups after implementing a tax of €100 per ton of CO_2e.

Carbon taxation is highly regressive: the poorest households dedicate around 12% of their equivalized income to the tax compared to only 4% for the richest. Based on a demand system and a microsimulation model, we analyze three redistribution schemes, which target either the reduction of vertical or horizontal inequality. Beyond the social improvements of revenue recycling, we found slight backfire effects (between a 2.55% and 6.51% uptick in emissions with respect to the no tax situation). However, results suggest that low-income households, which are likely to be compensated, are expected to substantially increase their emissions (0.57 kg of CO_2e per euro compensated), while the highest emitting households are less sensitive to price signals (-0.21 kg of CO_2e per euro lost). The trade-off between social and environmental aspects seems to be a key factor in the transition risk if net zero targets imply considerably reducing GHG emissions.

Keywords: physical risks, transition risks, social inequality, carbon tax, energy sobriety, backfire effect

JEL classification: D12, H23, Q54

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1 Introduction

The latest IPCC report stipulates that over the coming decades, a world with better adaptation is preferable to a world with fewer CO_2 emissions. Given the climate inertia (i.e., the relationship between greenhouse gas (GHG) accumulation in the atmosphere and the surge in global mean temperature), past emissions will drive up future natural disasters. As a result, one of the greatest challenges of the 21^{st} century is to find efficient ways to adapt to climate change. However, we are observing that the impacts of global warming, which has raised the global mean temperature by 1.1°C above its pre-industrial level, are irreversible (World Meteorological Association, 2022). Temperature shifts increase the likelihood of extreme events, contributing to humanitarian crises (UNEP, 2019; IPCC, 2021). Floods and droughts provoke food insecurity and malnutrition (Gregory *et al.*, 2005; Douglas, 2009); higher temperatures generate conditions that favor the proliferation of viruses (Karvonen *et al.*, 2010; Paz, 2015); rising sea levels force populations to migrate (Perch-Nielsen *et al.*, 2008; Hauer, 2017; Hauer *et al.*, 2020); loss of biodiversity, especially on plant species, could eradicate traditional and modern medicine (Alves and Rosa, 2007). All of the above effects are even more alarming when they overlap and accumulate for years. Thus, physical risks exacerbate social distress, which can only be alleviated by solid adaptation measures.

The warning in the IPCC's sixth report comes with broad and ambitious pledges to reach carbon neutrality by 2030-2050, also known as net-zero engagements. These pledges seek to disengage from fossil fuels while keeping up with economic growth and sustainable development. To do so, countries are expected to mitigate carbon emissions to reach total decarbonization of their economy. Low emissions technologies and energy efficiency are key to reaching this target. In addition, the transition also involves encouraging consumption sobriety, which is compelling economic actors to reduce their environmental footprints. This relatively new notion is becoming a major aspect of the environmental transition. Fundamentally, sobriety is the main target of carbon taxation since consumption sobriety would not instinctively germinate, but rather be imposed by a price signal. Based on its simplest definition, a carbon tax seeks to create a margin on the price of goods and services to correct the negative externality[1] resulting from GHG emissions (Pigou, 1920). This induced cost of transitioning to a low-carbon economy is based on the carbon footprint, one of the best proxies to assess the transition risk. The carbon footprint measures the amount of GHG emissions associated with a particular actor (a country, a business, a household, or an individual) and thus its respective contribution to global warming. In general, the urgency to decarbonize is a crucial driver of carbon footprint reduction, making the transition risk material if the capacity to shift toward green industries quickly is low.

The aforementioned climate risks are not distributed evenly among the population (Goklany, 1995; Burton, 1997; Mendelsohn *et al.*, 2006; Stern, 2006; Heltberg *et al.*, 2009; Füssel, 2010). Social inequality is at the forefront of the debate since vulnerable people disproportionately bear climate risks. To better understand the nexus between climate risks and social inequality, we interlink the main transmission channels from climate risks (i.e., physical risks, transition risks, and liability risks) with three leading dimensions of social inequality:

- The interregional aspect of inequality characterizes the unequal distribution of the burdens of climate change between countries.
- The intraregional aspect of inequality characterizes the unequal distribution of the burdens of climate change across income groups within regions.

[1] In economics, a negative externality translates the fact that consuming or producing a good or service can harm, without any compensation, another person.

- The intergenerational inequality, which affects both interregional and intraregional inequality. This describes the unequal distribution of the burdens of climate change across generations.

Regarding physical risks, the three dimensions mentioned above of inequality are concerned. The literature[2] advocates that impacts of natural hazards are borne disproportionately by poor countries (Schelling, 1992; Goklany, 1995; Burton, 1997; Mendelsohn *et al.*, 2006). This is mainly due to their respective locations but also to their vulnerability to climate change, which is heavily related to their development level (Kates, 2000). Thus, the parts of the world expected to be the most vulnerable to climate change are also the most under-developed (Mellinger *et al.*, 2000). Moreover, extreme events are expected to significantly impact poverty hubs within poor regions where adaptation is inadequate (Tol, 2002; Mendelsohn *et al.*, 2007; Byers *et al.*, 2018; Harrington *et al.*, 2016; Formetta and Feyen, 2019). This is particularly the case for resources depletion (Redclift and Sage, 1998), floods and droughts (Jongman *et al.*, 2015), indirectly through health risks (Kolstad and Johansson, 2011), food insecurity and soil depleting crops (Hallegatte and Rozenberg, 2017; Hasegawa *et al.*, 2018). As we are not inclined to drastically reduce our GHG emissions in the coming years (UNEP, 2019), the aforementioned facts concerning physical and social risks are expected to surge in the coming decades, more frequently and with a greater impact (IPCC, 2021). Delaying action to curb the CO_2 concentration, and similarly, the global mean temperature is shifting the burdens of climate change onto future generations. This is the well-known argument of the "*tragedy of the horizon*" (Carney, 2015). This sword of Damocles weakens the availability of resources to maintain living standards and well-being. The intergenerational aspect of climate change is predominantly associated with physical risks.

Given that the development of a country is also a function of its fossil-fuel dependency, the world's most developed regions have the most outstanding share of the global carbon footprint. As a result, those countries shoulder the greatest responsibility for global warming and should bear the brunt of adaptation and mitigation costs. This statement refers to the climate justice argument, which is closely related to the polluter pays principle (Neumayer, 2000; Heyward, 2007; Comim, 2008; Klinsky and Dowlatabadi, 2009; Füssel, 2010; Jakob and Steckel, 2014; Leimbach and Giannousakis, 2019). Thus, there is a negative correlation between a country's vulnerability to climate risks and the share of global emissions (Tol, 1997; Roberts, 2001; Füssel, 2010). From the liability aspect, rich regions should disproportionately support the cost of fighting climate change. In contrast, the direct effects of climate actions, either mitigation or adaptation, might benefit poor regions first (Schelling, 1997; Füssel, 2010; King and Harrington, 2018).

From both the macroeconomic and microeconomic viewpoint, this argument holds. Even if such policies are implemented, intraregional inequality is a pivotal factor in terms of transition risks within developed countries. Instances of civil unrest in France, Chile, and Sweden showed that implementing a carbon tax without redistribution primarily affected the living standard of low-income households. The regressive nature of the carbon tax contravenes the social justice argument, which in turn postpones its implementation (Symons *et al.*, 1994; Wier *et al.*, 2005; Kerkhof *et al.*, 2008; Verde and Tol, 2009; Feng *et al.*, 2010; Baiocchi *et al.*, 2010; Mathur and Morris, 2014). In developed countries, this effect can be explained by the high share of income allocated by poor households to carbon-intensive products such as fossil-fuel cars, electricity, and food, but also by how difficult it is for them to substitute lower-emission products. However, when comparing their absolute emissions with those of

[2] See Semet (2020) for a broader literature review on the nexus between social inequality and physical risks.

high-income households, the amount becomes modest, strengthening the risk of misdirected policies. In addition, even if income inequality (i.e., vertical inequality) can explain a large part of the tax burden, other sources of vulnerability (i.e., horizontal inequality) such as socioeconomic and sociodemographic factors can also prevent the acceptability of the tax (Poterba, 1991; Lenglart *et al.*, 2010; Büchs and Schnepf, 2013; Cronin *et al.*, 2019; Douenne, 2020; Pottier *et al.*, 2021). One potential tool to reverse this adverse effect would be the use of tax revenue. It is well established that social transfers between income groups could reduce the regressive nature of the carbon tax by lightening the tax burden of low-income households (West and Williams, 2002; Metcalf, 2009; Carattini *et al.*, 2017; Berry, 2019; Fremstad and Paul, 2019). Redistribution strongly supports the implementation of the carbon tax while improving the social situation, but at what cost? Reducing income inequality by redistributing tax revenue could, in turn, drive up emissions due to increasing demand for carbon-intensive products (Ravigné and Nadaud, 2021). On the one hand, the carbon tax drives consumption sobriety by dissuading households from consuming carbon-intensive products and significantly reduces GHG emissions. On the other hand, consumption sobriety is not a one-size-fits-all solution since price increases can push vulnerable households into poverty. Thus, social transfers can correct the impediment of the carbon tax design at the cost of environmental improvement. This would ultimately result in a trade-off between social and environmental objectives.

In this context, any effort to produce either adaptation or mitigation progress must consider these three sources of social impediments (Mendelsohn *et al.*, 2006; Nightingale, 2009). However, the social risk in climate economic modeling is still a secondary parameter (Kirman, 1992; van Ruijven *et al.*, 2015; Hallegatte and Rozenberg, 2017; Rao *et al.*, 2017). The uncertainties induced by considering social inequality lead to ignorance or under-assessment by many models (Stern, 2006; Saelen *et al.*, 2008; Stanton *et al.*, 2009). Studies that consider these elements together are rare. It appears that the climate urgency is pushing practitioners towards a trade-off between environmental and social considerations, whereas a core purpose of these policies should be to reduce environmental footprints and also alleviate poverty and income inequality within a common framework (Arrow *et al.*, 1996; Shue, 1999). At the global level, the few studies that consider social inequality produce different conclusions on the sustainability pathway the world should follow (Dennig *et al.*, 2015; Rao *et al.*, 2017; Anthoff and Emmerling, 2019; Czupryna *et al.*, 2020). This study seeks to understand the nexus between the two aspects and shed light on their potential trade-offs.

The rest of the paper is structured as follows. In Section 2, we review some important works on incorporating social inequality into climate economic modeling. One prominent tool is the NICE model of Dennig *et al.* (2015), an IAM that incorporates social inequality into a common framework to compute the optimal social cost of carbon. Based on various improved versions, we could assess the relevance of including intraregional risk to optimize and study several redistribution processes at the global level. We also complement this modeling analysis with a short review of the findings from researchers working on income inequality projections in accordance with the shared socioeconomic pathways (SSPs). In Section 3, we empirically inspect the social risk induced by the transition risk in France at the household level. After analyzing the distribution of the carbon footprint across income groups, we estimate the welfare impact of a €100 per ton of CO_2e carbon tax from an environmental and social viewpoint. We aim to emphasize a potential backfire effect of revenue recycling. Section 4 offers some concluding remarks.

2 A review of social inequality in climate economic modeling

Cost-benefit analyses of climate policy have been widely studied through IAMs. Those models compare the costs induced by implementing environmental policies with the long-term benefits of such policies. Welfare-maximization of GHG reduction strategies produces an optimal pathway of CO_2 emission expected to converge toward a Pareto optimal solution, meaning that the policy might correct the emissions path compared to the business-as-usual situation with the aim of increasing the global welfare. Usually, the model's framework is composed of two modules, the economy and the environment, which are linked by causal chains. While the feedback flows between the environment and climate change can be infinitely complex to model, the interaction between the environment and the economy seems straightforward: economic activities emit GHG, and GHG emissions warm Earth's temperature, leading to irreversible economic damages and provoking growth losses. Given these interactions, the social planner optimizes a social welfare function characterized by the inter-temporal utility of consumption. Since the level of consumption depends on the economy's growth, the social planner seeks to reach the Pareto optimality under a set of constraints and a number of assumptions. The model's output is known as the social cost of carbon (SCC), a metric translating the quantifiable costs of emitting one additional ton of CO_2 in terms of current consumption. This amount represents the shadow price of carbon, which cannot be interpreted as the implicit price of a carbon tax in the economy.

2.1 Conceptual overview

2.1.1 The DICE model as a baseline model

The seminal Dynamic Integrated model of Climate and the Economy (DICE) model of Nordhaus (2017) is commonly presented as a reference model thanks to its simplicity. The DICE is based on the neoclassical growth theory in which agents invest in capital, education, and technology to increase consumption in the future. The model optimizes a social welfare function (SWF) that ranks consumption paths given a set of economic and geophysical constraints. The SWF can be defined as the discounted sum of the population-weighted utility of per capita consumption. In the case of one aggregate region, the model maximizes a single utility function, which is a decreasing function of per capita consumption. When the current level of mitigation is low, future generations lose income due to climate damage. When the current level of mitigation is high, investment decreases the consumption of current generations to preserve consumption in the future. The assumption of economic growth theory implies that per capita consumption is an increasing function across time while the marginal utility of consumption is diminishing. The social planner optimizes the utility regardless of income or consumption by making a trade-off between climate damages (i.e., future costs) and abatement costs (i.e., current costs). We propose a more detailed presentation of the DICE model in Appendix B.1 on page 95.

2.1.2 The debate over the discount rate

The central parameter in inter-temporal economic modeling is the discount rate. Originally, discounting was used to assess the future payoff of an investment in current monetary value. It enables determining if the future benefits of the investment justify the current costs. In the case of the inter-temporal problem of climate change, the current mitigation of GHG emissions is the investment required to improve the expected benefits of reducing the damages. Formally, the future benefits induced by reducing current emissions should be greater than the loss of current welfare required to curb pollution. The discount rate can be viewed as a "*cursor*" that moves across time to give more or less weight to one specific generation. In other words, discounting permits to gauge the importance of the present compared to the future. Indirectly, this discount rate is the principal social aspect, and maybe the only one, to be represented in many IAMs. As future generations can be more or less important compared to present generations, discounting speaks for intergenerational inequality. Given the large time span of temperature stabilization, the optimization deals with centuries-long maturities. Adjusting the discount rate by an incremental change could considerably modify the path. A high (low) discount rate implies a higher (lower) significance of present generations. It is important to distinguish between "*prescriptive*" and "*descriptive*" approaches to discounting (Arrow *et al.*, 1996). The former approach considers philosophical insights to translate intergenerational ethics and morals. The latter approach forms the discount rate by taking empirical proxies and, more precisely, the market interest rate and the consumption preferences of individuals. The rationale behind choosing the interest rate as the discount rate is that investing in a project with a lower rate of return than the market rate will be sub-optimal. However, it is impossible to observe a liquid asset with a time horizon and a risk profile identical to climate change, suggesting that the two approaches tend to complement each other (Gollier, 2013).

Following the work of Ramsey (1928), the "*prescriptive*" discount rate is built on two components. The first component is the rate of pure time preference (ρ), which refers to the discount rate's ethical aspect. The rate of pure time preference is used to estimate the present value of utility at any future date. Given that utility maximization depends on consumption, this rate typically discounts the value of future consumption. Putting it differently, this parameter transcribes the impatience of individuals, which transcribes if an individual cares more or less about future consumption than today. A high rate suggests a lower weight accorded to future generations' well-being than today's. The second component is the product between the consumption elasticity of marginal utility (η) and consumption per capita growth rate (g). The consumption elasticity of marginal utility describes the decreasing marginal utility associated with consumption over time (i.e., how fast an extra unit of consumption declines utility as consumption rises)[3]. In the case of global aggregation, assigning a high value to this parameter suggests that greater importance is given to future generations' welfare than to current generations' welfare. The growth rate of per capita consumption is assumed to be positive over a long period, implying that future generations will be wealthier than current generations. This is a central assumption in inter-temporal modeling since a change in income in a rich world has a lower weight than a similar change in a poorer world. In that context, a decreasing marginal utility of consumption means that the future world is less important than the relatively poorer present. Under the hypothesis of a positive growth rate, a greater value assigned for either ρ or η will raise the discount rate and, thus, delay mitigation. The discount rate has the following form:

$$r_t = \rho + \eta\ g \tag{1}$$

For Ramsey (1928), the appropriate value of ρ is zero, arguing that all individuals, no matter their respective generation, should be valued the same and if not, the economic argument would be "*ethically indefensible and arises merely from the weakness of the imagination*". This altruistic approach values future consumption in the same manner as current consumption. Cline (1992) was the first economist to argue for a rate of pure time preference of zero in the climate economic modeling, saying that "*morally there is a greater responsibility to avoid imposing harm on others than there is to make sure they can enjoy an extra benefit*

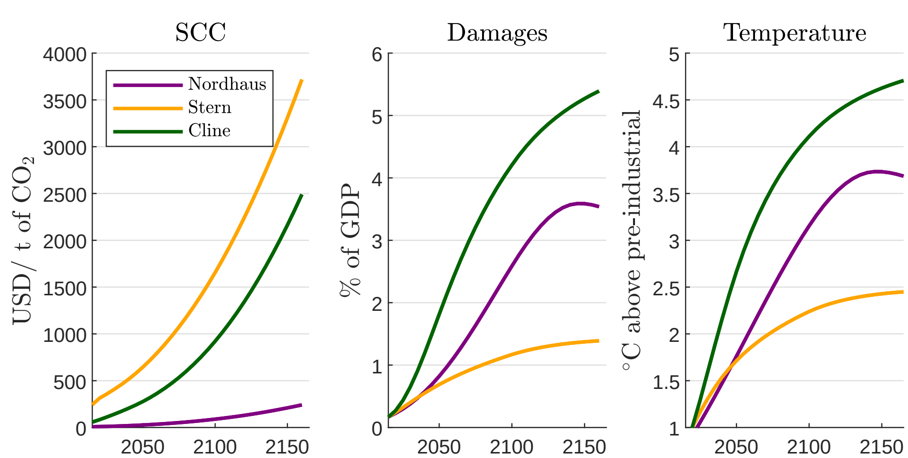
[3]The concavity of the utility function implies that a given loss of consumption has a more considerable impact on utility than an equivalent increase.

at a cheap cost". Setting a pure time preference value of zero implies that future costs and benefits are just as important as the value of current gains and losses. Conversely, in setting a positive and high rate of pure time preferences, we assumed that the gains from reducing climate change would be small. Sen (1982) advances that even if the marginal utility from the welfare gain is lesser than the marginal welfare loss of present generations, they might act to avoid long-term environmental degradation. Nordhaus (2007) used market interest rates to account for the opportunity cost of capital, implying a higher discount rate.

Assuming a low growth rate or even a negative GDP per capita growth in the future conflicts with the economic growth theory. However, resource scarcity, the long-lasting effects of climate change on biodiversity, or the declining marginal productivity of the production factors could support this assumption. According to a more pessimistic scenario, a declining consumption growth rate induced by the consumption deterioration over time would imply a negative discount rate (Dasgupta *et al.*, 1999; Fleurbaey and Zuber, 2012). The effect of climate damages on GDP could even be more accentuated in poor regions (Moore and Diaz, 2015). Under this hypothesis, future generations are poorer than the existing ones, advocating more sacrifices today to improve the well-being of future generations. Therefore, this rate should not be constant over time since g could vary substantially. Here, uncertainty is mainly characterized by the calibration of the damage function to GDP, which seems to be underestimated in several IAMs (Dietz and Stern, 2015).

In Figure 1, we illustrate the importance of discounting in the economic modeling of climate change. We present the different paths of the social cost of carbon, the damages fraction in terms of GDP, and the atmospheric temperature given a set of parameters for the discount rate. The purple curve translates the assumptions of Nordhaus (2007) in the DICE model, with $\rho = 1.5\%$, $\eta = 2$, and $g = 1.3\%$. The yellow curve takes the assumptions of the PAGE model of Hope (2006) used by Stern (2006) with $\rho = 0.1\%$, $\eta = 1$, and $g = 1.3\%$. Finally, the green curve illustrates the assumptions made by Cline (1992), with $\rho = 0$, $\eta = 1.5$ and $g = 1.3\%$. Applying the Ramsey rule, given in equation (1), we obtain a discount rate of 4.10%, 1.40%, and 1.95% for Nordhaus, Stern, and Cline, respectively.

Figure 1: Discount rate simulations on the social cost of carbon, natural damages and temperature across time



As illustrated in this figure, the results of the models differ substantially, given the assumption made on the discount rate. The paths are sensitive to relatively small changes in this rate mainly due to the vast horizon of the optimization problem. Even if we know that the discount rate selection is a value judgment of the modelers, these parameters have enormous repercussions on the final output. For instance, an incremental change in the discount rate displaces the carbon price from \$35/tCO_2 in 2015 for Nordhaus to \$360/tCO_2 for Stern in the same year, all else being equal. Inevitably, along these pathways of CO_2 emissions, the fraction of damages amounts to more than 2% of GDP for Nordhaus and less than 1% of GDP for Stern in 2070. The repercussion of this rate on long-term atmospheric temperature is alike. Only a quick reaction of current generations would curb the rise of temperatures. In a way, the discount rate justifies the aggressiveness of the climate policy. A high rate implies a smooth implementation of carbon policy, while a low rate fosters immediate action. We understand the ethical argument for reducing the discount rate through these projections. If we suppose low discounting, the optimal policy is aggressive enough to curb current emissions and make the world healthier in the future.

2.1.3 The RICE model and the sub-regional issue of welfare

More complexity can be introduced in AIM to differentiate equations for several regions. The Regional Integrated model of Climate and the Economy (RICE) model developed by Nordhaus and Yang (1996) is a sub-regional neoclassical climate-economy model[4]. There are twelve different regions[5] producing a single good. The time dimension starts from 2005 to 2605 with a ten-year time timespan. The representative agent in each region makes choices of either to consume or to save. An overview of the model can be found in Appendix B.1 on page 96. The RICE methodology consists of solving the Ramsey saving problem for the twelve regions given the previous equations. The model is solved in two steps. The first step consists of estimating the optimal saving rates ($s^*_{i,t}$) in the absence of mitigation ($\mu_{i,t} = 0$). These optimal saving rates permit to estimate the optimal consumption in this baseline run. Then, the relative weights of the welfare function are estimated. They are defined as the inverse of the marginal utility of consumption at the baseline consumption level. In the second step, the mitigation policy is estimated, given the Negishi weights. The optimal policy is chosen when the marginal cost of mitigation is equalized across regions. Finally, given a carbon tax (τ_t), the mitigation rate for each region i is estimated.

When focusing on regional desegregated models, each region of the world has a different utility function. The optimization problem is similar to the previous one, but instead of maximizing inter-temporal welfare, the model maximizes the sum of utility in all regions. However, knowing that the decreasing marginal utility of consumption is similar for each region, solving the optimization problem could be optimal by transferring income from rich to poor regions. Modelers have principally used the Negishi process of weighting welfare to overcome this drawback. This process assigns welfare weights to regions depending on the share of global welfare the region accounts for. It enables to get rid of global welfare gain following income redistribution. This indirectly leads to attaching more importance to the welfare of the wealthiest part of the world than in the poorest regions. In doing so, the maximization of welfare suggests that every region has the same income per capita and mechanically disregards existing income distribution. In other words, little concern is addressed on the interregional justice argument. As emphasized by Stanton *et al.* (2009), inequality across time seems to be material to transfer costs between poorer and wealthier generations, while spatial inequalities do not represent a legitimate ground for shifting costs between

[4]The RICE model has been developed since 1996 and thoroughly improved. Here we present the RICE-2011 version (Nordhaus, 2011).

[5]The regions are the United States, the European members of OECD, Japan, Russia, non-Russia Eurasia, China, India, Middle East, Africa, Latin America, Other High-income countries, and non-OECD Asia.

poorer and wealthier regions. That is to say, the social planner scrutinizes the inequality aversion across time, while inequality aversion across space is insubstantial. Without this constraint, the model framework will converge toward a more significant consideration of climate impacts in low-income regions. When regional desegregation is performed, as in the RICE model, the current income distribution is assumed to be optimal in the social welfare function maximized. One leading framework that considers this caveat is the Nested Inequality Climate Economy (NICE) model developed by Dennig *et al.* (2015).

2.2 The incentives to take households heterogeneity

2.2.1 From RICE to NICE

With the NICE model, Dennig *et al.* (2015) have extended the RICE by integrating heterogeneous agents in estimating the optimal carbon tax. By including income quintiles in each region, the model takes into consideration the level of current inequalities within regions to study their implications on the optimal climate policy. This also permits to make different assumptions about the distributional effects of climate damages and mitigation costs. Heterogeneous agents imply a more granular representation of social strata than global aggregate in the case of DICE or regional aggregate in the RICE. Although a fair regional split improves the accuracy of a carbon tax, the hypothesis of a regional representative agent still restricts the analysis to average levels. Moreover, the lack of consideration of the distributional effects of climate risks misdirects the optimal pathway of the SCC. Something emphasized by Dennig *et al.* (2015):

> "*If the distribution of damage is less skewed to high income than the distribution of consumption, then weak or no climate policy will result in sufficiently large damages on the lower economic strata to eventually stop their welfare levels from improving, and instead cause them to decline.*"

In the knowledge that the repercussions of climate change are expected to hit harder the poorest regions, lower-income groups in these regions are indirectly excluded in the estimation of the optimal tax in IAMs. However, the low-income groups are naturally more vulnerable to environmental damage since they are unable to cope with this burden. The income elasticity of damages is, therefore, greater for them. Moreover, low-income groups are also vulnerable to income shocks related to changes in energy product prices and constrained consumption behavior. As a consequence, considering these impacts on consumption distributions within regions would lead to a more accurate estimation of the climate policy. While keeping the common assumption for the other parameters, the model determines other optimal trajectories, yielding dramatic changes in policy aspects.

The model construction As in the 2010 version of the RICE, the model optimization seeks an optimal carbon tax that maximizes the social welfare function defined by:

$$\mathcal{W}^{\text{NICE}}(c_{i,j,t}) = \sum_{i,j,t} \frac{L_{i,j,t}}{(1+\rho)^t} \frac{c_{i,j,t}^{1-\eta}}{1-\eta} \tag{2}$$

where $c_{i,j,t}$ is the consumption of region i of population quintile j at time t, and L the population. The social welfare function has a constant elasticity form, where η represents the elasticity of marginal utility, independent of whether the inequality is considered across contemporaries or across time. The Negishi weights are excluded from the function since the model restricts redistribution between regions. The central point of the NICE is to introduce population j's quintiles within the twelve regions. These quintiles are computed from the World Bank Development indicators. One specificity of the NICE model comes from the savings rate. For simplicity, the savings rate is not assumed to be endogenously chosen by economic agents according to climate damages and policies but rather set endogenously without a relationship with climate policy. The savings rate of an infinitely lived agent is given by:

$$s_{it} = \frac{\mathcal{C}}{(1+\rho)^{10}} \tag{3}$$

where $\mathcal{C}$ is the capital share in the Cobb-Douglas production function. The authors argued that this rate can be interpreted as the optimal savings rate of an economic agent with a logarithmic utility function, a time-separable and discounted objective[6]. This rate is fixed across time and regions, making a strong assumption on consumption behaviors. Given population $L_{i,t}$, and the saving rate $s_{i,t}$, the regional average consumption is defined by:

$$\bar{c}_{i,t} = \frac{1-s_{i,t}}{L_{i,t}} Y_{i,t} \tag{4}$$

where $Y_{i,t}$ is the economic growth of region i at time t. The desegregated pre-damage consumption quintiles are computed by:

$$c^{\text{pre}}_{i,j,t} = \bar{c}_{i,t} \left(\frac{1+D_{i,t}}{1-\lambda_{i,t}} \right) q_{i,j} \tag{5}$$

where $q_{i,j}$ is the income share of the j^{th} quintile in region i, $D_{i,t}$ represents damages and $\lambda_{i,t}$ is the mitigation cost . The post-damage consumption is given by:

$$c^{\text{post}}_{i,j,t} = c^{\text{pre}}_{i,j,t} - \bar{c}_{i,t} \frac{(1+D_{i,t})}{(1-\lambda_{i,t})} \lambda_{i,t}\ \mathbf{e}_{i,j} - \bar{c}_{i,t} D_{i,t}\ d_{i,j} \tag{6}$$

where $d_{i,j}$ is the damage share of the j^{th} quintile in region i, and $\mathbf{e}_{i,j}$ is the share of mitigation cost of the j^{th} quintile in region i, respectively defined by:

$$d_{i,j} = k_i^{\xi}\ q_{i,j}^{\xi} \text{ and } \mathbf{e}_{i,j} = k_i^{\omega}\ q_{i,j}^{\omega}$$

where ξ is the income elasticity to damages and ω is the income elasticity to mitigation costs. k_i^{ξ} and k_i^{ω} are constants chosen so that $\sum_j d_{i,j} = 1$ and $\sum_j \mathbf{e}_{i,j} = 1$ ensuring that only the distribution rather than the total amount of costs and damages, is modulated by the elasticity parameter.

Remark 1. *To illustrate, let us assume a population with two income groups, A and B, with A earning \$4,000 and B \$40,000. For a damage of 5%, the two income groups jointly lose \$2,200. In the case of proportional elasticity ($\xi = 1$), A loses \$200, and B loses \$2,000. In the case of independent elasticity ($\xi = 0$), both A and B lose \$1,100. In the case of inversely proportional elasticity ($\xi = -1$), A loses \$2,000, and B loses \$200. Assuming A and B experience a 2.5% abatement cost, the total joint cost amounts to \$1,100. In the case of $\omega = 0$, both A and B pay \$550. When $\omega = 1$, A pays \$100 while B pays \$1,000. When $\omega = 2$, A pays \$10.9 and B pays \$1,089. From this illustrative example, we understand that ξ and ω affect the distribution of damages and the mitigation costs but do not impact the total amount of regional damage and abatement costs.*

[6]Given $\mathcal{C} = 0.3$, $\rho = 1.5\%$ and a capital depreciation of 10% per year, the optimal saving rate equals 25.8%.

2.2.2 Households heterogeneity and the optimal carbon price

Assuming a distribution of damages ranging from -1 to 1 relates to the previously developed climate justice argument. In the world's poorest regions, the exposure and vulnerability of low-income people are expected to be high. As climate change risks surge, the social risk is even more alarming. Early estimates of people falling into extreme poverty suggest an increase of 122 million by the end of 2030 (Hallegatte and Rozenberg, 2017; Jafino *et al.*, 2020). The environmental risks represent a poverty multiplier, making poor people even poorer, through impacts on agriculture and food prices principally (Hasegawa *et al.*, 2018) but also through health burden (Kolstad and Johansson, 2011). This poverty escalation will ultimately put pressure on the average global incomes and their relative distributions, widening global inequality (Burke *et al.*, 2015; Diffenbaugh and Burke, 2019). The effects are mainly expected to hit Sub-Saharan Africa and South Asia but could also jeopardize developed countries where income inequality is also material. The repercussions of climate change are thus likely to overwhelm people experiencing poverty, strengthening the choice of income elasticity of damages less than 0.

Considering the income elasticity to abatement, the authors assume a parameter value between 0 and 2. In other words, the cost of mitigating CO_2 will be supported principally by high-income quintiles. However, this assumption can be contested. Since a substantial share of expenditures made by poor households is devoted to energy, one could expect that the impact of a carbon tax is more unevenly distributed, implying $\omega < 0$. Nonetheless, as suggested by the authors, a negative value could be unsuitable and even unthinkable to model. For instance, keeping with the baseline scenario in the Remark 1, setting $\omega = -1$ will result in \$1,000 expense for A and \$100 expense for B, that is, 25% and 0.25% share of income for A and B respectively[7].

In Figure 2, we illustrate the direct impact of the income elasticity of damages. Given the value taken by the parameter ξ, we observe substantial differences in the policy trajectories. The backstop price, representing the price at which zero emissions technologies are assumed to be competitive with carbon-intensive ones, is integrated into the plot[8]. When the backstop technology is available, it will help to lessen the side effects of mitigation costs and maximize the welfare gains from the policy when the technology is efficient. For instance, assuming proportional impact of damages on income, the path of the social cost of carbon is smooth, very close to the one simulated for the RICE model. Therefore, when damages are expected to hit richer individuals more heavily than poorer ones, the model suggests a carbon tax similar to the RICE model, suggesting that the RICE model indirectly assumes no income inequality within regions[9]. When the elasticity parameter is set to be inversely proportional, the carbon price is substantially shifting. The maximization of inter-temporal welfare results in a higher shadow price at the beginning of the period. We observe that the $\xi = -1$ trajectory coincides roughly with the Stern trajectory we simulated using discounting and inequality aversion assumptions of 0.1% and one, respectively. We understand that in its assumptions, Stern indirectly integrates greater importance to income inequality and especially a greater exposure of poorer individuals to climate damages. As emphasized by Weitzman (2007), the results of the Stern Review are all related to the same conclusion, to model "*the uncertain distribution of damages*". In the baseline scenario, $\xi = 0$, the carbon tax stays in the middle of the road, with a lesser price than Stern's one but reaching a temperature trajectory below 2°C. Overall, assuming a greater exposure of poor people

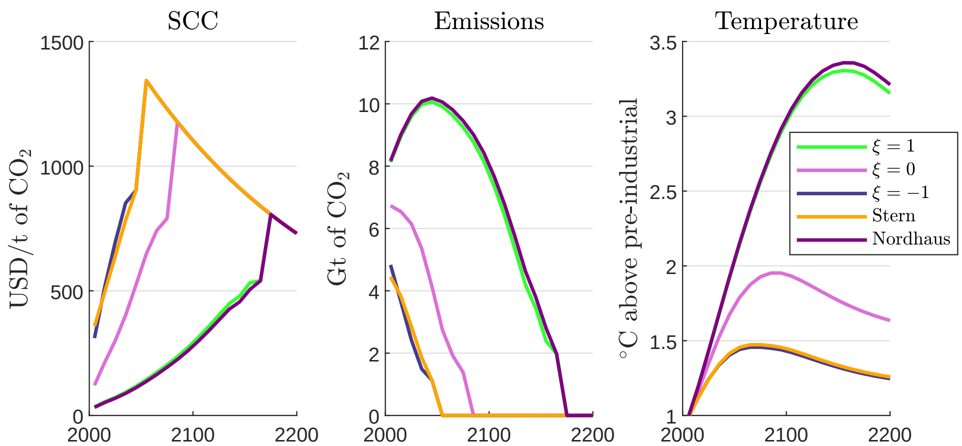
[7] The distribution of the carbon tax burden and the underlying effects of such a regressive carbon tax receive more importance in Section 3.

[8] The price of the backstop technology is decreasing by 0.5% per year.

[9] The estimation of the RICE of Nordhaus in the Figure 2 has been deduced by the implementation of the RICE under the discounting and inequality aversion values of Nordhaus, $\rho = 1.5\%$ and $\eta = 2$.

to damages affects the maximization of welfare and yields the implementation of a more aggressive mitigation policy than is usually proposed without heterogeneous agents and the distributional effect of damages and mitigation costs.

Figure 2: ξ simulations on the social cost of carbon, Gt of CO_2 and temperature across time



Source: Dennig *et al.* (2015).

2.2.3 The Schelling's conjecture

Taking into account the income distribution of individuals has several implications for the inter-temporal maximization of welfare. A key concern is related to the discount rate. We have previously stated that the discount rate of the Ramsey formula is a positive function of the inequality aversion parameter, meaning that a positive value raises the discount rate that reduces the climate policy's aggressiveness. However, when income distribution is considered, believing that a high inequality aversion leads to delayed action is suspicious. This argument has been proposed by Schelling (1995):

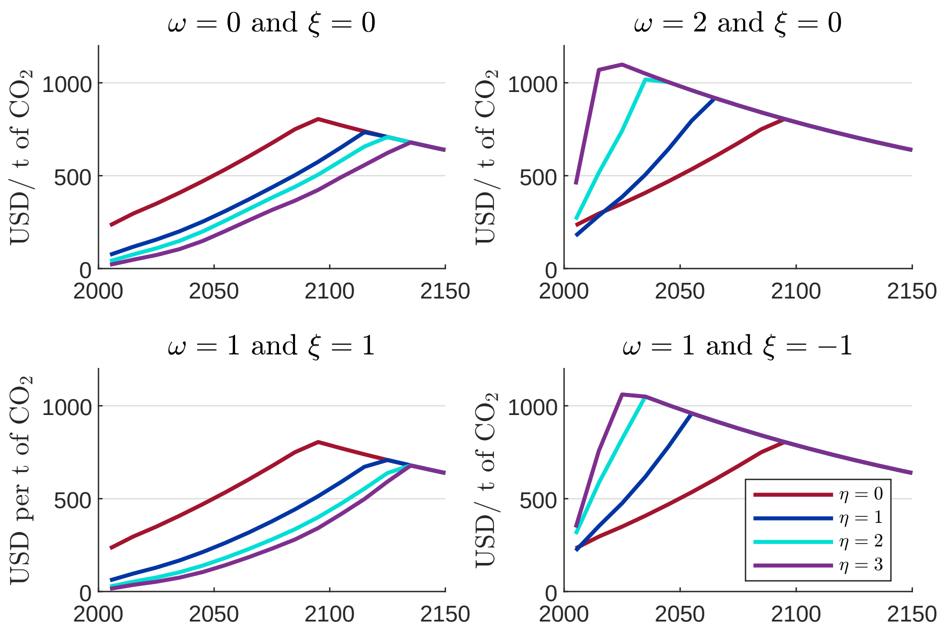
> "*[...] once we disaggregate the world's population by income level, it becomes logically absurd to ignore present needs and concentrate on the latter decades of the coming century.*"

Using the NICE model, Budolfson *et al.* (2017) examined the argument of Schelling, known as Schelling's reversal. In the study, they investigate the occurrence of the reversal when inequalities between regions and within regions are correctly accounted for. The idea is to simulate different trajectories of SCC given social objectives that account for a specific dimension of inequality. In other words, under a different set of parameter values, the optimal carbon price varies according to whether the objective focuses on intergenerational or interregional inequalities.

In Figure 3, we report the different pathways according to several setups of parameter values. The four panels represent the optimal carbon price for different elasticity values ($\eta \in 0, 1, 2, 3$) as well as different values for ξ (i.e., the income elasticity of damages) and ω (i.e., the income elasticity of abatement costs) under a rate of pure time preference of 2%

and a positive rate of growth. Compared to the previous optimal prices, these prices are slightly lower due to the assumption on the backstop price[10].

Figure 3: Simulations of SCC trajectories given several η values



Source: Budolfson *et al.* (2017).

When there is no inequality aversion, $\eta = 0$, the optimal price is similar in each panel, erasing the cost-benefit trade-off and, at the same time, the distribution of abatement costs and damages across quintiles. In this case, the price is relatively high (\$233/tC in 2015) because the discount rate only depends on ρ, meaning that the future damages are not discounted relative to abatement costs. Considering the first row, the right side panel assigns a lower income elasticity of abatement cost value while the left side panel assigns a higher value. In the second row, following the same logic, the left side panel combines a proportional income elasticity of damages, whereas the right side panel combines an inversely proportional income elasticity of damages. As shown in the left side panels, when the current poor are more integrated into the optimization ($\xi = 1$ or $\omega = 0$), we observe that increasing the inequality aversion tends to lower the value of the SCC. That is, the distribution of mitigation costs is more regressive, while the damages are distributed in a progressive manner. In the first case, decreasing the mitigation burden benefits the current poor, suggesting that when more concern is attributed to the poor, the optimal carbon price tends to be alleviated. In the second case, more mitigation benefits the future richest more than the future poor, so increasing the inequality aversion tends to favor the current poor, suggesting a lower optimal carbon price. In both cases, the rationale of Ramsey's equation stands for high inequality aversion when the distribution effects are light, delaying

[10]Here, it is assumed that all regions have a backstop price equal to the world's backstop price. In the previous specifications, each region has its backstop price, expressed as a proportion of the world's backstop price as in the original RICE model.

the policy's aggressiveness. Conversely, the opposite theory is also true. As shown in the right side panels, the future poor are more integrated into the optimization ($\xi = -1$ or $\omega = 2$) than in the previous specification. When the current rich predominantly bear the mitigation costs ($\omega = 2$), the current poor stay out of the mitigation cost burden. As the inequality aversion increases, the optimal carbon price increases as well. When future damages are borne predominantly by the poorest rather than the richest, greater inequality aversion increases the carbon price to protect them, even if future generations will be more prosperous. In this configuration, the Ramsey equation does not stand, handing over to Schelling's Reversal effect, meaning that the inequality aversion effect is inverted when sub-regional inequalities are internalized. Schelling's Reversal is likely to happen when the poor benefit from mitigation while not paying for it.

2.2.4 Income inequalities and consumption paths

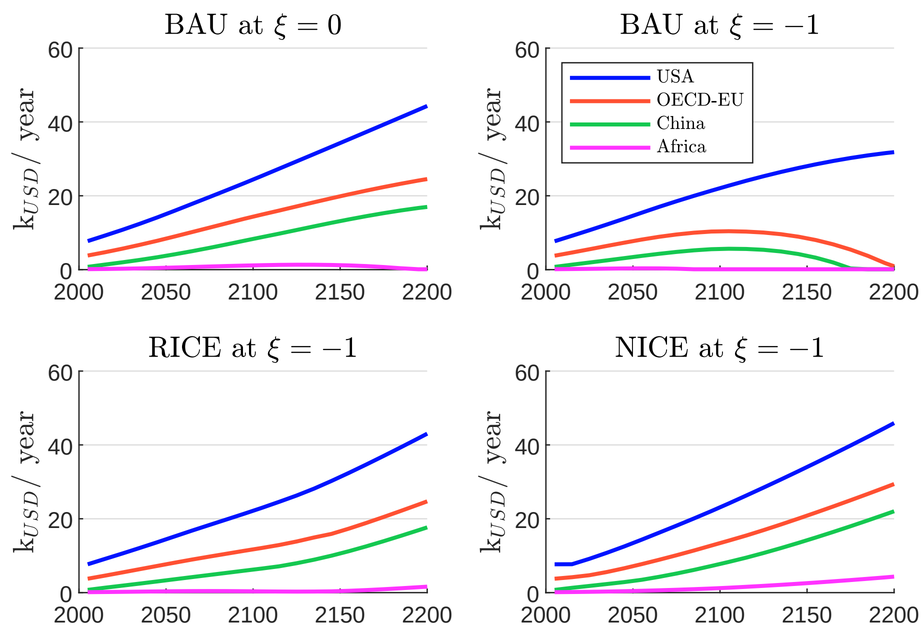
Developing sub-regional income quintiles aims to provide a better approach to understanding the need for social inclusion in climate economic modeling. The rationale is straightforward: low-income groups' high exposure to climate damages is extensively more concerning as their capacity to cope with these damages is feeble. As long as climate modeling integrates a representative agent with average region endowments (income, preferences, utility, etc.), low-income groups would be predominantly excluded from the analysis. Since the expected mitigation benefits are larger in poorer regions, a high carbon tax should reduce social inequality between generations within these regions. However, a high, global, and uniform carbon tax could lead to productivity shortfall and income losses in poor regions. Intuitively, there might be a reversing effect, which increases social inequality in the short run and suggests a trade-off between social and climate considerations.

In Figure 4, we illustrate the consumption path of the lowest income quintile (Q1) for different assumptions over the mitigation trajectory and the elasticity rate. The paths are selected for the United States (USA), the European members of the OECD (OECD-EU), China, and Africa. The two left panels are based on the business-as-usual (BAU) scenario in which no policy is implemented to reduce the economy's carbon intensity under the standard assumption of both ρ and η. To obtain these paths, we set the abatement cost to zero. As a result, economic growth is not constrained by the abatement cost but only impacted by climate damages. Hence, the per capita consumption of every region is only affected by damages. In the third panel, the average per capita consumption from the RICE of Nordhaus is transformed into consumption per quintile given the standard assumption of the original model but with an inversely proportional income elasticity to damages. In the fourth panel, the per capita consumption of the lowest quintile is computed using the NICE model.

In several regions, the climate damages-induced losses are skewed toward the lowest income group. When the emission path is assumed to follow a scenario with no policy implementation and an independent distribution of damages, per capita consumption of the lowest income quintiles in the United States, European members of the OECD, and China is expected to grow. The African region does not share a similar trajectory. The burden of climate change is predominantly borne in this region among others[11]. The effect is even more marked when the elasticity parameter is negative ($\xi = -1$). In this case, the consumption path of the poorest quintiles has a parabolic shape over the long term, even in developed European countries. In this situation, the gains of the lowest quintiles in Africa are approximately zero throughout the time span. Inevitably, climate change

[11] The following regions are also showing high exposure of diminishing per capita consumption under the same scenario: Latin America, Other non-OECD Asia, non-Russia Eurasia, and Middle East.

Figure 4: Per capita consumption net of damages for the lowest income quintile (Q1) across time and regions



Source: Dennig *et al.* (2015).

inaction increases the exposure of the poorest, ascertaining that the poorest are left behind in the climate change debate. This argument is also testified by the third panel in which the Nordhaus model is represented. We observe that the consumption gains are again close to zero in Africa while increasing in the other regions. Therefore, the assumption of the model is underestimating the underlying impacts of climate damage in the poorest income strata. On the opposite, when the optimization takes the distribution of income into account, income groups in each of the represented regions can expect a steady increase in per capita consumption. Considering the heterogeneity in income distribution permits to optimize the welfare gain of the poorest without neglecting the welfare of the richest. The mechanism is straightforward: the higher the carbon cost, the lower the damages. As soon as implementing a global carbon tax leads to consumption growth in each quintile, especially for the lowest one, the carbon tax becomes optimal. The model estimates the welfare consequences of ignoring the distribution of climate change damages. The results shed light on the incompatibility of current IAMs to support an inclusive pathway toward decarbonization. If there is no consideration of social justice in the climate debate, the tax will be optimal only in a few parts of the world, making a trade-off between environmental targets and interregional and intergenerational inequalities achievements.

2.2.5 Social transfers to alleviate vulnerability

As emphasized by Dennig *et al.* (2015) and Byers *et al.* (2018), the distributional issue of climate change is critical since the current level of income inequality within and between countries is still ominous. In other words, the lack of transfers between high- and low-income quintiles and between developed and emerging countries hampers the environmental transition. Thus, we assume that nonexistent or inefficient social transfers throw a spanner in the works of climate policy. Regarding the climate justice argument, the optimal climate policy should be preceded by social policies. Turning to a more egalitarian income distribution will not hamper climate hazards but might alleviate the vulnerability of low-income people.

A redistribution process might be deployed to understand better the social transfer required to decrease the vulnerability of the population highly exposed to environmental damage. The NICE model is a valuable tool to examine the underlying effects of such transfers. The idea is to assess if the additional mitigation effort computed here could be withdrawn following the introduction of an exogenous level of income redistribution. A revenue-neutral flat tax is added to the post-damage consumption levels. It is redistributed equally as a lump-sum basic income. Authors investigate the value of a potential tax that will lead to the carbon price initially obtained in the RICE model, even when $\xi = 0$. Two variants are studied. Firstly, the transfers are considered only within regions. The tax rate transfer is the same across regions and time. Secondly, the transfers are assumed to be cross-regional. More specifically, the wealthiest four regions assist the residents of the eight poorest regions by distributing in equal quantity a share of the tax collected[12]. At this point, the post-damage consumption is modified as follows:

$$c^{\text{post}}_{i,j,t} = (1-\bar{\tau})c_{i,j,t} + \varrho_{i,t} \tag{7}$$

where $\bar{\tau}$ is the marginal tax rate and $\varrho_{i,t} = \bar{\tau}\ \bar{c}_{i,t}$. This is similar to a revenue-neutral transfer within regions. For the cross-regional transfers, a constant proportion ζ is levied on the consumption of the donor region $\mathcal{D}$:

$$c^{\text{tax}}_{i,j,t} = (1-\zeta)c_{i,j,t} \quad \forall i \in \mathcal{D} \tag{8}$$

The consumption of the receiver regions is given by:

$$c^{\text{aid}}_{i,j,t} = c_{i,j,t} + \frac{\Omega_t}{\sum_{i \notin \mathcal{D}} L_{it}} \tag{9}$$

where $\Omega = \sum_{i\in\mathcal{D}} \zeta\ \bar{c}_{i,t} L_{i,t}$ represents the total amount of aid. These transfers consist of calibrating the tax to generate the same optimal mitigation effort in two scenarios: (i) NICE with the re-distributive tax and $\xi = 0$ and (ii) RICE without redistribution.

Intraregional social transfers In the first case, the results of Dennig *et al.* (2015) suggest that the redistribution of the tax on consumption amounts to 65% in order to find convergence between the two carbon price trajectories. More precisely, if the redistribution revenue of a 65% flat tax were implemented in every region and every period, the optimal carbon price trajectory at $\xi = 0$ would be close to the optimal carbon price trajectory at $\xi = 1$ without redistribution. This result points out the inefficiency of the original RICE model to account for ethical arguments. Indeed, it becomes an acceptable shadow price trajectory only if a substantial amount of the tax redistribution is implicitly undertaken to correct the no inequality assumption.

In Table 1, we illustrate the implicit effect of the redistribution process, expressed as the value of the damage in the percentage of consumption for each quintile, when the distribution of damages is independent of the income levels. For instance, before any redistribution, the first decile in the USA loses 1.68% of consumption due to damages. After the redistribution process, damages represent 0.57% of consumption of the first decile in the USA. Note that

[12] The donor regions are the United States, Japan, European members of OECD, and other high-income countries. The receiver regions are the eight remaining regions of the analysis.

the two paths assume the same amount of damages[13]. We keep with the United States and the European members of OECD to portray the effect in high-income regions and China and Africa, regions with a lower income level and a higher exposure to climate damages. In relative terms, the effect of the redistribution process is greater for highly exposed regions, which are also marked by high inequality. The tax reduces the damage burden of climate change for the three lowest income quintiles while increasing it slightly for the two highest quintiles. After redistribution, the share of consumption impacted by damages is roughly the same for every quintile within regions. The regressive effect of the transfers admits to a more equitable distribution of the cost of damages.

Table 1: The effect of the first redistribution process ($\zeta = 0.65$) on damages distribution (in % of total consumption)

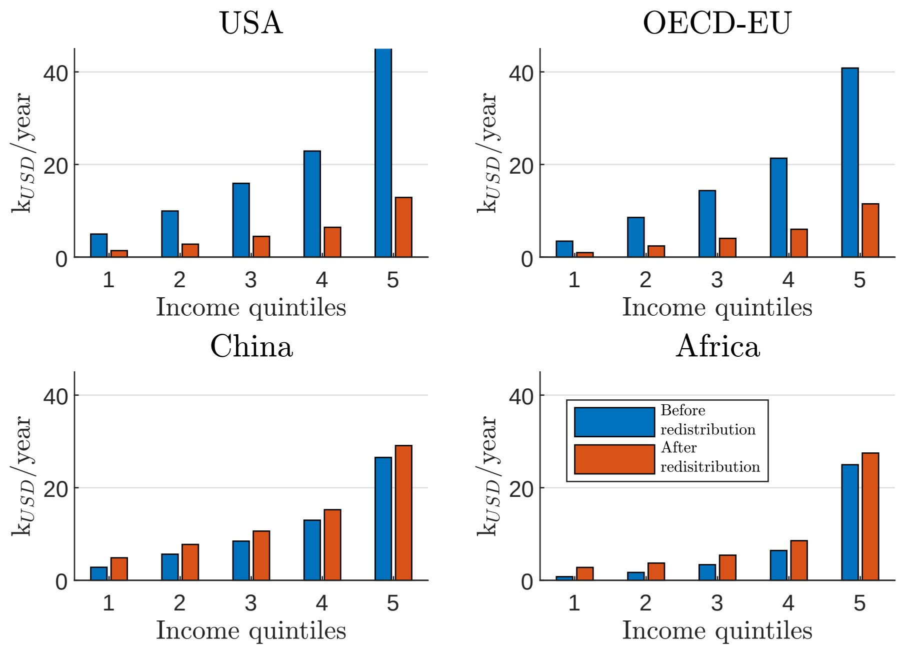
	USA		OECD-EU		China		Africa	
Quintile	pre-tax	post-tax	pre-tax	post-tax	pre-tax	post-tax	pre-tax	post-tax
Q1	1.68	0.57	3.94	1.06	13.60	4.61	41.73	6.44
Q2	0.84	0.51	1.59	0.93	6.80	4.12	19.29	6.06
Q3	0.52	0.45	0.95	0.82	4.53	3.72	9.77	5.47
Q4	0.36	0.40	0.64	0.71	2.95	3.23	5.12	4.64
Q5	0.18	0.29	0.33	0.52	1.44	2.31	1.32	2.43

Source: Dennig *et al.* (2015), author's own calculations.

Interegenional social transfers In the second variant, Dennig *et al.* (2015) stipulate that the results are inconclusive. No sufficient and efficient transfers would bring the shadow price trajectory at $\xi = 0$ to meet the level of the RICE model. Notwithstanding, we illustrate in Figure 5 the implicit effect of the second redistribution process under an arbitrary $\zeta = 0.75$. Again, we assume the same pair of damages between the two runs. The blue bars show the consumption level of each quintile before redistribution, while the red bars depict the consumption level of each quintile after the interregional redistribution process for our four illustrative regions. Here, we decide to show the pure income effect to testify to the inefficiency of this global transfer. First, we observe that all income quintiles in the donor regions heavily support the impact of the tax. Such a tax would unreasonably be costly for households to be optimal and acceptable. This will trigger social issues within those regions since all quintiles, except Q5, are falling below the national poverty threshold. Second, we also observe that the policy might have a reverse effect. Despite the reduction of global inequality, the level of inequality within regions is still alarming in lowest-income regions, just as well as in high-income regions. Third, we find that the redistribution is disoriented. When looking at the beneficiaries of the policy. The improvement of consumption following the lump-sum transfers benefits the highest quintile in absolute terms. The change in consumption level is incremental for the poorest strata. Finally, one might be surprised by the level of consumption after the redistribution as the first decile of income in Africa is more than twice that of the first decile in OECD-EU and USA regions, for instance. This is mainly due to the hypothetical and extreme value of ζ. Such an amount of redistribution is far from reality.

[13] In this illustration, we aim to describe the tax's implication on consumption quintiles. However, the original results yield a different path since the optimization incorporates the social transfers induced by the tax (lowering damages) and the resulting income effect (increasing consumption). Indeed, there is a feedback effect between redistribution and total emissions.

Figure 5: The effect of the second redistribution process ($\zeta = 0.75$) on consumption levels



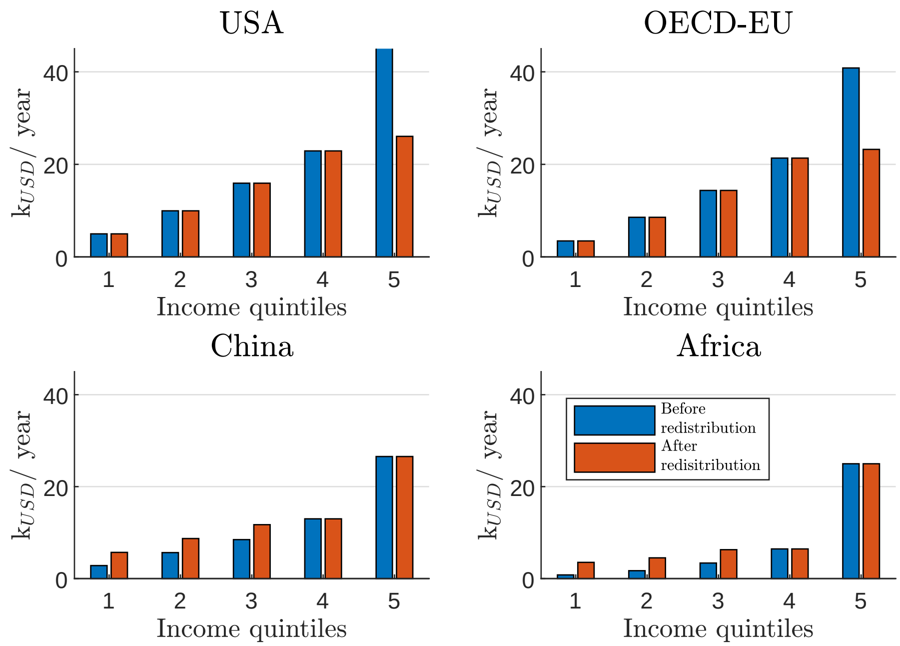
Source: Dennig *et al.* (2015), author's own calculations.

To overcome the drawbacks of the previous interregional redistribution process, we study another variant in which the distribution scheme is more progressive. This variant aims to restrain the levy only on high-income quintiles in the donor regions and to distribute the tax receipt between low-income quintiles in the receiver regions. In doing so, we control the regressive effect of the policy on low-income quintiles in the donor regions in order to keep their consumption levels unchanged. In the receiver regions, we orient the transfers toward the lowest income quintiles, keeping the consumption levels of the third and fifth quintiles unchanged. The social transfer is thus targeting the people in need. Obviously, this variant cannot reach the shadow price trajectory of RICE. Indeed, the tax receipt is lower than the previous variant since the tax is applied to a lower population share.

We illustrate the implicit effect of this policy in Figure 6. Only households in the highest income quintile are taxed at 75%, substantially reducing their consumption level but still above other income groups after redistribution. This mechanically reduces inequality within high-income regions and prevents social issues following the regressive tax burden effect on low-income quintiles. Considering China and Africa, we observe that benefits are shared between low-income quintiles, reducing inequality. This kind of policy permits alleviating highly exposed populations to climate change while avoiding the social trade-off between high- and low-income regions. Moreover, in this redistribution process, inequality improves in all dimensions.

Overall, we understand that social transfers would play a key role in climate change. Redistribution processes between income strata are needed since their implementations reduce vulnerability groups, yielding an improvement on the side of adaptation measures (Anthoff and Tol, 2011). However, as suggested by the different variants, the redistribution process must be optimal to produce the expected benefits. If not optimally estimated, social transfers can make trade-offs between income groups and thus replace the evil with another.

Figure 6: The effect of the third redistribution process ($\zeta = 0.75$) on consumption levels



Source: Dennig *et al.* (2015), author's own calculations.

These results also acknowledge the limited impact of social transfers considered solely. That is, redistribution processes cannot resolve the problem independently and must be accompanied by a strong climate policy. The distributional effects of social transfers could not entirely outweigh mitigation's effects. However, we believe the two policy tools are complementary. A robust and optimal carbon tax should be preceded by social transfers, as tiny as they are, to make the carbon policy acceptable.

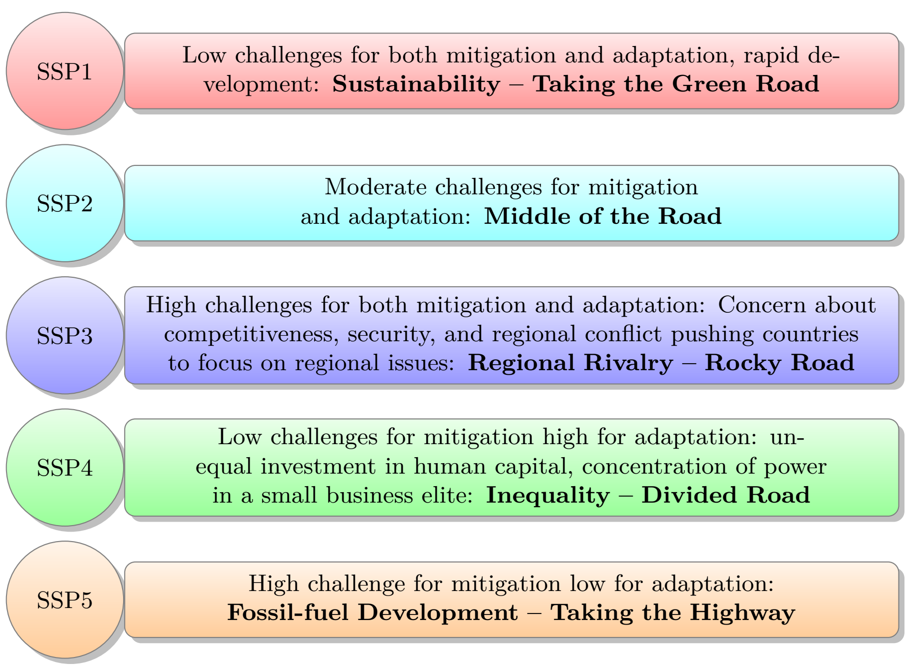
2.3 The social risk in the shared socioeconomic pathways

The nexus between social inequality and climate risks depends on the evolution of society since development pathways are critical to understanding the future drivers of emissions and the capacity to adapt or mitigate them. The shared socioeconomic pathways (SSPs) appear as a reference framework to make assumptions on long-term trends of the social risk. After a brief description of each SSP, we also analyze the work made by researchers on quantifying some social narratives. We then propose to focus on the literature on social inequality trends. Given the narratives of the SSPs, the aim is to give an overview of the range of possible impacts of income distribution, social segregation, and poverty alleviation.

2.3.1 Projections of socioeconomic scenarios

Forward-looking projections of socioeconomic factors can be abstract since those dynamics do not follow a standard golden rule as in physics. Following the work of the IPCC urging the necessity to tackle climate change, analyses have been deployed to estimate numerous emission paths, temperature increases, and resource depletion. However, assessing those paths with a limited estimation of economic projections is conceptual. Thus, one objective of the International Institute for Applied Systems Analysis (IIASA) was to estimate qualitatively the world evolution in line with socioeconomic factors. The SSPs developed by Kriegler *et al.* (2012) are not to model the future in a predictive analysis but rather to investigate plausible scenarios based on socioeconomic assumptions. Environmental impacts of climate change and climate policies are not considered in order to keep this reference framework free from these effects (O'Neill *et al.*, 2014). In other words, they constitute the narrative projections of the world integrating sociodemographic and socioeconomic dimensions such as political risks, inequality, education attainment, investment, international trade, energy mix, land use, or productivity. The primary purpose of the SSPs is to conclude on the expected challenges for climate change adaptation and mitigation if the world is set to follow one of the five trends. Mitigation challenges depend on the intensity of climate impacts and the population's vulnerability. In the first case, adaptation can be more or less challenging because the impacts of climate change are more or less severe. In the other case, adaptation can be challenging if a high share of the population is vulnerable and economically weak. The SSPs have also enriched the research in climate change since they serve as baseline trajectories in the integrated analysis of technological development, GDP, social inequality, political system, population vulnerabilities, adaptation to climate change, and so on. Note that climate change impacts do not influence the economy in the scenarios.

Figure 7: The Shared Socioeconomic Pathways



Source: O'Neill *et al.* (2017).

In Figure 7, we briefly summarize the SSPs. SSP1 refers to the sustainable path where resource intensity and fossil fuel dependency are drastically reduced. Social inequality decreases between and within countries thanks to the rapid development of low-income regions, reducing the share of the population below the poverty line. Clean energy technologies and yield-enhancing technologies for land sustain growth. Stringent policies are implemented to achieve the Millennium Development Goals[14] (MDGs), and a consideration regarding natural resources has emerged. Investments in human capital, and especially education, reduce the fertility rate. A socioeconomic continuum marks SSP2. The development of low-income regions is uneven, making the convergence of income levels between developing and industrialized countries slow. Delaying development in various low-income countries hampers educational attainment, which in turn increases population growth and postpones SDGs by several decades. In SSP3, the world is fragmented due to no coordination between nations. The world is no longer globalized, leading countries to focus on local environmental and socioeconomic issues. Economic growth is slowing while the global population is surging, provoking high inequality and a low level of human capital investment. The SDGs are out of reach, extreme poverty is overwhelming. SSP4 is characterized by inequality both within and across countries. The world is separated between a tiny elite and a large poor population in industrialized and developing countries. Finally, in SSP5, the world follows economic growth, representing the solution to social and economic issues. Fossil fuel-intensive activities prominently lead this growth. Overall, SSP1 and SSP5 seem more desirable than the other three, in which poverty and environmental impacts are expected to give rise to cascading socioeconomic effects such as civil unrest, conflicts, depletion of resources, and migrations.

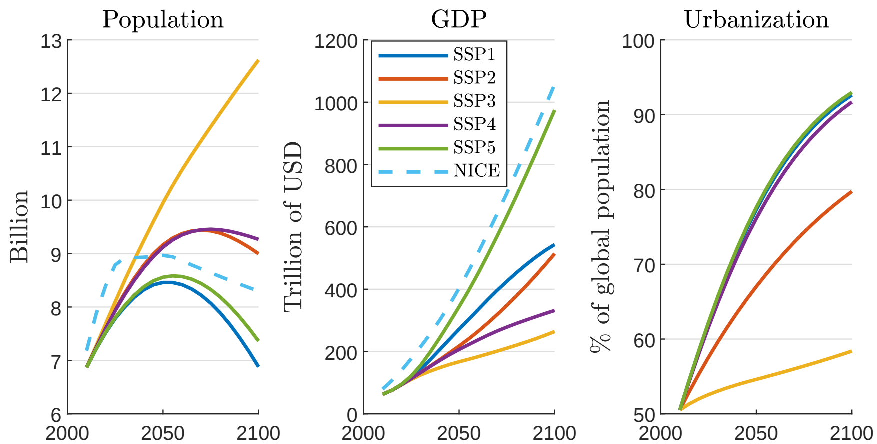
The quantitative projections of the SSPs Following the development and integration of the SSPs in IPCC reports, researchers tried to translate these narratives into quantitative forecasts. Three main series have been projected under the five scenarios. Thanks to these quantitative projections, some socioeconomic drivers were elaborated through IAMs to derive quantitative projections of energy, land use, and emissions associated with the SSPs (Riahi *et al.*, 2017). Globally, the core indicator of future socioeconomic pathways is related to demographics. Kc and Lutz (2014) determined demographic scenarios using projections by age, sex, and level of education up to 2100. The population projections are predominantly driven by fertility rate, which depends on female educational attainment and education-specific fertility[15]. GDP and GDP per capita scenarios were developed by Crespo Cuaresma (2017) and Dellink *et al.* (2017) using chiefly demographic series. GDP trends are determined from human capital, specifically, labor input differentiated by age and educational attainment. Economic growth is also dependent on savings behavior and technological development. A third aspect is the spatial distribution of the population. Jiang and O'Neill (2017) modeled scenarios for an urban and rural share of the total population. They assume that urbanization will follow a linear relationship between the difference in urban-rural population growth rates and urbanization levels while using each country's fast, central, and low urbanization pathways.

In Figure 8, we provide the aggregate trends for these global projections and the one used in the NICE model. Despite persisting uncertainty in the proposed projections, they are all consistent with the narratives. Considering population projections, we observe three groups of potential scenarios. The first group, composed of SSP1 and SSP5, projects the world population to peak in 2050. The population in 2100 will return to 2010 level. In the second group (SSP2 and SSP4), the population peaks in 2075 with barely 9.1 billion people. In the third group (SSP3), the population follows a high and steady growth rate. The population level would break through 13 billion persons globally, with no signs of peaking. When we consider future demographics, we note a profound disruption from long-term trends, especially through the last two centuries window. Indeed, in the majority of these scenarios,

[14] The MDGs were introduced by the United Nations in 2000 with the aim of reaching eight development goals by 2015. They have been replaced by the 15 Sustainable Development Goals (SDGs) in 2015.

[15] Here, female education strongly influences fertility rate and thus population growth.

Figure 8: Global trends of some SSPs' narratives



Source: IIASA SSP and Dennig *et al.* (2015).

the world will experience, for the first time, a declining rate of population growth. The underlying effects of this cardinal change will significantly impact the transition, notably on the age pyramid regarding prevailing elderly and labor market (Kc and Lutz, 2014) but also on emissions (Dalton *et al.*, 2005). Even if these scenarios seem more convenient, their implications regarding social risk are far from non-existent in the transitory period.

We present the projections of economic growth, expressed in constant 2005 USD at PPP exchange rate[16]. The methodology used by Dellink *et al.* (2017) to estimate these trends is based on several economic drivers such as population, employment, total factor productivity, and physical and human capital. Overall, the range of average growth rate over the 90 years varies between 1.6% to roughly 3.1% per year. In the high economic growth scenario (SSP5), the average income level is 140,000 2005 USD per year in 2100. Under the slow growth scenario (SSP3), the world average income stays around 20,000 2005 USD/ year in 2100. An essential feature of the GDP projections is related to the implication of current emerging countries in the world's economic growth. In every scenario, we note a thriving integration and catch-up of emerging countries in terms of GDP per capita. While we notice a declining growth rate after 2035 for all scenarios, there is no consideration for negative rates or a *degrowth* scenario. The scarcity of resources could put pressure on economic growth in some areas of the world.

For urbanization projections, the methodology consists of projecting historical trends in the share of the population living in cities, which is driven by income growth, technological change, and mobility (Jiang and O'Neill, 2017). The curves show that global urbanization will continue to rise across SSPs. However, the pace of urbanization widely differs across them, reaching 60% for SSP3, 80% for SSP2, and around 90% for others by the end of the century. An increasing number of urbanites may significantly affect consumption patterns, food security, production structure, vulnerability to climate change, pollution, biodiversity, and many other aspects. This socioeconomic aspect cannot be set aside for future economic pathways.

Finally, we have also represented the assumptions of the NICE model in dashed blue lines. Compared to SSP projections, the exogenous variables of the NICE model are not so

[16] It expresses the value of an *international dollar* translating the purchasing power in a specific country compared to the USD purchasing power in the United States.

disconnected. While the path of GDP growth is noticeably the same as in SSP5, the GDP is nonetheless greater than any other pathways, suggesting a high assumption on economic growth. The assumption is in line with the SSPs projections on the population side. The population peak appears around 2030 at 9 billion. Following the peak, the population slightly decreases, ranging from SSP2 to SSP5. Considering urbanization projections, the NICE model does not have this level of granularity, we thus cannot approximate the urban population trends.

2.3.2 Dynamics of long-term income distribution

Focusing on the pessimistic scenarios SSP4 and, to a similar extent, SSP3, are particularly interesting since they cover a world of deepening inequality. Among these projections, social, economic, and moral distress spill over adaptation and mitigation actions. While a high level of inequality characterizes SSP4 due to divergences within and between countries, SSP3 is more concerned with between countries' inequality. As defined qualitatively by O'Neill *et al.* (2017), the world is heavily fragmented. On one side, high-income regions expand their growth by increasing their energy demand (met by nuclear and renewable energy sources) and food. The high level of educational attainment contributes to the development of the capital-intensive sector of the economy. On the other side, due to limited access to energy policies, lower-income societies have poorly educated populations, making them reliant on traditional fuels and working in the labor-intensive market, low-tech sector of the economy. A small elite detains a large part of the political and business power, while a limited representation in national and global institutions penalizes a sizeable vulnerable group. This group is trapped in long-term poverty, from which access to water, sanitation, and health care is hampered. As a result, regional conflicts and civil unrest are occurring. With the presence of a strong political and business elite, the mitigation issue is quickly and decisively resolved, resulting in limited challenges to mitigation. However, challenges to adaptation are high due to a substantial share of the world population falling into poverty, struggling to cope with economic and environmental distresses. The work of Calvin *et al.* (2017) on SSP4 described in quantitative terms the underlying narratives in an integrated framework using the Global Change Assessment Model (GCAM; Edmonds and Reilly (1983)), a partial equilibrium model. The model incorporates granular and well-detailed descriptions of the world's energy demand, supply, and land-use systems. Despite a complete representation of energy discrepancies (a division of the world into 32 distinct regions) and land-use sector (238 distinct regions), the model does not explicitly integrate regional disparities. Income inequalities are fairly detailed between regions. Therefore, results suggest a widening gap between high-income and low-income regions that could underpin the possibility of meeting strict climate targets such as the RCP 2.6[17].

In SSP3, inequality between countries is surging due to weak global institutions that cannot resolve human and technological issues. Poverty hubs are exploding all around the world, especially in emerging economies. The thin economic growth will benefit a small portion of countries and the population, leading to surging inequality between and within countries. In this context, with the low level of global cooperation, societies face high climate mitigation and adaptation challenges. However, the world's poorest are disproportionately suffering from natural hazards, notably in Africa and southern Asia (Byers *et al.*, 2018).

[17]The Representative Concentration Pathway (RCP) 2.6 is the lowest greenhouse gas concentration trajectory. In this trajectory, the radiative forcing does not exceed 2.6 W m^{-2}, keeping the global temperature below 2°C by 2100.

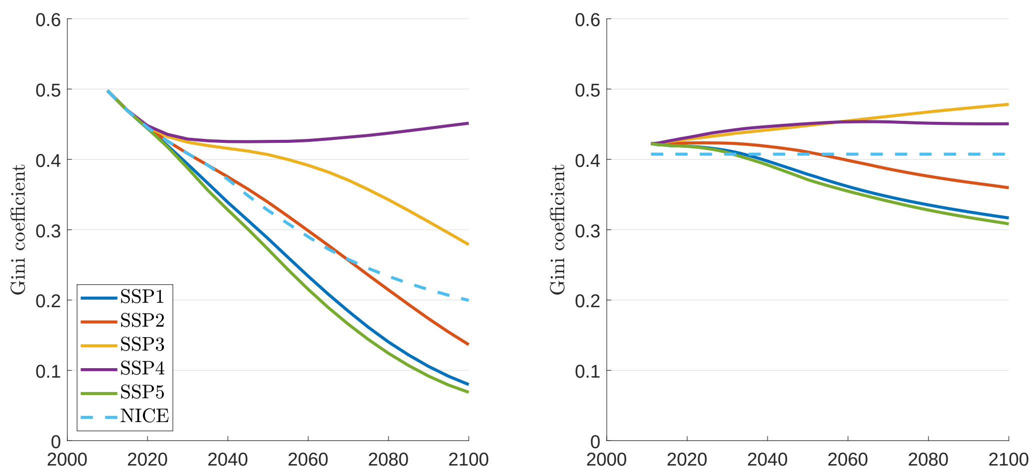
Income distribution within and between countries Abandoning the assumption of the mainstream use of national representative agent is required to depict a more socially oriented IAMs. As emphasized by Kornek *et al.* (2021), ignoring heterogeneity within countries when fixing a carbon policy will ultimately negatively affect inequality both within and between countries. However, predicting future income distribution is beyond any social science's capacity and even more unthinkable when corroborated with climate change events. Even when we look backward, economists still disagree on the responsible impact of a set of macroeconomic and microeconomic parameters of income inequality (Piketty, 2013; Atkinson, and Bourguignon, 2014; Stiglitz, 2015; Milanovic, 2016). In the context of socioeconomic narratives, prominent indicators such as population growth, age structure, productivity, education, labor, capital intensity, social policy, and human capital permit income inequality pathways to be developed. Several methodologies have been used to estimate future income distribution and their subsequent poverty indicators for the different SSPs. van der Mensbrugghe (2015) generated income distribution for each country, each year, and each SSP using a parametrized distribution function. Given population and GDP per capita, the parametric Lorenz curve for each country and time period generates artificial household distribution. Crespo Cuaresma *et al.* (2018) developed a methodological framework to estimate future poverty rates globally, given the SSPs. The econometric model is based on the historical distribution of income, Beta-Lorenz curves, and projected economic series. Rao *et al.* (2019) tried to approximate the inequality argument of the SSPs by projecting national Gini coefficients. The scenarios are derived from an econometric model estimated over the last three decades. Total factor productivity, education attainment, and social public spending explain the most inequality dynamics in the model. However, these inequality projections need to be revised to integrate mitigation and damage costs under different scenarios, knowing that not only consumption but also employment, assets, or inflation can have indirect impacts. Soergel *et al.* (2021) used the Gini projections of Rao *et al.* (2019) to construct a baseline income distribution to estimate future poverty. Jafino *et al.* (2020) worked on climate-driven poverty projections for 2030 using household survey data. They assumed five main climate impact channels: agricultural productivity, food prices, losses from natural disasters, labor productivity, and health burden. The latter seems to be the most prominent driver of poverty. Using the NICE model, Budolfson *et al.* (2021) investigated the recycling of the carbon tax revenue in a progressive manner. They model income distribution by adding or subtracting a proportional tax, redistributing equally per capita in line with the rate of change estimated in Rao *et al.* (2019) for each SSP.

In Figure 9, we have represented the global Gini trends of the SSPs. It is important to differentiate between cross-country inequality and within-country inequality. The former is related to the difference in mean income between countries, while the latter results from the income differences within countries. In the left panel, the Gini coefficients represent the level of inequality between countries. This is equivalent to assessing the global income distribution based on the SSP trends for population and economic growth under a perfect within-country distribution (Bourguignon and Morrisson, 2002). In this specification, we relate each country's respective share of GDP, assuming that each person in the country receives the same income. The assumption of a perfect income distribution within a country is strong and underestimates future global inequality. The different curves illustrate the different assumptions made by the OECD on the distribution of growth. As stated before, income inequality between countries tends to narrow, except for the case of SSP4. SSP1 and SSP5 assume significant cuts in global inequality as the Gini coefficient drops from 0.5 in 2010 to less than 0.1 in 2100. From this representation of between countries inequality, we understand the critical objective of global convergence of income rather than solely global growth. A strong recovery of emerging countries leads to a convergence of income distribution, strengthening world development and thus achieving social and environmental milestones.

Figure 9: Global Gini coefficients trends

(a) Between countries

(b) Within countries



Source: IIASA SSP and Dennig *et al.* (2015), author's own calculations.

Source: Rao *et al.* (2019) and Dennig *et al.* (2015), author's own calculations.

In the right panel, we have represented the results of the Gini projections of Rao *et al.* (2019). We compute the world average Gini coefficient for each year and each SSP. In SSP1 and, to some extent, SSP5, inequality within countries decreases with significant change in most regions. In the low inequality scenarios, the Gini coefficient plunges by 26%. Conversely, SPP3 and SSP4 are marked by surging inequality within countries. In SSP4, it is attributable to the worsening of income distribution in low-income countries while unchanging income distribution in middle- and high-income countries. For the NICE model, we have determined the Gini coefficient as the global average Gini coefficient of the regional income distribution. There is no dynamic of the income distribution in NICE, suggesting a linear representation in the middle of SSPs projections. From this graph, we understand that the fixed income distribution is a strong hypothesis in light of the SSPs. As emphasized by Rao *et al.* (2017), the incentive to construct dynamic income convergence and divergence is crucial since a static framework of inequality underestimates the effect of both damages and mitigation costs. Under the economic and demographic growth assumptions of the NICE model, the income distribution should be either more equal or unequal but cannot be unvarying throughout the period. The assumption of either fixed sub-regional income distribution or convergence between countries is strong.

In summary, working on inequality within and between countries is an important exercise to represent inequality trends in the SSPs fully. Undoubtedly, a world with population, GDP, and inequality level close to SSP1 and SSP5 dominate the other three scenarios for their attractiveness and sustainability. In a similar world, implementing environmental policy is viable and makes sense since the trade-off between environmental and social concerns can be avoided. This argument holds if the reduction of inequality between and within countries results from income convergence between countries, notably between developed and emerging countries (Rao and Min, 2018). The practicability of adaptation measures is also more realistic in these scenarios. The increase of average income per capita and a fair distribution of it should reduce the vulnerability of exposed poor people globally, reducing the climate change burden and advocating more climate justice while limiting emissions. However, the challenge is enormous. Redressing inequality to reach the level of these scenarios would require social actions that are beyond social transfers solely. However, the aim is not to pursue the exact path, whatever it costs, but to avoid falling into a trajectory similar to one of the pessimistic scenarios. In these worlds, a significant fraction of the world population would live in undesirable economic conditions, increasing the risk of civil unrest and food insecurity, accentuating the risk of armed conflicts and massive migration. Additionally, the proliferation of poverty hubs would propel exposed and vulnerable people to climate change. Physical risks will predominantly impact those groups with low capacity to adapt.

3 Social inequality in the context of a domestic carbon tax: A case study on French households

To achieve net zero ambitions by 2050, a gradual transformation of our economy is required. However, the underlying effects of such transformation are difficult to estimate. Issues arise from the transformation's efficiency (economic growth and development) and equity aspects (the distribution of welfare gains and losses across individuals). Meanwhile, social inequality has become a rising concern, and its role in climate change cannot be left on the sidelines. When it comes to emissions reduction from consumption, the efficiency and equity aspects contradict each other. Strong mitigation policies should be implemented to support future generations' economic prosperity to avoid the worst effects of climate change. If the implementation of a carbon tax, aiming to internalize the negative externality of energy consumption, may reach its target in the long run, it could put at risk many households in the short run. This transition risk can be sufficiently essential to postpone mitigation, as we recorded in France with the yellow vest protest, flattening the hope of a gradual economic transition.

Environmental policies softening the carbon dependency of our economies are impacting the social structures. Low-income households are more impacted since their consumption patterns rely more on carbon-intensive products than high-income households. They also have a lower capacity to substitute their consumption when prices increase, making them dependent on fossil fuels and vulnerable to carbon taxation. In this context, the carbon tax is regressive by design. However, high-income households' emissions are considerably higher than low-income households, notably due to income level that orients consumption patterns, strengthening the risk of misdirected policies. The impediments of carbon tax policies are thus heavily related to this income inequality aspect. In addition, even if income inequality (i.e., vertical inequality) can explain a large part of the tax burden, other sources of vulnerability (i.e., horizontal inequality), such as socioeconomic and sociodemographic factors, could also explain opposition to carbon tax. One potential tool to reverse this adverse effect would be the use of tax revenue. It is well established that social transfers between income groups could reduce the regressive nature of the carbon tax by lightening the tax burden of low-income households (West and Williams, 2002; Metcalf, 2009; Carattini *et al.*, 2017; Berry, 2019; Fremstad and Paul, 2019). Redistribution strongly supports the implementation of the carbon tax while improving the social situation, but at what cost? Reducing income inequality by redistributing tax revenue could drive up emissions due to increasing demand for carbon-intensive products (Ravigné and Nadaud, 2021). On the one hand, the carbon tax stimulates consumption sobriety by dissuading households from consuming carbon-intensive products and significantly reducing GHG emissions. On the other hand, consumption sobriety is not a one-size-fits-all since price increases can push vulnerable households into poverty. Thus, social transfers can correct the impediment of the carbon tax design at the cost of environmental improvement. This would ultimately result in making a trade-off between social and environmental objectives.

This section is devoted to the intraregional inequality in climate economic modeling. First, we seek to disentangle the carbon footprint of French households given income and socioeconomic dimensions to attach importance to both vertical and horizontal inequality. We use a bottom-up analysis, which links a national input-output model with the household budget survey. By doing so, we are able to estimate both direct and indirect emissions induced by consumption. After analyzing the distribution of GHG emissions between and within income groups, we propose an analysis of the carbon footprint elasticity with respect to income and expenditures. This analysis will help us to understand what is leading to the carbon footprint of French households. Second, we study the social and environmental implications of the carbon tax and the subsequent compensation measures used to resolve the regressive nature of the carbon tax. We propose a microsimulation model to exacerbate the fallout from a potential domestic carbon tax while controlling for substitution effects. In a very short-term context, we look at the critical role of social inequality in the policy's acceptability and the potential backfire effect following the redistribution of tax revenue through lump-sum transfers. We are willing to oppose the capacity of households to make consumption sobriety (following the carbon tax implementation) and the potential backfire in emissions (following redistribution). In the first case, we challenge the risks it may cause to households, notably poor and constrained households. In the second case, we look at the potential limitation of mixing environmental and social policies from an environmental viewpoint.

The standard methodology adopted by economists to translate the impact of a carbon tax on household welfare follows three steps. The first step consists of computing households' carbon footprint[18]. Based on national accounts, we can deduce the carbon intensity of each product consumed by households. Using a household budget survey, which gathers annual expenditures along socioeconomic characteristics, consumption is paired with carbon emissions. Given these metrics, the emissions elasticity to income can be deduced. In the second step, the prices of goods and services are stressed by applying a tax margin on the carbon content of products. By introducing this tax, which is generally supported by final consumers although imposed on producers, the change in welfare can be approximated with post-tax consumption losses. To be consistent with the economic theory, a demand system models the behavioral reactions of households following the tax implementation. This model consists of approximating substitution effects of households depending on their revenues, their share of expenses allocated to pre-tax products, and other characteristics. The idea is to consider the potential shifts in consumption following price increases. Finally, a third step emphasizes tax recycling. To supersede the initial regressive effect of the tax, the revenue is redistributed between households in three different manners, considering inclusiveness (flat-recycling), horizontal inequality (tailored scheme), and vertical inequality (social cushioning). This ultimate step permits accentuating the benefits of implementing such a tax and, in most cases, concealing the tax's original regressive effect. Indeed, social transfers are prone to reduce the fiscal burden of low-income households. Meanwhile, they can substantially reduce the original environmental benefits if additional spending is attributed to carbon-emitting goods and services. This income could support energy demand and increase carbon footprints, exacerbating a backfire effect.

[18] Throughout this part, we talk about carbon footprint, but we are not only considering carbon dioxide in the footprint since other equivalent GHG emissions are integrated.

We start this section with a brief and non-exhaustive review of the literature to give a bit of context on measuring households' carbon footprint and the welfare effect associated with carbon taxation. Then, we detail the methodology adopted, the data, and the indicators used to determine the domestic household carbon footprint and to explore the implication of taxing carbon on the welfare of French households. Finally, we present the results and related discussion with some policy recommendations.

3.1 Carbon footprint and optimal tax, a literature review

Consumers responsibility in GHG emissions Looking at carbon emissions through the lens of households indirectly stipulates that final consumers are mainly responsible for global warming. Nonetheless, this is a debatable perception. As suggested by Tukker *et al.* (2020), attributing carbon footprint can be consumer- and producer-based. In the second case, emissions and pollution are seen as the responsibility of the actor who operates the production, while in the first case, the final demand of households is the main driver of upstream emissions and pollution. The consumer-based responsibility is linked to individuals' critical role in consuming for their functional needs and preferences. As the leading actor of the demand, they "*drive*" the economic production. The final demand is thus the coordinator of the economic activity, reflecting a significant responsibility in global warming. More and more considerations of the "*citizen-consumer*" notion, positioning individual at the center of ecological responsibilities and as the central actor of the transition (Rumpala, 2009) tend to confirm the predominance of the consumer-based responsibility. Meanwhile, if we only consider the responsibility of consumers, producers could legitimize their contribution to global warming. Producers are the master hand of their production through technological improvement, supply chain locations, and energy use. This statement suggests that while consumers are responsible for their consumption, it is ambiguous if they are responsible for upstream emissions since no information on the carbon content of a good or service is generally made available (Pottier *et al.*, 2021). All in all, we are aware that consumption behaviors must change to mitigate GHG emissions and reach decisive environmental targets. This is the main idea of energy sobriety, targeting emissions reduction induced by consumption reduction. On the other side, such behavioral shifts could not resolve the climate issue alone. Again, businesses and governments play a vital role in the transition (Dugast and Soyeux, 2020) transition. Therefore, we should talk about shared responsibility instead of individual responsibility. Still, the scope of households and individuals is greatly justified for assessing social issues in climate economic modeling.

Households carbon footprint Generally, the household or individual carbon footprint computation comes from purchasing produced goods and services for immediate use. From an environmental point of view, consumed items are split into two categories. One category gathers goods that directly emit GHG and another category of goods and services that indirectly emit GHG. Direct emissions are commonly concentrated in individuals' heating/cooling and transport requirements. Indirect emissions are released throughout the production of goods and services [19]. The carbon footprint is the sum of direct and indirect emissions induced by the basket of household goods and services.

[19] Each good and service has an indirect carbon intensity coming from its production. For instance, the consumption of shoes is related to processing materials (leather, plastic, cardboard, and fabric), transportation, and retail. From each part of the production, households have finally emitted GHG emissions to be consumed by households. The measurement of these intensities encompasses indirect emissions of consumption without entailing direct emissions since wearing shoes does not emit GHG.

Two methods are generally considered to deduce the carbon content of goods and services consumed. The most common is the extension of input-output tables (Leontief, 1970; Miller and Blair, 1985). The idea is to take the monetary flows between sectors to determine the total carbon intensity of industries, which is then linked to final demand. This approach permits to take into account upstream emissions. Numerous studies have used this synthetic method to estimate the household's carbon footprint either at the global level (Lenzen *et al.*, 2006; Hubacek *et al.*, 2017a,b; Bruckner *et al.*, 2022) or at the national level (Baiocchi *et al.*, 2010; Renner, 2018; Malliet *et al.*, 2020; Pottier *et al.*, 2021). In the second method, quantities consumed are used to estimate the carbon footprint of households. These quantities of products are then converted into emissions using life cycle assessment (LCA). LCA aims to accurately inventory the energy and materials required throughout production to determine the cumulative emissions (Hendrickson *et al.*, 1998; Joshi, 1999; Suh *et al.*, 2004). On the one hand, estimating households' carbon footprint with this method permits catching granularity in the carbon intensity of a bunch of products compared to input-output framework (Steen-Olsen *et al.*, 2016). On the other hand, LCA is more complex since the carbon content of any good or service is challenging to assess, and the estimation of induced quantity consumed by individuals is unusual (Pottier *et al.*, 2021). The mix of the two methods is practical since indirect emissions can be well estimated through input-output analysis and direct emissions by LCA.

Key drivers of the carbon footprint The analysis of social inequality within the environmental transition suggests taking income as the primary driver of emissions. While a consensus seems to be reached about the positive relationships between households' carbon footprint and the income level (Wier *et al.*, 2001; Weber and Matthews, 2008; Golley and Meng, 2012; Büchs and Schnepf, 2013), the intensity, more or less proportional to income, is still debatable (Lenzen *et al.*, 2006; Steen-Olsen *et al.*, 2016). However, taking the income solely cannot perfectly describe the distribution of the carbon footprint. Studies point out the substantial role of expenditures as the primary driver of carbon footprint (Lenzen *et al.*, 2006; Lenglart *et al.*, 2010). Pottier (2022) performed a literature review on households' carbon footprint by confronting different types of elasticity. He distinguished between expenditures elasticity (i.e., how much the carbon footprint rises as expenditures grow by 1%) and income elasticity (i.e., how much the carbon footprint rises as income grows by 1%). The results confirm that the elasticity with respect to expenditures is always greater and more accurate than with respect to income. This phenomenon can be explained by the Keynesian view advancing that the marginal propensity to consume is decreasing while the marginal propensity to save is increasing. In other words, as households get richer, the extra income unit will be devoted to savings rather than consumption. Therefore, the income group is critical to understand this parameter. It is also fundamental to distinguish between direct and indirect emissions to understand the relationship between income and emissions. Rationally, the amount of direct emission induced by consumption is capped since the volume of fuel used for mobility or gas used for heating is relatively limited. On the other hand, indirect emissions induced by the purchase of clothes, electronic equipment, or vehicles do not seem to be capped. Therefore, the share of indirect emissions in the total carbon footprint could be driven by income (Golley and Meng, 2012). This phenomenon advocates the potential non-linearities between income and emissions as consumption patterns vary substantially at the top of the distribution (Ravallion *et al.*, 2000). Thus, in the context of social inequality, the nexus between income and emissions should be preferred to the nexus between expenditure and emissions. However, in a consumption-based principle, consumption is the deterministic aspect of carbon accounting, letting the saving share of income, and in a way, investment, less material. Moreover, as the permanent income hypothesis of Friedman (1957) suggests, expenditures represent a good proxy for estimating the households' standard of living if they smooth consumption across time. Finally, as we are focusing on the carbon policy's expenditures-related impact, the tax's distributional effect will be on expenditures rather than income. In this study, we do not want to set aside one of these two determinants as both can be helpful in the economic interpretation of the results. Moreover, we believe that keeping the two variables aside would support the robustness of our results throughout the study.

The regressive nature of the carbon tax While a high carbon tax should be perceived as a stringent incentive to reduce the carbon footprint, it can create a major impediment to social equity. Formerly, the carbon tax objective was to reduce the demand for carbon-intensive goods and services while inciting the development of clean energies. In this context, households should progressively arbitrate between reducing overall consumption or substituting high-emitting for low-emitting goods or services. This target of energy sobriety is thus controversial since such mitigation policy diminishes the purchasing power, at least in the short run. This is even more exacerbated for low-income households since they tend to allocate more of their permanent income to energy spending. Moreover, their capacity to substitute their energy consumption is limited, and they may not have alternatives for transportation, for instance. This is characteristic of a regressive tax in that the relative share of expenses in the scope of the tax is higher for low-income households than high-income households. Constrained by the environmental policy, targeting energy sobriety could be at the cost of fuel poverty (Legendre and Ricci, 2015; Berry, 2019).

Low-income households would pay a more significant percentage of their income than high-income households, yielding an increase in vertical inequalities, at least when considering direct emissions. However, this effect could be completely different when considering only indirect emissions. As previously said, the share of indirect emissions in the total carbon footprint should increase with income. As a result, the carbon tax could be sizable for high-income groups. Nevertheless, the effect can be softened since the carbon intensity of direct emissions is generally greater than the carbon intensity of indirect emissions in the methodology commonly adopted. In most of the cases, the regressive nature of the carbon tax holds for developed countries, either on direct fossil fuel taxation or indirect emissions from private consumption (Symons *et al.*, 1994; Wier *et al.*, 2005; Kerkhof *et al.*, 2008; Verde and Tol, 2009; Feng *et al.*, 2010; Baiocchi *et al.*, 2010; Mathur and Morris, 2014). This finding is more contrasted for developing countries (Brenner *et al.*, 2007; Yusuf and Resosudarmo, 2015; Da Silva Freitas *et al.*, 2016; Grottera *et al.*, 2017; Renner, 2018; Dorband *et al.*, 2019). The carbon taxation in these countries seems to be more progressive, reflecting a proportional tax burden. This difference might result from different consumption patterns and especially lower energy spending from the poorest in developing countries (Shah and Larsen, 1992; Brenner *et al.*, 2007).

Vertical and horizontal inequalities Beyond the income dimension, other aspects should be considered when examining the cross-segment of social and environmental inequality. Two dimensions of inequality should be considered. The most studied dimension, previously detailed, is related to vertical inequality and links carbon emissions with income. The second dimension is commonly expressed as horizontal inequality, which reflects the differences in emissions between households within the same income group. The differences can be important and might arise from numerous aspects related to individual or constrained choices, for instance, electing train transportation rather than plane to go on holidays or consuming locally produced food rather than imported food substantially change the composition of the carbon footprint. However, the organization of the territory for mobility constraints or the average temperature for heating system efficiency and diet does not rely on individual choices (Chancel, 2014). Sociocultural and sociodemographic aspects such as differences in tenancy status (owner-occupiers versus tenants), differences in household size (household composition), education attainment (high education level versus low education level), and the status of the households (retired or worker), also play a crucial role in horizontal inequalities (Poterba, 1991; Lenglart *et al.*, 2010; Büchs and Schnepf, 2013). Numerous studies argued the significant effect of horizontal inequality in carbon taxation, which could be wider than vertical inequality but hidden in income cohorts (Cronin *et al.*, 2019; Douenne, 2020; Pottier *et al.*, 2021). Therefore, underestimating these factors could misdirect environmental policies, reducing the acceptability of climate mitigation policies.

Redistribution scheme and backfire effect The French episode of yellow vest protests in 2018 illustrated the central issue of introducing a high and unequal carbon tax on fossil-fuel products. Protesters have criticized the imbalance of such a policy, as their daily life was more impacted by the tax than the richest, judged as more responsible for emissions than the poor. The tax increase and rising gasoline prices hit disproportionately vulnerable people, specifically rural people while keeping affluent households' welfare unchanged. Among other things, the civil movement claims more social justice in the transition (Douenne, 2020). Given that a potential adverse effect of emission taxation may occlude its acceptability[20], studies have been particularly attentive to designing revenue recycling schemes to make them progressive. Academics have analyzed different revenue recycling schemes, but no consensus has been reached on the best design to tackle vertical and horizontal inequality. Nevertheless, three main approaches are commonly adopted. In targeting compensatory measures, the tax receipts can be distributed through lump-sum transfers (West and Williams, 2002; Metcalf, 2009; Berry, 2019; Fremstad and Paul, 2019; Ravigné and Nadaud, 2021). In the case of a complete redistribution of tax revenue, the carbon tax is thus a revenue-neutral reform. One can expect that the tax revenue could help the development of green activities such as subsidizing public transport or residential energy (Brännlund and Nordström, 2004; Bourgeois *et al.*, 2021). Improving transport infrastructure permits households to substitute car mobility with greener transport and to make the policy socially acceptable (Steg *et al.*, 2006; Klok *et al.*, 2006). Others imagine the tax revenue to achieve fiscal reform, which would reduce taxes on labor, goods, capital, corporate benefits, or property (Brännlund and Nordström, 2004; Jorgenson *et al.*, 2015; Williams *et al.*, 2015; Goulder *et al.*, 2019). It permits support the strength of carbon taxation to reduce emissions while reaching both environmental and social targets, or more specifically, reduce the costs of the tax system, known as the "*double dividend*"[21] (Pearce, 1991). While the intensity of the benefits of tax recycling relies on how revenue is used (Baranzini *et al.*, 2000), findings generally advocate a more progressive system and a reduction of inequality and poverty (Berry, 2019; Budolfson *et al.*, 2021). This kind of transfer is also inherent to acceptability since deliberating the use of proceeds is vital to public acceptability (Hammar and Jagers, 2007; Kallbekken and Sælen, 2011; Douenne and Fabre, 2020), and notably for environmental purposes (Carl and Fedor, 2016). However, in the sense of Tinbergen (1952), each economic policy must have the same number of achievable policy goals as it has several policy instruments, suggesting that social benefits from environmental policy could happen but may come at the cost of tax efficiency (Rausch *et al.*, 2011). In addition, while vertical inequalities seem to be alleviated after redistribution, the effect on horizontal inequality is still uncertain (Boyce, 2018;

[20] To see a complete literature review on the resistance to carbon taxes, see Carattini *et al.* (2018).

[21] The concept of double dividend suggests that environmental taxes and their revenues could reduce the distortionary effects of other sub-optimal taxes. Thus, environmental purposes are reached while the tax system's efficiency is improved, improving the economic situation.

Douenne, 2020).

Another impact of revenue recycling schemes has been less studied by academics. Indeed, the specific case of lump-sum transfers is subject to a backfire effect, that is, an increase of emissions induced by the surge of demand for emitting products, likely to reduce the initial benefit of the carbon tax. This phenomenon is closely related but different from the rebound effect. The rebound effect arises from the surge of end-use energy services following emitting products' energy efficiency improvement. In other words, improving the energetic productivity of automobiles and heating or cooling tools, implying the reduction of the carbon emissions of these products, could motivate a growing demand for energy and materials, which in turn offsets primer energy savings (Sorrell and Dimitropoulos, 2008; Daumas, 2020; Böhringer and Rivers, 2021). For instance, if energy-intensive vehicles are replaced by low-emitting ones, potential energy savings arising from this technological efficiency could motivate consumers to increase the use of cars to travel, which in turn decreases the environmental benefits of energy efficiency policies (Benjamin and Hurtado, 2019). In this context, emissions can increase sharply, translating into a rebound in emissions. In the case of the backfire effect, we assume that behavioral reactions to lump-sum transfers, instead of energy efficiency gains, could propel the consumption of high-emitting products, which can lessen the original objective of the carbon tax without completely reversing it. At first sight, if consumption increases in the same proportion of income, then emissions could increase alike. On the first hand, the effect could be pronounced for low-income households since their share of expenditures toward high-emitting products is accentuated, and the demand elasticity of carbon-intensive products, notably gasoline, is close to zero (Baranzini and Weber, 2013). In this case, the social aspect of the policy (i.e., reducing income inequality) seems to outshine the environmental impact. On the other hand, emissions induced by extra income spent by households following the redistribution of carbon taxation could be less important than total environmental benefits in the long run so that the policy would be effective overall.

The French carbon footprint and the carbon tax effects In the French context, several studies have been dedicated to estimating households' carbon footprint and the social assessment of implementing a regressive carbon tax. Lenglart *et al.* (2010) studied the distribution of households' carbon footprint using input-output tables and national statistics. They found that the standard of living is important to explore the inequality in emissions, although some socioeconomic and socio-professional characteristics could significantly explain gaps between households. Pottier *et al.* (2021) provided a deep analysis of the carbon footprint of French households and discussed the issue of estimating such a measure with current tools and methods. They found a positive relationship between income and emissions while warning for hidden effects in the French household budget survey. On the front of carbon taxation effects, academics used national data to mix macroeconomic and microeconomic simulations. Bureau (2011) analyzed the effect of carbon taxes on car fuel consumption while controlling for household price responsiveness. He concluded that carbon taxation is regressive before recycling. Berry (2019) studied the distributional effects of energy tax for housing and transport and focused on the poverty effects they may create. She sheds light on the ability of carbon taxation recycling to reduce poverty substantially. Douenne (2020) used the Quadratic Almost Ideal Demand System (QUAIDS) to incorporate the behavioral responses to energy tax on transport and housing. He distinguished the tax's horizontal and vertical regressive effects and concluded that lump-sum transfers would correct it. Malliet *et al.* (2020) studied the impact of a carbon tax on direct and indirect emissions at the French borders. They concluded that carbon taxation at borders coupled with redistribution is less regressive than a domestic carbon tax on energetic products. Ghersi and Ricci (2014) used a static general-equilibrium model, IMACLIM-P, to estimate the effects of macroeconomic scenarios on poverty. They found that in all cases, the macroeconomic scenarios are increasing the prevalence of poverty at the 2035 horizon. Ravigné and Nadaud (2021) analyzed the potential backfire effect of a €158 per tonne of carbon in France. They found that the backfire effect of homogeneous redistribution is small for low-income households. Beyond the environmental impact, they shed light on the potential benefits for vulnerable households while signaling the exclusion of a part of the population from the positive social effect of such a policy. Using a dynamic, general-equilibrium framework, the Three-Me model, Ravigné *et al.* (2022) analyzed inequality's horizontal and vertical aspects following carbon taxation. They show that carbon taxation is regressive in the absence of horizontal recycling, while lump-sum rebates could alleviate vertical inequalities but keep horizontal inequalities the same. They also confirm a potential 3 percent rebound in GHG emissions following tax recycling.

3.2 Data and methodology

3.2.1 Data

National Accounts Input-output tables are frequently used to disentangle the trade relationship between industries to understand the interdependence of industries in the economy. In its simplest form, an input-output model is a system of linear equations, where each equation describes the distribution of an industry's product throughout the economy. Thus, input-output tables have a matrix form, where the rows describe the distribution of a producer's output throughout the economy, and the columns describe the composition of inputs required by a particular industry to produce its output. These flows are generally expressed in monetary terms. Additional columns express the final demand, reflecting the sales made by sectors to final markets composed of households and public government. Additional rows specify the value added, accounting for other non-industrial inputs required to produce a good or service, such as employment, depreciation of capital, or business taxes. The table only incorporates the interdependence of national industry and domestic final demand when considering national input-output. With the surge of open and globalized economies, multi-region input-output (MRIO) models have been increasingly studied. These models permit the incorporation of international interdependence, not only between countries but also between sectors. They consider differences between the production and technology structures of countries. Nonetheless, recent estimates of this kind of table are unavailable since they are demanding to compute.

For the purpose of this study, we use domestic statistics from Eurostat[22], which provides national input-output tables. They are preferred to MRIO since we assume carbon taxation applies only to domestic emissions regardless of imported emissions. Moreover, working only with national statistics (i.e., household consumption surveys, emissions inventories, and national accounts) is more convenient for merging and aggregation. Commonly referred to as the "*tableau entrées-sorties*" (TES) in French, it provides the flows of goods and services between industries of the French economy. Our input-output model is composed of 64 products satisfying the final demand of households, public administrations, and non-profit organizations. The table is expressed for the domestic economy at basic price, suggesting that prices exclude trade taxes, transport taxes, and taxes on products net of subsidies.

National budget survey of French households: the BDF framework Data on consumer expenditures were taken from the 2017 version of the *enquête Budget de Famille*

[22]The Institut National de la Statistique et des Etudes Economiques (Insee) is the leading provider of domestic statistics. However, the available input-output tables lack granularity.

(BDF) provided by the Insee[23]. The Insee publishes at quinquennial path information about the expenditures and resources of around 12,000 French households[24]. The inquiry is conducted during six consecutive waves to correct seasonality effects. The whole sample is assumed to be representative when aggregated and is calibrated to approximate national accounts. Expenditures are classified into 900 items ventilated in the different categories of the Classification of Individual Consumption by Purpose (COICOP) nomenclature. The database also reports households' resources such as standard of living, taxable income, social subsidies, or tax base. We provide descriptive statistics of the database in Table 9 on page 83. The main resources used to describe households' income in this study are the following:

- Disposal income: it refers to the income net of taxes and subsidies, reflecting the whole amount of money available to consume or to save, excluding exceptional resources.
- equivalized income: reflects the standard of living. It corresponds to the disposal income normalized to the composition of the household[25]. It uses the modified OECD equivalence scale assigning a weight of 1 to the first adult, 0.5 to the second and each subsequent person aged 14 and over, and 0.3 to each child under 14.

Several sociodemographic and socioeconomic characteristics of the households are considered in this study. Based on the literature, we group households according to the number of children, the age of the head of the household, the education level, the geographic location, the household composition, and the type of tenure. The number of children is a critical factor in the management of the budget since a single person and a family do not share the same consumption pattern. However, it seems that the number of children is not linearly related to the level of expenditures, reflecting potential economies of scale. The age of the head of the household is also critical in the analysis of the distribution of the carbon footprint. Again, as the head of the household is getting older, its consumption tends to change gradually. The gap could be even more exacerbated between workers and retired individuals. The educational level is more or less related to the income level, but it can also have a reversal effect on emissions. We retain the indicator differentiating between 15 different education categories, from no to high education (MSc. and PhD). It follows the French educational process. We group eight categories considering the years after A-level. The geographic location of the household is undoubtedly one of the most essential characteristics of a household's emissions. The indicator retained split households according to the size of the urban unit[26]. From this indicator, we can differentiate rural households and households living in big cities such as the Parisian agglomeration. The household composition follows the scaling of consumption units in that a household with a single person has different needs compared to a household composed of a couple. Finally, we also explore the possibility of divergent behavior when considering the type of tenure, notably coming from home energy expenditures. All else being equal, households living in houses generally spend more on the energy bill than in buildings. The type of building (i.e., the number of inhabitants in the building) is also relevant.

On the expenditures side, we group consumption into nine aggregated items. The corresponding list of expenditures and items classification is presented in Table 14 on pages 85 and 86. In food, we gather expenditures linked to nutrition within the house. Tobacco and beverages expenditures are also included in this item. Manufactured goods item groups

[23] A complete overview of the survey is available at: https://www.insee.fr/fr/statistiques/4648335?sommaire=4648339.

[24] For this study, we only consider Metropolitan France.

[25] The equivalized income is the ratio between the disposal income and the equivalent size (i.e., the sum of the weights of all the members of a given household).

[26] The size of the urban unit considers the number of inhabitants in the urban area.

expenditures allocated to materials such as kitchen utensils, clothes, mobile phones, computers, etc. Market services include expenditures linked to hairdressers, cell phone contracts, insurance contracts, or real estate services (excluding rents and mortgages). Non-market services refer to education and health expenditures principally. The energy item is related to electric and gas bills and all other expenditures devoted to heating and cooling the dwellings. In the transport item, we do not differentiate between money spent on gasoline and general transport expenses. Mobility of households has declined between terrestrial (bus and train), maritime (boat), and air transport (airplane). Cultural expenditures integrate show tickets, sports club subscriptions, books, and newspapers. We also include spending on restaurants and hotels in this item. We also notice the payment of rent as a major share of total expenses. Effectively, the share is null for homeowners, while it can be significant for tenants. Finally, building reports expenses made by the household to renovate or build a home. We do not consider these two items when looking at the effect of the carbon tax since many households do not report anything on these items. Expenses related to the payment of taxes and subsidies are ignored throughout the study.

Matching microeconomic with macroeconomic data One difficulty of this analysis is to make legitimate correspondence between the consumption survey and the final demand in the national input-output table. The difficulty arises in the correspondence of macroeconomic aggregates and microeconomic consumption. Although the carbon intensity of an economic sector can reflect the carbon content of a product, this is more or less the case for consumption items since a household does not effectively consume a sector's mean production but rather a final product (Pottier *et al.*, 2021). Indeed, the two sides have no direct link since they differ in their categories (industries versus consumption items) and their level. Generally, national figures at the sector level are more significant than the consumer survey. We construct a correspondence matrix between household expenses and sector homogeneous products expressed in the COICOP and the Nomenclature d'activités française (NAF), respectively. For some items, the allocation to a sector product is unambiguous since there is a perfect match between the two categories. Note that the granularity of some items of the budget survey results in multiple matching with one sector of the NAF. However, it is also possible that one item corresponds to more than one ICOP sector. Indeed, some consumption items can be directly or indirectly linked to the production of several sectors. This is notably the case for food consumption as vegetables can be sold directly by farmers and thus corresponding to the agriculture sector, or instead processed and thus corresponding to the food and beverages economic sector. Therefore, we match some of the items in an ad-hoc way. In Table 14 on page 85, we give some examples of the connections.

After assigning the consumption items to sector products, the household demand for goods and services can be connected to input-output production. One method[27] consists in assuming a perfect relationship between production and consumption (Isaksen and Narbel, 2017; Malliet *et al.*, 2020; Lévay *et al.*, 2021, 2022). One monetary unit spent on household food will equal one monetary unit of food and beverages gross output. In other words, we use the carbon intensity of 64 sectors to assign the carbon footprint of indirect emissions linked by the expenditures on all items. Notice that this match implies a static relationship between economic sectors and consumption categories. In other words, there are no feedback

[27] Another method can be used to link the emissions and consumption. It consists of assigning consumption items from the household budget survey to one or various sectors of the ICIO and then to scale the consumption survey data for each sector by income groups to fit the total final demand of each table's sector (Gough *et al.*, 2011; Hubacek *et al.*, 2017a; Pottier *et al.*, 2021). The method assumes that the amount of final demand in the input-output table is more reliable than the total consumption of goods and services in consumption surveys.

loops in our model, we only use input-output tables to compute the carbon intensities of products.

Another drawback arises from the price unit. As in most studies inspecting the household's carbon footprint, input-output tables are expressed at basic prices. The basic price is the amount of money received by the producer from the purchaser for one unit of a good or service produced as output, excluding taxes on products, any subsidies, retail margins, and transport margins. This is why input-output tables at basic prices have significant flows for transport and retail industries. Conversely, prices in consumption surveys are expressed at purchaser prices. Purchaser price is the amount of money paid by the final purchaser for the good or service produced, including taxes, subsidies, and margins. Therefore, the two units can be significantly different and should be transformed. To do so, we use the price converter of Cazcarro *et al* (2022), which consists in restating and deflating purchaser prices to basic prices by integrating taxes, subsidies, and margins based on separable national account table[28]. We then obtain carbon intensity, and expenditures expressed both at basic prices. The ultimate step is multiplying the expenditures in basic prices by the carbon footprint multiplier, reflecting the GHG emissions embodied in expenditures per monetary unit. The method permits keeping the input-output framework at basic prices unchanged while not overestimating emissions from purchases.

Direct emissions estimates The input-output model calculates indirect emissions included in the household carbon footprint. We applied emission coefficients to energy quantities (kWh, kg, and ℓ) to estimate direct emissions. Price estimates for energetic products are extracted from annual statistics of the *Service Des Donnés et Études Statistiques* (SDES). The emission structure of energetic products is provided by the French Agency for Ecological Transition (ADEME), which lists the emission factors of numerous products. From these data, we establish an emissions converter table to adapt household expenditures on energetic products into carbon emissions. To do so, we divide expenses by average energy price (expressed in €/kWh, €/kg, €/ℓ), and then we multiply it by its emission factor (expressed in kg of CO_2e). Table 12 on page 83 provides the emission converter table. We use consumer prices, which include taxes, and the total emission structure (i.e., upstream plus combustion). We cannot make any distinction of the price of energetic products between geographic location or household characteristics as in De Lauretis (2017). However, we could avoid misspecification by including the main energy source and the household's main heating system. Thus, we could differentiate between propane and butane, as well as between coal and wood. One issue emerges from the non-separation of energy bill expenditures that include both gas and electricity. We follow the methodology of Pottier (2022) to approximate the split between the two energetic sources. It consists of allocating expenditures between the two items given the proportion of expenditures dedicated to electricity and gas (which are separable) for a given group of households sharing the same characteristic in terms of heating system.

The BDF survey is designed to be representative of the consumption behaviors of the French population when aggregated. However, a lack of granularity in several expenditures can be misleading when working on differences between and within groups. In our case, the assessment of French carbon footprint rests on an accurate estimation of direct emissions, which is, above all, based on individual transport and especially on transport fuel consumption. Since the survey framework is elaborated with weekly expenditures, the survey tends to underestimate the trips of households every year and, thus, the total amount of money spent on gasoline. To limit this potential under-reporting, we rely on a similar household

[28] To have a complete overview of the methodology and limitations, see Mongelli *et al.* (2010).

survey describing French households' mobility during a year based on socioeconomic characteristics, with a methodology close to the one adopted in BDF. Known as the *Enquête sur la mobilité des personnes* (ENTD), the survey is conducted every ten years on the trips and transportation of French households by the SDES[29]. To reduce the gap between the two datasets on households' mobility, we approximate the true value of fuel transport expenditures and trips of households to improve the accuracy of the carbon footprint of households within and between deciles[30]. To do so, we merge the two datasets following the statistical methodology of Douenne (2020), based on the work of D'Orazio *et al.* (2006), which consists of associating households of the two datasets, sharing the same characteristics, by minimizing the distance between observations[31]. Trips made in kilometers are then transformed into expenditures using an expenditure by kilometer factor estimated at the decile and geographical location level to keep expenditures relatively proportional to the ones in the income decile of BDF. Finally, we use disaggregated data on household vehicles to assess direct emissions for mobility purposes accurately. Given the type of car in the household, we can differentiate between gasoline, diesel, liquefied petroleum gas, and electric consumption. If there is more than one vehicle type in the household, car fuel expenditures are split between the different sources.

The domestic carbon tax design In France[32], the carbon taxation has been introduced in 2014 with the inclusion of a carbon component in the TICPE ("*taxe intérieur de consommation sur les produits énergétiques*"). The tax applies mainly to energetic products using fuel as an input for the engine, excluding fuel for fluvial and air transport. Electricity[33] is also excluded from the field of the TICPE. The carbon tax is also levied on hydrocarbon products used for heating, such as coal or lignite, but excluding natural gas[34]. The tax receipts are affected by tax credit for employment and also to finance energetic transition through renewable investment. The carbon price initially amounted to 7€ per ton of CO_2, then followed an increasing path: 14.5€ in 2015, 30.5€ in 2017, and 44.6€ in 2018. As oil and natural gas prices were low at this time, the tax increase was not a source of discontent from households. The price shift in 2018 reversed the tax effect, which consumers felt notably for mobility, acting as a catalyst of the yellow-vest protests. As a consequence, the gradual increase of the tax was abruptly revoked, making the carbon tax of France unaltered since then. The primary objective of the tax to achieve the €100 per ton of CO_2 target by 2030 seems unreachable nowadays.

In this study, an *ad valorem* carbon tax is designed to simulate a sharp increase in the prices of goods and services of the economy. We keep with the projection of the French government to establish a carbon tax of €100 per ton of CO_2e. Unlike most other studies, the tax is applied to any sources of CO_2e emissions ranging from energy needs to cultural and entertainment expenses. We want to stress the price of any bundle of goods and services consumed by households, assuming a policy seeking to break the stalemate of fossil fuel. This price jump is also a facade to analyze the effect of an energetic shortage as the repercussions

[29]We use the latest transport survey conducted in 2019, known as "*Mobilité des personnes*". A complete overview of the survey is available at: https://www.statistiques.developpement-durable.gouv.fr/enquete-sur-la-mobilite-des-personnes-2018-2019.

[30]Notice that we are only interested in the kilometers made by households. They must detain a vehicle to be matched.

[31]As in Douenne (2020), we are using non-parametric NND hotdeck method. We use the following characteristics to match households: income decile, geographic location, type of household, number of vehicles in the household, consumption units, and disposal income.

[32]More detail can be found at: https://www.ecologie.gouv.fr/fiscalite-des-energies.

[33]Electricity has a specific tax.

[34]Natural gas has a specific tax.

on consumption could be alike, despite assuming that producers entirely pass price increases onto consumers, a solid but common simplification and that the model fits for a closed economy.

3.2.2 Methodology

The input-output model The starting point of input-output analysis is based on the monetary values of the flows of products from each sector (as a producer/ seller) to each of the sectors (as a purchaser/ buyer). The transactions between pairs of sectors (from each sector i to each sector j, usually expressed as $z_{i,j}$. In other words, sector j's demand for inputs from other sectors is related to the amount of goods and services produced by sector j over the same year. External sales to households, government, and foreign trade constitute the exogenous part of the model, which describes the total final demand. Assuming that n sectors constitute the economy. If we denote by x_i the total output of sector i and by f_i the total final demand addressed to sector i, we can write the following standard equation:

$$x_i = z_{i,1} + ... + z_{i,j} + ... + z_{i,n} + f_i = \sum_{j=1}^{n} z_{i,j} + f_i \tag{10}$$

where x_i is the total production of sector i, which is distributed between sales to other sectors ($z_{i,j}$) and to final demand (f_i). A fundamental assumption of the input-output model is the dependency between inter-sector flows and total production. If there is an increase in the demand for Sector 1 output, which depends on the output produced by Sector 2, Sector 2 should increase its production to satisfy the demand of Sector 1. In this context, the interdependence of sectors is commonly expressed as the ratio between the required output of sector one from sector 2 and the total output of sector 1. These ratios refer to technical coefficients, expressed as: $a_{i,j} = z_{i,j}/x_i$. The main objective of the input-output analysis is to determine each sector's required output growth following the change in final demand. Since final demand is exogenous, technical coefficients are constant, and total output is endogenous, we can represent the model in matrix form, as follows:

$$x = (I - A)^{-1} f \tag{11}$$

where I is the identity matrix of size $n \times n$, A the matrix of technical coefficients and f the column vector of total final demand. $(I - A)^{-1}$ forms the total requirement matrix, also known as the Leontief inverse. It gathers the amount of total output from sector i required to satisfy the final demand of sector j.

Model extension to environmental purpose We now want to extend the model to environmental purposes (Lenglart *et al.*, 2010; Mardones and Mena, 2020; Adenot *et al.*, 2022). To do so, we use Eurostat's air emissions accounts (AEA) that record the amount of gas emitted into the atmosphere by economic activity (Keuning and Steenge, 1999). It provides a detailed breakdown of our 64 economic activities and household emissions from transport and heating. Assuming a proportional relationship between total production and total emissions for each sector, we obtain the direct carbon intensity as: $y_i = u_i/x_i$ where u_i is the total absolute amount of direct emissions or the ton of CO_2 equivalent (t of CO_2e) emitted by the sector i in term of its total output[35]. Therefore, these intensities only consider

[35] We use the estimates related to GHG emissions composed of seven gas transformed in carbon dioxide equivalent. The calculations of AEA, in line with the Kyoto protocol, gather CO_2 from 7 sources: CO_2, N_2O in CO_2e, CH_4 in CO_2e, HFC in CO_2e, PFC in CO_2e, SF6 in CO_2e and NF3 in CO_2e. This measure turns a greenhouse gas into carbon dioxide based on its global warming potential. For instance, each ton of CH_4 and N_2O emitted has the equivalent of CO_2 emitted of around 25 and 298, respectively.

the direct emissions of a particular industry. To get the total (direct and indirect) carbon intensity of sector i, we have to integrate indirect emissions from the inputs produced by each of the j sectors. In numerical form, the relationship is defined by:

$$b_i = y_i + \sum_{j=1}^{n} a_{j,i}\ b_j \tag{12}$$

where b_i is the total carbon intensity of sector i. In matrix form, we have:

$$b = y + A^\top b \tag{13}$$

where y is the column vector of direct intensities and $A^\top$ the transpose of matrix A. The previous equation can be written as:

$$b = (I - A^\top)^{-1} y \tag{14}$$

where b is the column vector listing the total carbon intensity of each sector, translating the ton of CO_2e emitted across the production line for one monetary unit of output, conditional on final demand.

To obtain the domestic carbon footprint of French households, we link the production required to satisfy the final demand with household consumption reported in the budget survey. We assume that the carbon intensity of sectors can reflect the carbon content of consumption given an accurate match between the economic sectors and the goods and services consumed by households. For indirect emissions, we can approximate the domestic carbon footprint of French households by multiplying the level of expenditures $w_{i,h} \times\ m_h$, expressed in euros, for each item i and each household h, and the total carbon intensity of a peculiar sector i:

$$e_h^{\text{ind}} = \sum_{i=1}^{k} b_i\ (w_{i,h} \times\ m_h) \tag{15}$$

where m_h is the total expenditures (expressed in euro) of household h and $w_{i,h}$ is the share of expenditures allocated to sector i output. For direct emissions (e_h^{dir}), we used the previously developed methodology, that is, transforming expenditures into quantities and applying carbon intensity per quantity consumed. The correspondence between units is presented in Table 12 on page 83. By summing the two amounts of CO_2e emitted, we obtain the household carbon footprint e_h.

In this study, the carbon tax takes the form of an *ad valorem* tax, meaning that the carbon margin of the prices depends on the CO_2e content of goods and services. For the computation of indirect emissions, the carbon tax enters the model as follows:

$$t_i = \nu\ \times\ b_i \tag{16}$$

where ν is the carbon price (i.e., the € per ton of CO_2e), b_i is the ton of total CO_2e per monetary unit of gross output. Thus, t_i represents the carbon cost for a monetary production unit from the sector i. It can be seen as an additional cost of the production.

Carbon footprint elasticity with respect to income A prominent question in social inequality and carbon footprint research is the link between emissions and income. To understand the role of income inequality in the distribution of households' carbon footprint, and thus inequality in emissions, carbon footprint elasticity to income is a powerful metric. In other words, the carbon footprint elasticity to income depicts how emissions behave given wealth improvement, that is, the percentage change in the household carbon footprint following a one percent increase in income. Since we are able to compute the bottom-up distribution of emissions across households, we can easily determine the elasticity of carbon footprint with respect to income. The elasticity of household carbon footprint with respect to income $\varepsilon^{\mathrm{CF}}$, is defined by:

$$\varepsilon_v^{\mathrm{CF}} = \frac{\partial e}{\partial v}\frac{v}{e}$$

where v represents disposal income and e the households carbon footprint, expressed in t of CO_2e. We do not use equivalized income since the carbon footprint is not equivalized.

For the reason that there is no consensus on the best model to fit elasticity and for sensitive analysis, we present in Table 2 three common functional forms used in the literature to estimate the carbon elasticity (Weber and Matthews, 2008; Isaksen and Narbel, 2017; Lévay *et al.*, 2022). The models are estimated using ordinary least squares regressions[36]. By adding quadratic, cubic, and logarithmic terms in the regressions, we seek to capture non-linearities in the elasticity. We add the consumption unit variable (l) to control for household size and composition.

Table 2: Model specifications for the computation of carbon footprint elasticity

	Model	Functional form	Elasticity
(1)	Quadratic	$e = \beta_1 v + \beta_2 v^2 + \delta l + \epsilon$	$\varepsilon_v^{\mathrm{CF}} = (\beta_1 + 2\beta_2 v)\,\frac{v}{e}$
(2)	Cubic	$e = \beta_1 v + \beta_2 v^2 + \beta_3 v^3 + \delta l + \epsilon$	$\varepsilon_v^{\mathrm{CF}} = \left(\beta_1 + 2\beta_2 v + 3\beta_3 v^2\right)\frac{v}{e}$
(3)	Log-log	$\log(e) = \beta_1 \log(v) + \delta l + \epsilon$	$\varepsilon_v^{\mathrm{CF}} = \beta_1 \frac{e}{v}\frac{v}{e} = \beta_1$

Source: Lévay *et al.* (2022).

Given that income could be a less stringent emission distribution indicator due to a reduced share of expenditures when income rises, we also explore the alternative relationship between total expenses and emissions. To go deeper in assessing the household's carbon footprint, we also make a distinction with respect to direct and indirect emissions. The specific point where the elasticity is calculated is commonly assumed to be at the mean distribution. However, as Lévay *et al.* (2022) remarked, it can significantly vary if we take another point in the distribution and even more when the income distribution is skewed. Thus, the elasticity estimation is also computed on median income and expenditures. We proceed to an outliers removal process using an exclusion threshold of 3 considering studentized residual[37]. As a result, 225 and 193 out of 12,081 observations were removed from the sample when looking at the income and expenditures, respectively.

The household demand system To assess the impact of environmental policies on welfare, we have to model the behavioral response of households after price increases. In doing so, we seek to assess the consumption sensitivity of price variation in the very short run. For this purpose, we estimate, in a microeconomic framework, the price and budget elasticity of demand. Furthermore, the model specification permits the inclusion of heterogeneity between households within the same income group. The estimation of the household demand

[36] ϵ is the error term.

[37] A studentized residual is a residual divided by its estimated standard deviation. We assume that if an observation has a studentized residual larger than 3 in absolute value, it is an outlier.

system is based on a system of equations that are functions of the whole set of prices and total expenditures. In this study, we use the Quadratic Almost Ideal Demand System (QAIDS) of Banks *et al.* (1997), which is an extension of the original Almost Ideal Demand System (AIDS) of Deaton and Muellbauer (1980), to approximate Engel curves[38] mainly for its compatibility with cross-sectional data as in household budget surveys. The model extension introduces a quadratic component in the budget to better integrate non-linearities in the Engel curves. The model and the estimation process are presented in Appendix B.2 on page 98.

Several studies have used the QAIDS model in the carbon tax context (Brännlund and Nordström, 2004; Labandeira *et al.*, 2006; Nikodinoska and Schröder, 2016; Tiezzi and Verde, 2016; Renner, 2018; Douenne, 2020). The main concept of a demand system is to express the budget share $w_{i,}$ allocated to the k different items by household h given the price of the item p_i, the prices of the other items p_j and its standard of living m_h (here, m represents total expenditures). We estimate for each household and each item the following expenditure share system:

$$w_{i,h} = \alpha_{i,h} + \sum_{j=1}^{k} \gamma_{i,j} \ln p_j + \beta_{i,h} \ln \left\{ \frac{m_h}{\mathbf{a}_h(p)} \right\} + \frac{\pi_{i,h}}{\mathbf{b}_h(p)} \left[\ln \left\{ \frac{m_h}{\mathbf{a}_h(p)} \right\} \right]^2$$

where $\mathbf{a}_h(p)$ and $\mathbf{b}_h(p)$ are aggregated price indexes and $\pi_{i,h}$ is a differentiable and homogeneous function of degree zero of prices p. Notice that if we set $\pi_{i,h} = 0$, we reduce the model to the Almost Ideal Demand System. The estimated parameters are difficult to interpret directly (Lewbel, 1991). However, from these equations, the estimation of the parameters permits the computation budget and price elasticities of demand as developed in Appendix B.2 on page 99. We estimate the model based on three rounds of budget surveys, namely BDF 2006, BDF 2011, and BDF 2017, to maximize the number of observations to represent household behavior consistently.

One central limitation of most demand systems is the incompatibility between elasticity estimation and censoring. Due to the short report period, many households do not report expenditures on several goods and services, implying zero consumption, even if we aggregate expenditures by item. The censoring problem can be linked to households' behavior, such as non-preference, non-affordability, or directly linked to the survey itself caused by infrequent purchases or non-availability (Boysen, 2016). Although common in household expenditure data, censoring cannot be addressed by the QAIDS model since $w_{i,h}$ is part of the elasticity computation, and if it's equal to zero, the budget elasticity of demand will be infinite. In other words, integrating these expenditures into the demand system would bias the estimates. As a result, we retain only seven items in our specification, namely food, manufactured goods, market services, energy, non-market services, transport, and culture. Expenditures related to building and rent are excluded due to too small representativeness since more than 70% and 63% of households are reporting zero consumption, respectively. We must also reduce the sample size since the remaining censored households must be rejected. We keep 80% of the original sample from BDF 2017 (9,637 households out of 12,081). In Table 10 on page 83 we count the number of zeros by item and income decile. We also provide the descriptive statistics and the histogram of households carbon footprint in Table 11 on page 84 and in Figure 22 on page 94 respectively. As one could expected, the problem of censoring is skewed toward low-income households, which do not report expenditures for mobility and non-market services essentially. Although the carbon footprint is greater for the reduced sample than for the original sample, we still obtain a representative sample.

[38] Engel curves represent the budget share allocated to a good or service as a function of the consumer income.

For the seven items retained in the model, the prices used in the demand system are derived from monthly consumer index prices provided by the Insee. To catch the maximum heterogeneity in the model, we match monthly price indexes with the survey's wave period, which can differ between households. Moreover, the item price indexes for each household also depend on the budget share allocated to a particular item, that is, for each household, its respective index price is the average of the index price weighted by the budget shares within the item under consideration.

The redistribution schemes One option to reverse the domestic carbon tax's regressive nature is to make social transfers using the carbon tax's revenue. The recycling of the tax seems to be socially optimal through lump-sum transfers (Carattini *et al.*, 2017), also known as green cheques. Above all, lump-sum transfers' simplicity permits directly orienting cash transfers toward low-income households, mostly affected by the tax burden, and constitute a potential detractor of a regressive tax system. Since low-income households have lower absolute expenses, notably on energy, transport, and food items, the compensation received generally exceeds the initial carbon tax burden, making the tax progressive. Households are considered to be "*winners*" (resp. "*losers*") when the amount they received from the recycling of the tax is superior (resp. inferior) to the amount they pay for the tax.

If the initial effect on vertical inequality can be reversed through income transfers, this kind of redistribution could miss totally horizontal targets (Douenne, 2020). As previously unveiled, many households could suffer from the tax but may be out of the scope from an income level perspective. Unlike vertical aspects, horizontal inequality depends on consumption patterns, notably energy use. Fortunately, these consumption patterns have approximate proxies such as geographic location, household size and composition, or tenure type. The redistribution scheme seeking to reduce horizontal inequality should account more for household characteristics than income but can be imperfect or impractical (Pizer and Sexton, 2019).

In this study, we use three redistribution schemes as lump-sum transfers. The schemes are almost revenue-neutral since 80% of the tax receipt is recycled to social transfers. We assume that the government keeps a residual amount of the fiscal policy to establish the tax. Each redistribution is independent of the level of consumption, making no incentives to change the consumption patterns of households to benefit more. In the baseline scenario, we consider homogeneous lump-sum transfers, that is, each household receives an equal amount of tax revenue. This flat-recycling scheme is used to understand how households behave when they are compensated when prices surge. We consider a redistribution scheme seeking vertical inequality reduction in the second case. The social cushioning scheme applies only to households with a disposal income below the national poverty line. If the disposal income of the household is lower than 60% of the median disposal income of the sample, the household is considered to be in extreme poverty. This redistribution seeks to reverse the regressive trend of the carbon tax given income decomposition, which only considers the vertical aspect of the carbon tax inequality. Finally, we consider a tailored redistribution scheme attempting to catch socioeconomic characteristics to determine the most dependent and vulnerable households to the carbon tax. We assume those households will likely oppose the carbon tax if they are not compensated. Therefore, this scheme seeks to reduce horizontal inequality. To do so, we spot households with the same socioeconomic characteristics based on energy and transport dependency. We do not attempt to gather conventional metrics used in the literature to define fuel poverty or transport dependence to flag households. Instead, we rest on the report of Devalière and Teissier (2014) emphasizing the prominent factors of energy poverty in France. Using three indicators, namely the energetic effort rate[39], the low-income high-expense[40] and the cold perception[41], they unveiled three main groups of households subject to energy poverty:

- Retired households: the first group comprises old persons, generally one or two retired, living in large dwellings and overusing fuel to heat their homes.
- Young workers: the second group comprises young workers renting their flat or reimbursing a credit.
- Unemployed: The last group is formed by unemployed people in precarious situations, benefiting aid from the state.

On the mobility side, we consider households living outside big cities, which require their vehicle to go to work. Based on estimates from the ENTD survey, the median distance of households' trips can also be determined. We estimate that rural households making more than the median yearly trip are also concerned about fuel dependency. However, to avoid the subsidy of affluent households' emissions, we only consider the transport segment of the tailored scheme households within the first five deciles and households using fossil fuel cars.

Table 13 on page 84 shows that we split these characteristics between dependency and vulnerability factors. Dependency refers to households' difficulty substituting from carbon-intensive consumption due to several factors. For instance, the size of the dwelling underlies a substantial budget share of home energy. Factors of vulnerability reflect the difficulty of households facing high energy prices. For instance, households are more vulnerable to a carbon tax if they allocate an important share of their budget to the payment of either the rent or their credit. To be compensated, households must be part of at least one group.

The microsimulation model In the first step, we estimate the model based on three rounds of budget surveys. From the estimated parameters, we compute budget elasticities and compensated and uncompensated price elasticities. We also take a look at the differences between elasticities given income groups. However, we are not using these estimates directly in the microsimulation. We follow the methodology of Renner (2018) consisting of estimating predicted shares given price changes induced by the tax[42]. It is necessary to appraise tax revenue since we use the predicted shares as the determinants of substitution effects given the price increase. We simulate the price change as follows:

$$\frac{\Delta p_i}{p_i} = \frac{p_i^{\text{tax}} - p_i}{p_i} \tag{17}$$

where p_i^{tax} is the new price level, including the additional cost of the carbon tax, and defined by:

$$p_i^{\text{tax}} = \left(1 + \frac{\Delta p_i}{p_i}\right) p_i \tag{18}$$

This new set of prices is then incorporated in the demand system in order to simulate the budget shares of item i for each household according to:

$$w_{i,h}^{tax} = \hat{\alpha}_{i,h} + \sum_{j=1}^{k} \hat{\gamma}_{i,j} \ln p_j^{\text{tax}} + \hat{\beta}_{i,h} \ln \left\{ \frac{m_h}{\mathbf{a}_h(p^{\text{tax}})} \right\} + \frac{\hat{\pi}_{i,h}}{\mathbf{b}_h(p^{\text{tax}})} \left[\ln \left\{ \frac{m_h}{\mathbf{a}_h(p^{\text{tax}})} \right\} \right]^2 \tag{19}$$

[39] It captures households with energetic expenditures greater than 10% of total expenditures.
[40] It measures the ratio between energetic expenditures and disposal income, proposed by Hills (2012).
[41] It comes from a national survey and describes the perception of cold in the dwelling by households.
[42] This step applies to the latest round of the budget survey.

where the terms with hats are estimated coefficients from the previous QAIDS estimation, and the subscripts denote the pre-tax and post-tax period. Notice that household characteristics remain unchanged. From these predicted shares, we can compute the new carbon footprints of households by integrating the new shares into equation (15). Similarly to the carbon footprint estimation, we can approximate the carbon tax effectively paid by households as follows:

$$T_h = \sum_{i=1}^{k} t_i \; (w_{i,h}^{\text{tax}} \times \; m_h) \tag{20}$$

From this tax revenue collected, redistribution schemes are elaborated. We assume that the attribution of transfers is perceived as a gain in total expenditures[43]. Thus, the new budget equals the old budget with the cash transfer: $m_h^{\text{red}} = m_h + R_r$ where m_h^{red} represents total expenditures after the collect, R_r is the amount of cash collected for each r redistribution scheme. Notice that if the household does not collect the transfer, we assume he should behave as in the carbon tax implementation situation since only prices have changed. The direct cash transfers are then incorporated into the demand system as follows:

$$w_{i,h}^{red} = \hat{\alpha}_{i,h} + \sum_{j=1}^{k} \hat{\gamma}_{i,j} \ln p_j^{\text{tax}} + \hat{\beta}_{i,h} \ln \left\{ \frac{m_h^{\text{red}}}{\mathbf{a}_h(p^{\text{tax}})} \right\} + \frac{\hat{\pi}_{i,h}}{\mathbf{b}_h(p^{\text{tax}})} \left[\ln \left\{ \frac{m_h^{\text{red}}}{\mathbf{a}_h(p^{\text{tax}})} \right\} \right]^2 \tag{21}$$

Again, the predicted shares are used to estimate the carbon footprint of households. The potential backfire effect is thus the difference between the post-tax and post-redistribution emissions levels. As we are not moving from original carbon intensities, we have to subtract from total expenditures the share devoted to the tax payment. Assuming the same consumption pattern, that is, re-allocation is made at the level of item rather than goods and services, we can estimate new expenditures and their respective carbon footprint following the previous methodology.

Measuring the social impact of the carbon tax To measure the social impact of the carbon tax, we use a conventional measure of the tax burden, that is, the effort rate. The effort rate is the ratio between the amount of tax paid by the household and the household's income level. This metric permits to estimate the tax burden distribution. In the manner of Ruiz and Trannoy (2008), we use the aggregated effort rate, which corresponds to the sum of tax paid by households within each decile divided by the sum of disposal income of each household within decile[44]. This computation form permits aggregating the households in decile rather than taking the average effort rate. The latter can be biased due to a large number of zero consumption. The metric takes the following form:

$$ER_d = \frac{\sum_{h=1}^{H_d} T_{d,h}}{\sum_{h=1}^{H_d} v_{d,h}}$$

where $T_{d,h}$ is the amount of tax paid by household h in decile $d = 1, ..., 10$ including H_d households, and $v_{d,h}$ is its disposal income.

To testify to the carbon tax's regressive/ progressive nature, we complement the effort rate with the Suits index (Suits, 1977). The index measures the relationship between the cumulative share of tax paid and the cumulative share of income. The Suits index is closely

[43] We also run a simulation with estimating predicted shares given the monetary loss of consumption induced by the tax payment. This is notably useful to conclude the capacity of households to make carbon sobriety. In this configuration, household expenditures change as: $m_h^{\text{los}} = m_h - T_h$.

[44] We also provide the figures of the effort rate concerning equivalized income and consumption.

related to the Gini coefficient since it estimates the area below the 45-degree line that falls between the 45-degree line and the Lorenz curve for cumulative share of tax and income. The coefficient varies between −1 and 1. The index asserts a progressive tax system when the value is positive, while a negative value suggests a regressive tax system. As we are dealing with income decile, the Suits index can be defined as follows:

$$\mathcal{S} = 1 - \sum_{d=1}^{10} \left[\mathcal{F}(\mathcal{I}_d) + \mathcal{F}(\mathcal{I}_{d-1})\right] (\mathcal{I}_d - \mathcal{I}_{d-1})$$

where $\mathcal{I}_d$ is the cumulative share of income and $\mathcal{F}(\mathcal{I}_d)$ is the function of the cumulative share of tax paid by households earning $\mathcal{I}_d$. We also compute the Gini index for each redistribution process to attest to the change in social inequality with a standard metric. The Gini is computed before and after redistribution, taking into account social transfers between and within household groups. The Gini index takes the following form:

$$\mathcal{G} = 1 - \sum_{d=1}^{10} (\mathcal{L}_d - \mathcal{L}_{h-1})(\mathcal{I}_d - \mathcal{I}_{d+1})$$

where $\mathcal{L}_d$ is the cumulative share of population.

We are also interested in how social transfers are made between households to conclude the overall positive effect of tax recycling. To go beyond the Suits index, we analyze variance (ANOVA). It permits to compare the means of different samples according to groups[45]. We perform the test on the effort rate given the ten income groups of households according to each redistribution process. For that purpose, we measure the effort rate as the ratio between the amount of tax paid and the equivalized income, and in the case of revenue recycling, extended by the cash transfer, equivalized by the consumption unit of the household. We are particularly interested in the sum of squares for error SSE (or within groups), the sum of squares of treatments SSC (or between groups), and the total sum of squares SST:

$$\begin{aligned} SSE &= \sum_{d=1}^{10} (H_d - 1) \frac{1}{H_d - 1} \sum_{h=1}^{H_d} (ER_{d,h} - \overline{ER}_d)^2 \\ SSC &= \sum_{d=1}^{10} H_d (\overline{ER}_d - \overline{ER})^2 \\ SST &= SSE + SSC \end{aligned}$$

where $ER_{d,h}$ is the effort rate of household h located in decile d, $\overline{ER}_d$ is the mean effort rate of decile d and $\overline{ER}$ is the mean effort rate of the sample.

Metrics used to compute energy poverty measures would have also been relevant in order to estimate the social impact of the carbon tax implementation. However, as reported by Legendre and Ricci (2015) and Charlier *et al.* (2015), the major metrics to assess fuel poverty can move apart from one to another as they differ in their scope. Moreover, as we are modeling behavioral responses to a carbon tax, we expect those metrics to be adjusted for dynamic assessment of consumption patterns. Indeed, as households support the tax burden, they take another look at their budget allocation. If the price increases, they can move away from transport and energy expenditures and be less exposed to energy poverty, even if their welfare is significantly reduced. Something emphasized by Reanos and Lynch (2022).

[45] We test the hypothesis of normality distribution (Kolmogorov-Smirnov test and Shapiro-Wilk test), the hypothesis of homogeneity of variances (Bartlett's test) and performs Welch's alternative for robustness.

3.3 Results

3.3.1 The domestic carbon footprint of French households

The budget of French households Before getting to the heart of the matter, we focus on the consumption patterns of French households. In Table 3, we report the share of total expenditures consecrated to each item by income decile (the first decile includes the 10% of households with the lowest equivalized income). We also illustrate consumption patterns for household characteristics in Figure 16 on page 88. Overall, we observe that there are several persistent consumption patterns[46]. Two major trends relate to consumption and income. The budget share allocated to food, market services, energy, and rents seems negatively related to income. As income grows, the share of these products in the household budget tends to decrease. Conversely, the share of expenditures devoted to manufactured products, culture & entertainment, and building seems positively related to income. These relationships make sense since food products, market services, energy bills, and rents are irreducible consumption, while culture, manufactured foods, and building are not in priority consumption.

Table 3: Aggregated households expenditures (in % of total) by item and income decile

Income decile	Food	Manufactured goods	Market services	Energy	Non-market services	Transport	Culture & entertainment	Building	Rents
1	20.13	18.02	17.13	5.98	3.44	11.71	11.98	1.90	9.71
2	20.55	17.94	17.38	6.00	3.24	11.05	11.64	2.76	9.44
3	19.27	18.88	17.55	5.62	3.39	11.10	12.18	3.30	8.71
4	19.76	18.47	16.50	5.57	3.23	11.51	13.37	3.30	8.29
5	18.75	19.53	16.30	5.17	3.15	12.03	13.67	3.77	7.64
6	18.05	20.52	16.56	4.75	3.31	11.96	14.10	4.52	6.24
7	16.77	22.00	15.44	4.94	3.56	12.08	14.47	5.70	5.03
8	17.45	22.11	15.73	4.48	3.93	11.39	14.92	5.53	4.45
9	15.97	21.41	15.09	4.24	3.36	11.68	16.81	7.84	3.60
10	14.55	21.61	15.53	4.37	3.43	10.95	18.71	7.73	3.12
Total	17.55	20.45	16.11	4.94	3.42	11.52	14.86	5.22	5.93

Source: BDF 2017, Insee, ENTD 2019, SDES, author's own calculations.

We notice a substantial share of expenditures is spent on food products (around 18%). Low-income households allot around 20% of their expenditures to food products, while high-income households spend less than 15%. The same is true for market services, which represent around 18% of the budget in low-income households and less than 16% of the budget of high-income households. Although not so important overall (around 5% of total expenditures), the burden of energy is greater for low-income households than for high-income households. The same is true for the difference between rural and urban energy spending. Rural households spend a share of their budget 1.6 times more on energy than urban households. Moreover, households living in houses rather than big buildings (with more than ten apartments per building) have a share of energy expenditures 1.7 times bigger. The share of expenditures spent on rent follows a rational path as richer households tend to own their house while those who rent are generally less wealthy, which explains the inverse relationship of the rent payment item.

When considering the expenditures that tend to be proportional to income, we notice that they characterize the household living standard. The share of expenditures dedicated

[46] Budget surveys assume homothetic preferences, in that poor and rich households consume the same basket of goods and services. However, consumption at different income levels should demonstrate nonhomothetic preferences, reflecting apparent differences in the categories of goods and services demanded given the income level.

to manufactured goods is 1.2 times greater for high-income households than low-income households. The consumption of cultural and entertainment products and services is also increasing with income. High-income households allot 1.2 times more of their budget than the average. The gap is even more prominent when looking at entertainment. For instance, households in the top 10 income group spend 2.4 times more of their budget on hotels than those of the lowest income decile. Expenses on building is also increasing with income since we notice a difference of around six percentage point between the expenditures' share of D10 and D1.

The share of expenditures used for mobility tends to be stable across income deciles. However, when looking at the breakdown of this item, we notice that the share of transport expenditures dedicated to car mobility is 2.5 times greater for the lowest income groups than for the highest income group. On the car-fuel expenses, the poorest 30% allocated on average 60% of their transport budget while the most affluent households around 50%. The more striking difference is between rural and urban residents. The budget share spent by a rural household on car fuel is 3.43 times higher than for an urban household. The gap between the two cohorts is exacerbated with air transportation. On average, the share of expenditures allocated to air transport is four times greater for urban households than rural households and more than two times higher than the sample average. When considering income disparity and air transport, the biggest gap occurs between D10 and D3, with an inter-decile ratio of 10 between the two budget shares. Non-market services, which contain mostly expenditures on health and education, do not show clear progressive or regressive trends with income. However, when considering household size, we notice that households with a growing number of children are expected to spend more on education but less on health.

Prior to the estimation of carbon footprints, we acknowledge that consumption patterns are effectively linked to income levels but also to other socioeconomic features. We expect these socioeconomic characteristics would orient the carbon footprint of French households. Furthermore, consumption preferences are good proxies of the social issue of carbon taxation, thus, we also expect that the tax will not be equally distributed across households because of their size, location, or household type, irrespective of income level.

The households carbon footprint Before detailing the distribution of carbon intensity of household consumption, we provide estimates based on the work of the French Ministry of the Energetic Transition, which provides bulk information on national GHG (including CO_2, CH_4, N_2O) emissions for France. The French carbon footprint is estimated with an input-output analysis. From the report[47], we acknowledge that in 2017, the French carbon footprint amounted at 633 Mt of CO_2e for an average emission per capita of 9.5 t of CO_2e. The carbon footprint is principally constituted of CO_2 (around 80% of total emissions). Domestic production, excluding exports, emitted around 208 Mt of CO_2e while emissions associated with imports required for intermediate consumption in the production amounted to 175 Mt of CO_2e, reflecting an important dependency of the economic activity from foreign production (around 46% of emissions from production). Considering only direct emissions of households for heating and transport, the amount stands at 120 Mt of CO_2e. When looking at the carbon footprint induced by imported products to satisfy directly the final demand, the figure is relatively high, around 130 Mt of CO_2e. Overall, 305 Mt of CO_2e or 48% of the French carbon footprint is emitted out the borders either for production purposes or to satisfy final demand. A predominant effect in the French carbon footprint is the steady level

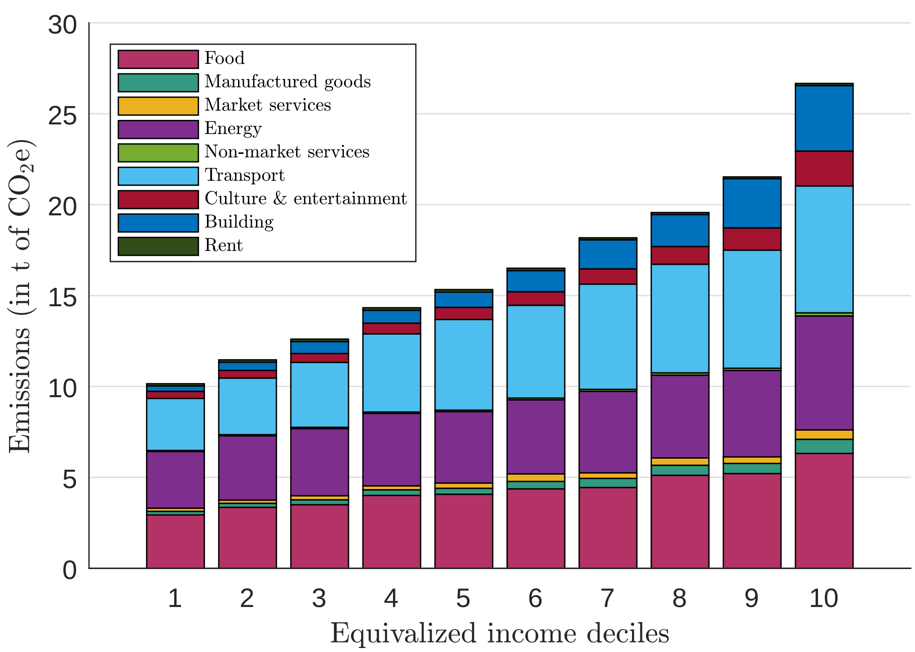
[47] https://www.statistiques.developpement-durable.gouv.fr/estimation-de-lempreinte-carbone-de-1995-2020.

of total emissions but a quick decline in domestic indirect emissions (−25% between 1995 and 2017) while a surge of imported emissions (+27% between 1995 and 2017).

Remark 2. *The main conclusion of these figures is the significant effect of foreign emissions induced by French household consumption, which is out of the scope of a domestic carbon tax and thus out of reach by this study. Therefore, the subsequent results must be taken cautiously as they only include a reduced share (only domestic) of the total household carbon footprint.*

From the domestic input-output analysis and the households budget survey, we found relatively similar figures for French households with an average emissions per household of 16.6 t of CO_2e and a median of 14.6 t of CO_2e. We decompose the household carbon footprint in Figure 10. Unsurprisingly, the main contributors to the total carbon footprint expressed in CO_2e are transport (31% of total), food consumption (26%), and home energy (25%). Alone, these three sources account for more than 80% of the domestic carbon footprint of French households. We observe that household emissions evolve with income. A household belonging to the wealthiest 10% emits on average 26.7 t of CO_2e, which is more than 2.6 times the carbon footprint of a household belonging to the poorest 10% of households, emitting on average 10.2 t of CO_2e.

Figure 10: Average carbon footprint decomposed by decile and item
for each income decile



Source: BDF 2017, Insee, ENTD 2019, SDES, author's own calculations.

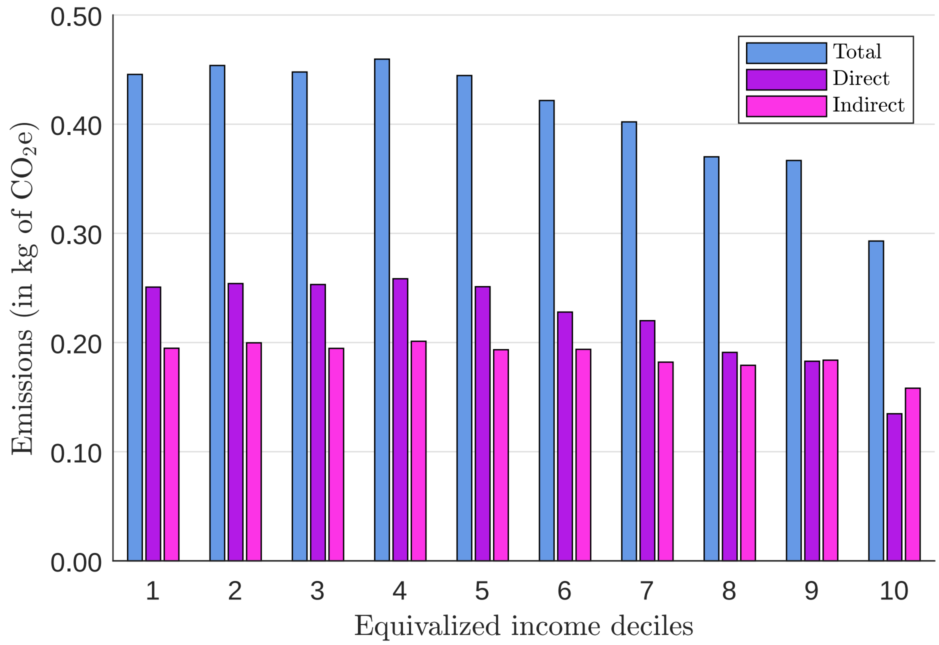
Three main effects can explain the unequal distribution of the carbon footprint (Pottier *et al.*, 2021). There is a volume effect that drives up emissions as income grows. At consumption pattern constant, this volume effect implies that when the level of consumption increases, emissions should increase alike. However, we notice a slightly greater figure for expenditures than emissions when comparing the interquartile ratio of expenditures and emissions between D1 and D10. It means emissions grow less rapidly than expenditures, reflecting the structure effect, which partially contrasts with the volume effect. Since the basket decomposition of consumption (see Table 3) differs substantially between high-income and low-income households, the carbon footprint may differ substantially. For instance, emissions induced by spending made by the richest households for building are equivalent to emissions made by households in the lowest decile for transport on average. In Figure 18 on page 90, we illustrate a more granular distribution of the carbon footprint by differentiating between some goods and services composing the direct and the indirect part of the carbon footprint. Even if the gap in absolute emissions between households is bigger for direct emissions, we notice a larger dispersion of indirect emissions than direct emissions. Indeed, we notice an interquartile ratio of 4.12 between D10 and D1 in indirect emissions, while the interquartile ratio of direct emissions between the two cohorts amounts to only 2.13. Since direct emissions characterize necessary goods, the relationship between direct emissions and income seems to be marginal, while indirect emissions include less necessary goods that are less carbon-intensive but more appreciated by high-income households. This effect is clearly illustrated in Figure 11 where we plot the ratio between aggregated emissions and expenditures to obtain the kg of CO_2e induced by euro spent given the income level of households. The split is also made on the direct and indirect emissions. We notice a decreasing trend of CO_2e embedded in expenditures as income grows. One monetary unit spent by households belonging to the poorest cohort emits 0.44 kg of CO_2e, while one monetary unit spent by households belonging to the wealthiest cohort emits 0.29 kg of CO_2e. When considering the desegregated carbon footprint, we notice that households in D9 and D10 have a slightly greater ratio of kg of CO_2e per € spent than the others.

A third effect is related to the methodology used to compute the household's carbon footprints. The quality effect is responsible for significant bias in the carbon footprint estimation since no distinction is made between good-quality products with high prices and low-quality products with low prices. Indeed, the methodology implies that one monetary unit spent on mass-produced clothes has the same GHG content as luxury clothes. Needless to say, expenditures made by households belonging to D10 are not comparable to the ones made by households belonging to D1 in terms of quality[48]. We expect that the richest households spend more on certain items, not because of quantity but because of prices, regardless of GHG emissions generated during production. While it is commonly assumed that necessity goods are more energy intensive than luxury goods (Lenzen, 1998), which could explain the negative trend of emissions per monetary unit spent, it is not clear how the environmental impact behaves with the price of products overall.

Regardless of the household's standard of living, several aspects influence the carbon footprint. In Figure 17 on page 89, we provide some illustrative graphs about the socioeconomic and sociodemographics divergences in the carbon footprint, which also represent proxies for horizontal inequality. When looking at the number of children in the household, we notice that having one child impacts the carbon footprint by increasing food and transport emissions. However, the relationship tends to fade as the number of children in the household increases, reflecting a potential economy of scale. This is mainly due to decreasing emissions from transport and culture, compensating for increased food and energy emissions. As a result, the total carbon footprint of households with more than two children seems relatively lower than that of households with two children. When confronting the age

[48] From our data, the unique source of quality assessment concerns the type of vehicle owned by households. We notice that, on average, the richest households have four times more electric vehicles than the poorest households.

Figure 11: Aggregated ratio of CO_2e emissions per euro spent



Source: BDF 2017, Insee, ENTD 2019, SDES, author's own calculations.

of the head of the household with its carbon footprint, we notice that, on average, emissions tend to rise as they get older, but beyond 65 years old, emissions decrease. Transport is the major factor explaining the decrease of CO_2e emissions for older people. Due to mobility requirements, a household with a head between 50 and 65 emits, on average, 16% more than an elderly. Educational attainment of the head of the household is decisive in understanding the distribution of the carbon footprint. We notice that the education level orients emissions positively. Households with highly educated heads are expected to emit, on average, 26 t of CO_2e. Households with a level of education close to a bachelor's degree are significantly lower, while households' heads with or without the A-level emit, on average, 13 t of CO_2e. All else being equal, a higher level of education results in a greater level of emissions. There is no need to say that education attainment is a proxy of income level, justifying these results. When considering geographic location, we notice that rural households are, on average, emitting more than urbanites. The effect is largely explained by emissions coming from home energy and transport. On average, rural households emit around 11 t of CO_2e for both energy and mobility purposes, while households living in the Parisian agglomeration emit around 7 t of CO_2e. Similar to the number of children in the household, the household composition is relevant to explain the distribution of the carbon footprint. The carbon footprint substantially increases on every item, from a single person to a family. Finally, the type of tenure suggests that households living in detached houses emit more than households living in buildings. The energy and transport items largely explain the effect, but we also notice a slight effect of food. It also suggests that households living in large buildings tend to emit less than households living in small buildings, a mark of potential energy efficiency. All of these characteristics are more or less related. For instance, rural households are more likely to own a house than urban households; households with a head older than 40 are more likely to have kids than a household older than 65; a higher education level supports high income.

Meanwhile, they inform on the potential hidden vulnerability of some households regarding the distribution of the carbon tax.

Carbon footprint elasticity of income and expenditures As previously stated, volume and structure effects drive household consumption and, thus, carbon footprint. To disentangle the links between income/ expenditures and GHG emissions, we estimate the carbon footprint elasticity of income and expenditures. This figure translates how much the carbon footprint increases when the level of income/expenditures grows by 1%. When elasticity is below one, the carbon footprint grows less quickly than income or expenditures. We speak about inelastic relationships. When the elasticity equals one, the carbon footprint grows at the same pace as income or expenditures.

In Table 4, we report the elasticity of households' carbon footprint with respect to disposal income[49] and total expenditures by differentiating when they are computed at the mean and at the median distribution. We also dismember the carbon footprint between direct and indirect emissions. Our estimations are close to the ones obtained by Lenglart *et al.* (2010) and Malliet *et al.* (2020) for France, Lévay *et al.* (2021) for Belgium, Weber and Matthews (2008) for the USA, and Mach *et al.* (2018) for the Czech Republic.

Table 4: Carbon footprint elasticity estimations by income (v) and expenditures (m)

	Model	Direct (e^{dir})				Indirect (e^{ind})				Total (e)			
		Mean		Median		Mean		Median		Mean		Median	
		v	m	v	m	v	m	v	m	v	m	v	m
(1)	Quadratic	0.49	0.30	0.48	0.25	0.65	0.70	0.75	0.70	0.60	0.66	0.61	0.58
(2)	Cubic	0.52	0.45	0.53	0.40	0.66	0.93	0.76	0.96	0.60	0.78	0.61	0.72
(3)	Log-log	0.53	0.49	0.53	0.49	0.63	1.00	0.63	1.00	0.55	0.71	0.55	0.71

First of all, we notice that all estimates for total emissions range between zero and one, reflecting that households' carbon footprint and income or expenditures are positively related (i.e., emissions tend to grow as income or expenditures rise). In most cases, the relationship between emissions and either income or expenditures is inelastic (i.e., emissions grow less quickly than income or expenditures). We also observe that expenditure elasticity is generally greater than income elasticity, with a significant gap between the two estimates. This is a stylized fact of the elasticity of households' carbon footprint analysis (Lévay *et al.*, 2021, 2022; Pottier, 2022) strengthening the hypothesis of a progressive saving rate. Indeed, if the difference between the two estimates were zero, then the saving rate would be constant across the income distribution. Finally, we observe that the capacity of expenditures to explain the household carbon footprint is more remarkable than income. Indeed, when looking at the coefficient of determination $\mathfrak{R}^2$ in regression tables located in Appendix A.1 on page 83, we observe slightly higher figures, close to the results of Mach *et al.* (2018) and Lévay *et al.* (2021). It seems rational since carbon footprints have been computed on expenditures rather than income. In short, we remark on a causal link between the three variables: carbon footprint tends to grow at a slower pace than expenditures, while expenditures increase less rapidly than income.

We also notice, as previous studies did, that the elasticity of the carbon footprint regarding income or expenditures is substantially sensitive to the model used to approximate it (Weber and Matthews, 2008; Lévay *et al.*, 2022; Pottier, 2022). Considering total emissions solely, elasticities vary from 0.55 to 0.61 for income and from 0.58 to 0.78 for expenditures,

[49] We use disposal income since the carbon footprint of households is not equivalized.

depending on the model and at which point of the distribution we compute them. As shown in the table, we confirm higher estimates when we use the median distribution of income or expenditures to compute elasticity rather than the mean distribution. One reason for these gaps is the presence of significant heterogeneity between households or horizontal inequality. The choice of the methodology is thus very informative in the estimation of elasticities and, what is more, it's the use of expenditures versus income.

Beyond these stylized facts, what is true for total emissions can be nuanced when considering direct or indirect emissions. Firstly, when we consider direct carbon footprint emissions, we notice that the sensitivity is greater for income (between 0.48 and 0.53) than for expenditures (between 0.25 and 0.49). It suggests that when considering emissions coming from home energy and transport only, income can be a suitable indicator to approximate it[50]. Moreover, we remark a sharp distinction between direct and indirect estimates. Elasticities are noticeably more critical when considering indirect rather than direct emissions. The carbon footprint elasticity to expenditures for indirect emissions equals one when we use the log-log model. It suggests that when the expenditure level increases, the carbon footprint's indirect part tends to grow faster than the direct part. This result strengthens the idea that energy requirements are more rapidly saturated than other expenses. We understand why, as a household becomes more affluent, its carbon footprint tends to be predominantly driven by indirect emissions, reinforcing the important effect of the structure effect. Results also reveal that constrained consumption (including food and energy) represents around 70% of the carbon footprint for low-income households and approximately 60% for high-income households[51]. Conversely, unconstrained consumption (including market services, manufactured products, and culture and entertainment) represents roughly 8% of the total carbon footprint of low-income households while around 16% for high-income households on average. Again, this is largely explained by the prevalence of the structure effect, in that growing expenditures leave the door open to consume more sustainably (i.e., reducing preferences for carbon-intensive products). In contrast, preferences for essential goods and services such as energy requirement, transport mobility, and food (carbon-intensive products) are saturated. Therefore, a big spender has the choice not to be a big emitter.

3.3.2 Carbon tax and redistribution schemes

Households behavioral response to the carbon tax After estimating the parameters of the demand system, we compute the demand elasticities to testify to the model implications before introducing the carbon tax. In Table 5, we present the budget and price elasticity of demand computed at means. For each item, we provide the budget elasticity and both the uncompensated and compensated price elasticity with their standard errors. In diagonal, we have the own-price elasticities. Budget elasticity illustrates the percentage change in demand following a 1% increase in expenditures. Price elasticity depicts the shift in goods and services demanded following a 1% increase in the price. Uncompensated price elasticity refers to Marshalian demand functions, in which the nominal income of the consumer is held constant, suggesting that both substitution and income effect play a role in utility maximization. When price elasticity is compensated, the demand function is a Hicksian type, in which it is assumed that the consumer is compensated for the loss of income to keep the same utility level as before the price change. Thus, in the case of compensated price elasticity, the substitution effect is isolated.

[50] We also have differentiated the source of direct emissions between home energy and transport since our merging process could bias the results. Energy-induced GHG emissions also show larger income estimates than expenditures.

[51] It is hard to distinguish the constrained aspect of mobility expenses, but we suppose that it accounts for a large part of the carbon footprint.

Table 5: Budget elasticity, compensated and uncompensated cross-price elasticities of demand from the QAIDS model at means

	Food	Manufactured goods	Market services	Energy	Non-market services	Transport	Culture & entertainment
Uncompensated cross-price elasticities							
Food	**−0.515*****	−0.055***	0.145***	−0.077**	−0.022***	0.039	−0.329***
	(0.046)	(0.015)	(0.013)	(0.032)	(0.005)	(0.034)	(0.052)
Manufactured goods	−0.116*	**−0.784*****	−0.034*	−0.056	−0.069***	0.024	−0.033
	(0.063)	**(0.021)**	(0.019)	(0.044)	(0.007)	(0.048)	(0.071)
Market services	0.168***	−0.013	**−1.353*****	−0.002	0.037***	0.009	0.226***
	(0.055)	(0.018)	**(0.016)**	(0.038)	(0.006)	(0.042)	(0.062)
Energy	−0.264***	−0.122***	0.029	**−0.083***	−0.011	0.151***	−0.421***
	(0.072)	(0.023)	(0.021)	**(0.050)**	(0.008)	(0.054)	(0.081)
Non-market services	−0.136	−0.334***	0.177***	−0.025	**−0.594*****	0.102	−0.033
	(0.140)	(0.046)	(0.041)	(0.097)	**(0.016)**	(0.106)	(0.159)
Transport	0.075	0.096***	0.028	0.076	0.036***	**−1.456*****	0.304***
	(0.074)	(0.024)	(0.022)	(0.052)	(0.008)	**(0.057)**	(0.084)
Culture & entertainment	−0.591***	−0.130***	0.132***	−0.198***	−0.032***	0.128***	**−0.781*****
	(0.057)	(0.020)	(0.017)	(0.039)	(0.006)	(0.043)	**(0.064)**
Compensated cross-price elasticities							
	Food	Manufactured goods	Market services	Energy	Non-market services	Transport	Culture & entertainment
Food	**−0.329*****	0.122***	0.283***	−0.027	0.010**	0.130***	−0.190***
	(0.045)	(0.014)	(0.014)	(0.032)	(0.005)	(0.034)	(0.052)
Manufactured goods	0.128**	**−0.551*****	0.148***	0.010	−0.027***	0.143***	0.149**
	(0.063)	**(0.020)**	(0.019)	(0.044)	(0.007)	(0.048)	(0.071)
Market services	0.381***	0.189***	**−1.195*****	0.055	0.074***	0.112***	0.384***
	(0.055)	(0.017)	**(0.017)**	(0.038)	(0.006)	(0.042)	(0.062)
Energy	−0.099	0.035	0.152***	**−0.039**	0.017**	0.232***	−0.298***
	(0.071)	(0.022)	(0.021)	**(0.050)**	(0.008)	(0.054)	(0.081)
Non-market services	0.057	−0.150***	0.321***	0.027	**−0.561*****	0.196*	0.111
	(0.139)	(0.044)	(0.042)	(0.097)	**(0.016)**	(0.106)	(0.159)
Transport	0.267***	0.279***	0.172***	0.128**	0.069***	**−1.362*****	0.448***
	(0.074)	(0.023)	(0.022)	(0.051)	(0.008)	**(0.057)**	(0.084)
Culture & entertainment	−0.254***	0.190***	0.383***	−0.107***	0.025***	0.293***	**−0.530*****
	(0.056)	(0.019)	(0.017)	(0.039)	(0.006)	(0.043)	**(0.064)**
Budget elasticities							
Budget	0.814***	1.070***	0.928***	0.721***	0.844***	0.842***	1.471***
	(0.013)	(0.018)	(0.015)	(0.020)	(0.039)	(0.021)	(0.016)

Considering the budget, most elasticities are statistically significant at the 1% level. Items related to food, market services, energy, non-market services, and transport seem to be necessary goods, as their budget elasticity is positive and below one. Conversely, the budget elasticities for manufactured goods and culture & entertainment purchases are positive and superior to one, reflecting luxury goods. We notice that the item related to market services is close to elastic. Given our construction of items, those results are in line with expectations as, in most cases, a household needs food, energy, health (expenditures in non-market services), and transport to live decently while expenditures to manufactured foods, cultural products and in other extent, market services are not so important[52]. Moreover, we observe that energy demand is the least sensitive to income change, reflecting the prerequisite of energy in households' budgets. To further understand the budget elasticities, we provide the average budget elasticity by income decile for each item in Figure 20 on page 92. We observe different sensitivity of budget elasticities depending on income level. Only two items have a reversal effect on budget allocation: manufactured goods and market services. While demand for manufactured products is close to being inelastic for D1, it is elastic for all other income deciles. Conversely, for market services, the demand is inelastic for all income deciles except for the highest income decile. We notice that for energy, the elasticity tends to rise as income

[52] Although less specific, our results are close to the one obtained by Nadaud (2020) and Ravigné and Nadaud (2021) except for transport for which they found a budget elasticity greater than one, as found by Ruiz and Trannoy (2008).

grows, contrariwise, for transport, the elasticity tends to decrease as income grows.

Considering price elasticities, we notice close results between compensated and uncompensated price elasticities despite lower values for compensated ones, as they only integrate the substitution effect. As expected, the own-price elasticities are negative for all items. Results advocate very low own-elasticity of demand for energy, food, and non-market services. These items gather expenditures that cannot be reduced quickly, regardless of their respective share in the budget, as suggested by compensated and uncompensated price elasticities. Unlike food, energy, and non-market services, the demand for transport and market services is very elastic[53]. On average, an increase in the price of these items leads to a sharp decrease in their respective consumption. Overall, cross-elasticities are lower than own-price elasticities, reflecting the low substitutability between items. This is directly linked to the low comparability of aggregated items. However, this result does not hold for energy demand. Since the price elasticity of demand regarding energy is close to zero, when households are compensated after prices increase, they keep their level of expenditure for energy consumption but reduce mainly their consumption of culture & entertainment goods and services while increasing their demand for mobility. Furthermore, the result computed at mean should be taken cautiously as behavior also depends on the income group and socioeconomic drivers. In Figure 21 on page 93, we illustrate the trends in compensated elasticities given income decile for each item. Low-income households respond more intensively to price changes for energy, food, and non-market services than high-income households. The demand of low-income households for these products is more elastic than the demand of high-income households. Conversely, high-income households respond more intensively to price changes in manufactured goods and market services. The price elasticity seems to be slightly decreasing across the income decile for transport and culture & entertainment items as found in Nadaud (2020) and Ravigné and Nadaud (2021).

From the estimated parameters and their elasticities, the model is used to predict budget allocation after prices increase. The demand system has been directly estimated for items rather than goods and services. Thus, we assume constant consumption patterns, meaning that only the budget share allocated to items can vary, but the basket of goods and services within items cannot change. The carbon tax mainly affects transport, food products, and energy prices. According to behavioral responses, the shares allocated to non-market services and culture and entertainment must decrease to offset the energy price surge to keep roughly the same budget allocation. In a very short-term context, households move away from non-necessary carbon-intensive consumption toward either carbon-intensive but necessary products or low carbon-intensive but non-necessary products.

3.3.3 The social implications of the domestic carbon tax

First, we analyze the social impacts after implementing a €100 per CO_2e tax without compensation. In doing so, we can estimate the effect of the tax, assuming that households reallocate their budget efficiently between items. In Table 6, we illustrate the aggregated impact of the tax by measuring the effort rate[54]. We also describe the distribution of the disposal income and the tax payment across income deciles to emphasize the tax burden. Regardless of the carbon price, we found similar results as in Berry (2019).

When looking at cumulative aggregates, we observe that the tax implies that the 40% poorest households contribute to 32.30% of the carbon tax while perceiving only 24.55% of the total national revenue. The average effort rate, concerning disposal income, is around

[53] While Berry (2019) and Douenne (2020) found that transport is inelastic, Malliet *et al.* (2020), Nadaud (2020) and Ravigné and Nadaud (2021) found elastic values.

[54] The methodology used to compute the metric is presented on page 49.

Table 6: Aggregated income and tax burden by income decile

Income decile	Disposal income Amount	Disposal income Share of total (%)	Disposal income Cumulative share (%)	Carbon tax Amount	Carbon tax Share of total (%)	Carbon tax Cumulative share (%)	Effort rate (in %)
1	15,613,388	4.07	4.07	1,124,260	7.14	7.14	7.20
2	22,295,117	5.82	9.90	1,233,600	7.83	14.98	5.53
3	26,569,294	6.94	16.84	1,335,838	8.48	23.46	5.02
4	29,526,843	7.71	24.55	1,390,016	8.83	32.30	4.70
5	32,627,071	8.52	33.07	1,463,314	9.29	41.59	4.48
6	36,191,687	9.45	42.53	1,542,306	9.79	51.39	4.26
7	40,847,346	10.67	53.20	1,710,056	10.86	62.26	4.18
8	45,968,423	12.00	65.21	1,781,248	11.31	73.58	3.87
9	52,889,379	13.81	79.02	1,882,465	11.96	85.54	3.55
10	80,277,995	20.97	100.00	2,275,211	14.46	100.00	2.83
Total	382,806,548			15,738,318			4.11

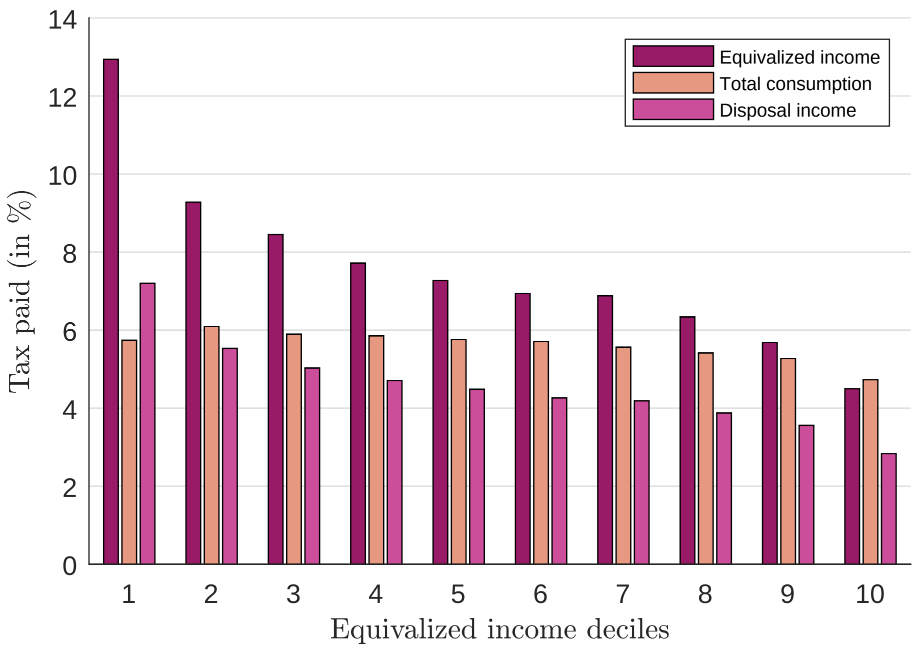
4.5%, suggesting that the most affected by the tax are located in the bottom 40%. Interestingly, we observe that until the 7^{th} income decile, households are, on average, net contributors to the carbon tax, with a contribution of the tax payment superior to their respective share of total income. Beyond this threshold, households perceive, on average, a higher share of the total income than they contribute to the carbon tax payment. Thus, the 30% richest households are net beneficiaries of the tax implementation since their aggregated income is strictly superior to their tax duty. In the short term, household carbon tax costs are carelessly unbalanced. When considering the two extremes of the distribution, we notice that the tax burden is 2.5 times higher for households in the first decile than households in the tenth decile when looking at aggregated disposal income.

In Figure 12, we illustrate the aggregated effort rate distribution as a percentage of equivalized income, total consumption, and disposal income. From this graph, we assert undoubtedly the regressive nature of the tax. The intensity of the carbon tax on the budget decreases with the level of income. The effect on D1 is particularly strong since, on average, those households devote more than 12% of their equivalized income to the tax payment, whereas on average, households spend 8%. Although slightly regressive, the trend of the effort rate considering consumption is flatter, which nuanced the previous results. Regardless of their living standard, households contribute the same proportion to the carbon tax. However, as found before, the richest 10% have carbon intensity of expenditure lower than the poorest 10%, reflecting a lower tax payment per unit consumed. The two groups have a €1 gap in tax payment per €100 consumed. Again, we acknowledge the positive relationship between saving rate and income since, for all income groups except D1, the effort rate on consumption is greater than the effort rate on income. For now, results suggest that, despite emitting 2.6 times more than the 10% poorest households, the 10% richest households experience almost three times less of the tax burden.

3.3.4 Compensation and the backfire effect

Revenue recycling of the domestic carbon tax We propose three schemes to compensate households for the regressive effect of the carbon tax. The flat-recycling scheme is the benchmark scheme in which every household receives an equal share of the carbon tax revenue. Each household (9,637 households) collects 1,306 euros. The two other schemes are more specific. The carbon tax revenue is assigned to households given their characteristics or disposal income to target the reduction of horizontal or vertical inequality reduction, respectively. When we focus on the reduction of horizontal aspects, 3,148 households meet the required characteristics. Each of them collects 4,000 euros. When we only consider

Figure 12: Aggregated effort rate distribution on equivalized income, total consumption and disposal income by income decile



income, 1, 776 households are collecting 7, 089 euros.

In Table 7, we summarize the winners[55] of each redistribution design. In the flat-recycling scheme, each household receives a cash transfer, but only a few are net beneficiaries. The redistribution process seems progressive: the number of winners tends to rise as income decreases. Overall, this scheme is suitable for acceptability, around 40% of households in the sample collect a greater amount of money than they paid. On average, winners gain 9% of their disposal income. However, the flat-recycling scheme is not optimal from a social perspective. Indeed, households from D7 to D10 are expected to be compensated for the carbon tax payment, likely increasing inequality. However, the cash transfer benefits more low-income groups than any other income group. In the tailored scheme, households in the 50% poorest are the main beneficiaries of the revenue recycling.

In Table 16 on page 86, we present the number of households compensated in the tailored scheme by differentiating the sources of dependency and vulnerability. We also provide the tax burden regarding energy and transport separately[56]. We notice that the transport aspect is the main determinant of the scheme, with more than 2, 404 households vulnerable to high gasoline prices. As expected, the tailored scheme mainly supports low-income households, notably unemployed and young. In the social cushioning scheme, households at the bottom of the income distribution are highly compensated. More than 70% households located in the D1 are benefiting from the social transfer, with additional cash at their disposal accounting for around 35% of their total expenditure on average.

On the one hand, there is little overlap between households targeted by the tailored scheme and the social cushioning. Less than 10% of the sample are considered as winner in both processes, mainly located in the first decile (35%). In a sense, socioeconomic drivers

[55] To be considered a winner of the process, the household must receive a greater cash transfer than the amount it pays for the tax.

[56] It corresponds to the share of tax paid for energy and transport as a percentage of total tax paid.

Table 7: Winners of the revenue recycling by income decile

		In absolute			In percentage		
Income decile	Number of households	Flat-recycling	Tailored scheme	Social cushioning	Flat-recycling	Tailored scheme	Social cushioning
1	964	635	474	697	65.87	49.17	72.30
2	964	579	521	440	60.06	54.04	45.64
3	964	492	553	243	51.03	57.36	25.20
4	964	473	567	248	49.06	58.81	25.72
5	964	422	518	148	43.77	53.73	15.35
6	964	332	255	0	34.43	26.45	0.00
7	964	286	73	0	29.66	7.57	0.00
8	963	247	64	0	25.64	6.64	0.00
9	963	215	62	0	22.32	6.43	0.00
10	963	109	51	0	11.31	5.29	0.00
Total	9,637	3,790	3,138	1,776	39.32	32.56	18.42

of the carbon tax's vulnerability are irrespective of purely income consideration (Charlier *et al.*, 2015) and make the horizontal and vertical targets fundamentally different. Given our assumption on energy and transport dependency and vulnerability, the redistribution scheme is substantially different compared to social cushioning. On the other hand, households are much more compensated in low-income groups for any scheme. For instance, on average, the transfer for the winners of the tailored scheme in D4 and D5 represents around 12% of their disposal income, while this figure amounts to 25% for households located in D1. Undoubtedly, the potential backfire effect will strongly depend on this income effect.

Social implications of tax recycling From a social point of view, recycling the carbon tax's revenue should bear our expectations, reducing the tax burden of households most affected by the tax. As previously unveiled, most winners are expected to be in low-income groups. However, we are interested in how social transfers are made between households to conclude on the overall positive effect of tax recycling. For that purpose, we perform an analysis of variance (ANOVA). In Table 8, we present the results of the one-way ANOVA as well as the Gini and the Suits index for each scenario. It permits the comparison of the means of different samples according to groups. The Gini index computed for the reduced sample is close to the one estimated by the Insee (0.289) in 2017, while the Suits index for the carbon tax case is also close to the one estimated by Sterner (2012) and Berry (2019). In the column source, we differentiate between the source of variance, either between or within groups. The test statistics show that the means of the different samples are different.

We observe that in comparison to the situation without redistribution, redistribution significantly alleviates the inequality in the distribution of the tax burden between groups, which is also reflected by the Gini coefficient and the Suits index. On this scope, without any doubt, the best redistribution scheme is attributed to the social cushioning scheme in which the sum of squares is reduced by more than 55% compared to the initial situation. However, in this configuration, the variance within groups tends to surge by 8%, notably due to households not benefiting from the redistribution in low-income groups, increasing inequality in the distribution of the tax burden as testified by the Suits index. The best tool to cut horizontal inequality and, thus, reduce the variation in the tax burden within groups is the tailored scheme. This scheme performs better than flat-recycling since it permits to reduce variance between groups by 42%, against 25% for the flat-recycling, and within groups by 5.4% rather than 5.3%. According to the Gini index, the two schemes are close, although the tailored scheme targets more within-group inequality. Overall, each process

Table 8: Gini index, Suits index and one-way ANOVA analysis on households effort rate with respect to equivalized income

Scenario	Gini index	Suits index	one-way ANOVA Source	Sum of squares	Degrees of freedom	Mean square	F-stat	p-value
Carbon tax	0.301	−0.15	Between	1.38	9	0.153	198.24	0.00***
			Within	7.11	9177	0.001		
			Total	8.50	9186			
Flat-recycling	0.296	0.05	Between	1.03	9	0.115	157.34	0.00***
			Within	6.73	9178	0.001		
			Total	7.77	9187			
Tailored scheme	0.289	0.03	Between	0.80	9	0.089	121.61	0.00***
			Within	6.72	9177	0.001		
			Total	7.53	9186			
Social cushioning	0.271	−0.05	Between	0.62	9	0.069	81.88	0.00***
			Within	7.74	9178	0.001		
			Total	8.36	9187			

is suitable to reduce the initial tax burden. Nevertheless, as suggested by the total source, the tailored scheme appears to be the most convenient process since it makes the lowest trade-off between and within groups difference.

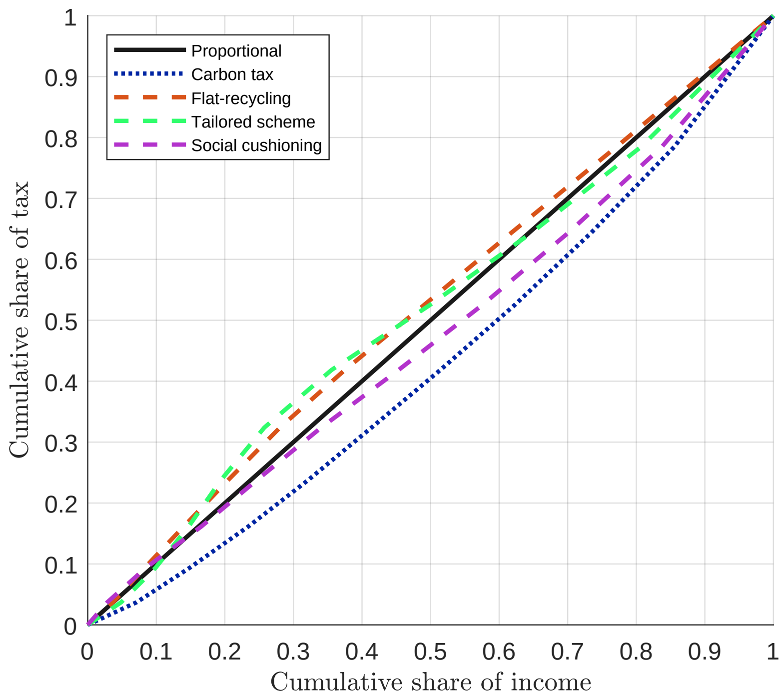
As illustrated in Figure 13, the effectiveness of each redistribution scheme depends on the social target: reducing vertical inequality, horizontal inequality, or both. In this figure, we provide an illustrative representation of the concentration curves of the tax burden. On the x-axis, we retrieve the cumulative share of income, and on the y-axis, the cumulative share of the tax paid. Note that, conversely to the Gini index, the concentration curve can be up to the 45-degree line (proportional), reflecting a progressive carbon tax.

First, we see the apparent effect of the carbon tax as previously found. What is interesting is the shape of the concentration curves for the different redistribution schemes. The flat-recycling scheme appears to be the best tool to turn the regressive nature of the carbon tax into progressivity. In the tailored scheme, the concentration curve oscillates around the proportional line, reflecting a decoupling of regressivity between low-income and middle-income households and middle-income and high-income households. As expected, the tailored scheme benefits primarily low- and middle-income households. Finally, a critical remark of this graph is the weakness of the social cushioning scheme to reverse the regressive nature of the tax. Even if we observe a progressive pattern for the lowest income group, the overall shape of the concentration curve is still regressive. The regressivity of the carbon tax is still accountable for favoring social policy. Overall, results suggest that redistribution makes the carbon tax closer to proportionality than progressivity.

Environmental implications of tax recycling As previously unveiled, tax revenue distribution is an effective tool to correct the regressive effect of a domestic carbon tax. In the case of lump-sum transfers, the allocation of "*green cheques*" can support carbon-intensive consumption, backfiring emissions which would reduce the initial aim of the carbon tax. In our case, coupled with cash transfers, the initial benefits of taxing emissions can be reduced following a surge in consumption induced by an income effect. In other words, we are looking at the short-term reactivity of households when they are financially compensated for their emissions[57].

[57] Notice that the following results might be completely different if tax revenue would have been used to finance energy efficiency or to force green cheque to be spent only on low emitting products, but in this case,

Figure 13: Concentration curves of the tax burden

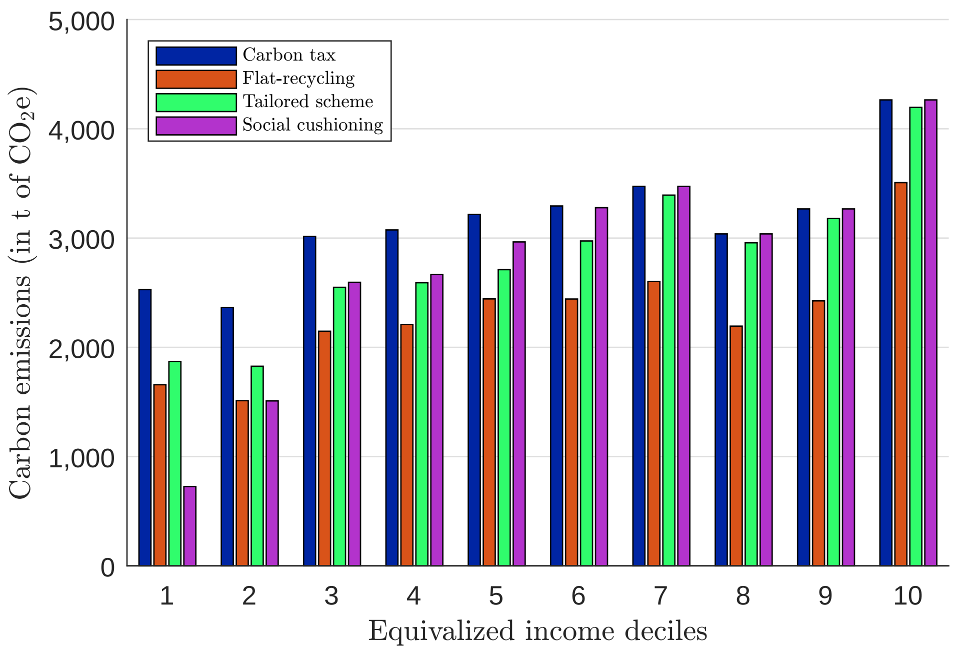


In Figure 14, we illustrate the environmental implications of introducing the carbon tax and revenue recycling. We compare the aggregated sum of carbon emitted (in tons of CO_2e) with respect to the initial situation with no tax. Notice that equivalized income deciles are assumed to remain the same as before, suggesting that social transfers are not taken into consideration to form post-tax income groups. Overall, we recognize the carbon tax's critical role in reducing households' GHG emissions. Around $31,500$ tones of CO_2e are avoided following the tax implementation, which represents a substantial reduction of 20% in total emissions. To put those results in perspective, it took seven years (from 2008 to 2016) to decrease total French emissions by approximately 16%. Even if the reduction is not perfectly related to income, the major shift in absolute emissions is reasonably attributed to the highest income decile since they pay the most considerable amount of carbon tax. Nevertheless, the emission variation is greater for the lowest income decile with a reduction of around 21%. The short-term benefits of the carbon tax implementation are genuinely effective but costly for low-income households. When considering redistribution schemes, we notice a sharp decrease in the absolute level of carbon saved even if the situation is still better than without any tax as more than 17% of total emissions is still abated. In all cases, $20,000$ to $30,000$, tones of CO_2e are saved compared to the no-tax situation.

Concerning the implementation of the tax, the flat-recycling scheme increases by 840 additional tones of CO_2e each of the decile emissions on average. Notice that the gap is higher for low-income households since the cash transfer is generally greater than the tax payment for these households (i.e., the number of winners is superior). The bottom 20% increase their emissions by 10% on average. The homogeneous redistribution leads to an increase in emissions of 6.51% concerning the situation with the tax. In the tailored scheme,

the issue of social acceptability might arise again.

Figure 14: Aggregated carbon saved with respect to no-tax situation by income decile

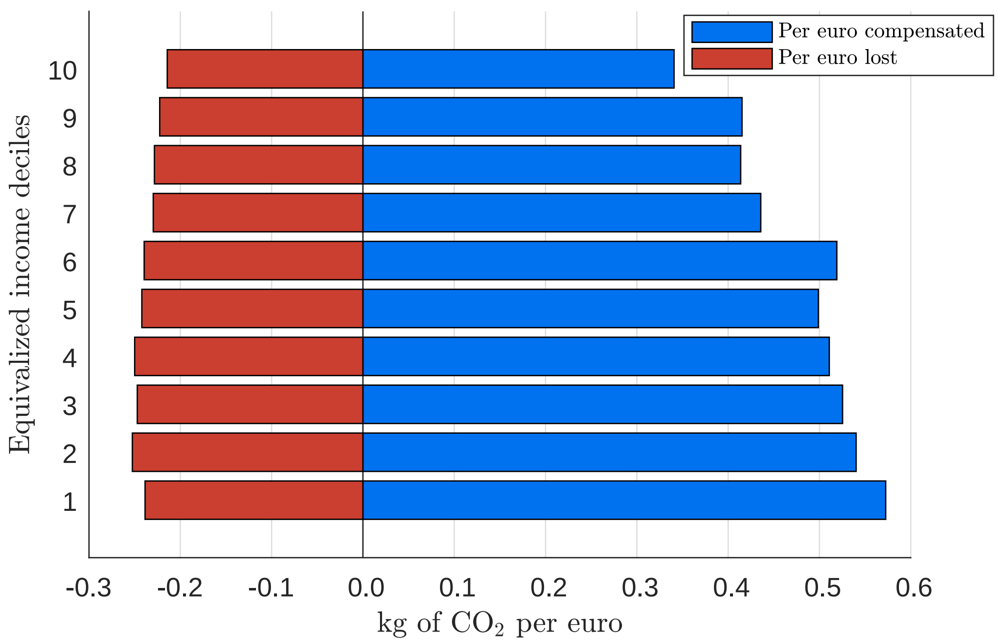


the carbon saved is the greatest among all schemes. Following this scheme, the increase in emissions amounts to 2.55% for the tax situation. On average, 320 additional tones of CO_2e are emitted per income group. This is notably due to a sharp reduction of emissions from the top of the distribution. Indeed, the 40% richest households increase their emissions by less than 1% on average. Meanwhile, households in the D3-D6 are responsible for 55% of the increase in carbon emissions. Finally, in the social cushioning scheme, the two first deciles of income are responsible for 70% of the increase in emissions. Emissions increase by 3%, mainly due to the surge in consumption of low-income households benefiting large compensations. While emissions from households located in D1 are increasing by 20%, less than $1,000$ tons of CO_2e can be saved within this decile.

From an environmental impact perspective, we notice that the flat-recycling scheme is the worst policy to preserve the carbon tax benefits. We notice a positive but slight surge in emissions for the two other schemes overall. This is attributable to the partial offset of uncompensated households constrained to reduce their carbon footprint. On the one hand, this should impose that high-income households are inclined to make consumption sobriety more than any other income groups. On the other hand, this could be the fact that compensated households are emitting less when they receive a green cheque. Several effects might help to understand this trend. First of all, let's consider how households behave when prices are affected by the carbon tax. In the carbon tax situation, households are not compensated, they make optimal choices to substitute consumption between items to face the price surge. Overall, households increase their food and manufactured goods consumption while keeping a stable share of their budget for energy, non-market services, and transport. Due to the domestic carbon tax and the almost impractical substitution between items, emissions decrease. In the case of redistribution, the loss of consumption induced by the implementation of the tax is partially compensated by cash transfers. The first driver of emissions is the net benefit of the social transfer, either positive (i.e., the social transfer is greater than the tax payment) or negative (i.e., the social transfer is lower than the tax payment), making the household a winner or a loser, respectively. The second driver is the specific behavior of households in response to budget increases, which corresponds to the marginal propensity to consume. It is established that the marginal propensity to consume tends to decrease as income rises. Therefore, the increase in emissions following revenue recycling is likely to depend on the absolute amount of cash transfer but also on the behavioral response of households' consumption.

In order to understand what is behind the uptick of emissions, we compute the kg of CO_2e emitted and saved per euro compensated and lost, respectively. We illustrate the trends by income decile in Figure 15. Those figures are the weighted average ratio between the excess emissions and the excess consumption for each scheme. If the social transfer is positive, we look at the carbon-induced emissions coming from this transfer. We do the same for the isolated loss of consumption and emissions following the tax implementation. Results and methodology are closely related to the carbon emission per euro spent.

Figure 15: Average kg of CO_2e emitted or saved per € compensated or lost



First, we observe a regressive trend between the kg of CO_2e per euro compensated. The general shape of emissions saved per euro lost is flatter but tends to decrease as income rises. Secondly, the graph reflects the critical relationship between compensation and emissions rather than deprivation and sobriety. Emissions induced by the euro compensated range between 0.57 and 0.34, while emissions reduction by euro lost is between 0.25 and 0.21 in absolute. Per euro lost, high-income households are less reducing CO_2e than low-income households. In terms of emissions, it suggests that high-income households are less sensitive to price signals than low-income households. In line with their propensity to consume, consumption loss is not necessarily associated with emissions reduction. Therefore, overtaxing the richest households seems to make a slight difference in carbon emissions. Even though it is usually assumed that rich households could potentially back carbon sobriety, the results do not suggest this. In the same way, the euro compensated seems to be more carbon intensive as income decreases. As low-income households are likelier to be compensated for the regressive nature of the tax than high-income households, the backfire effect is limited to low-income households. Unsurprisingly, this instrument gives access to purchasing power, likely to produce a potential backfire effect. Compensating the loss of purchasing power by consumption leads to a vicious circle.

4 Conclusion

Reducing social inequality and protecting the environment are two distinct objectives that can both complement and contradict each other. Throughout the first part of this study, we review some key literature on incorporating social inequality into climate economic modeling. Even though the debate over the discount rate has received much attention from economists, the value of this parameter is still a pivotal factor for including social considerations in the macroeconomics of climate change. This "*welfare cursor*" orients the social cost of carbon when the objective depends on one of the three dimensions of the social risks inherent in climate change, namely interregional, intraregional, and intergenerational inequality. As a result, a more or less aggressive policy to tackle climate change can be derived. The NICE model of Dennig *et al.* (2015) is particularly useful for understanding the interactions between the physical risks, the transition risks, the liability risks, and social inequality. By extending the RICE model of William Nordhaus with heterogeneous agents when estimating the optimal carbon tax, the NICE model enables us to make different assumptions about the distributional effects of climate change damages and mitigation costs.

Assuming that low-income groups will be more affected by climate change damage, the current social cost of carbon should be very high to limit GHG emissions and prevent future temperatures from rising above alarming levels. The subsequent carbon pathway diverts drastically from early estimates that do not consider current regional inequalities. The support for an inclusive pathway depends heavily on the assumptions made on inequality and how damages and costs will be distributed. In attempting to outline optimal social transfers between or within regions to alleviate the burden of inequality, the results suggest that such policies alone may have limited effect. Although intraregional redistribution can significantly reduce the vulnerability of low-income groups, interregional transfers are insufficient to disrupt the unbalanced distribution of the burdens of climate change.

Related to these results, we understand that the nexus between social inequality and climate risks will depend on how our society evolves. As narrated by the SSPs, different development pathways are critical when assessing the future drivers of emissions and the capacity to adapt to or mitigate them. To complete this review, we focus on prominent findings in the modeling of income distribution projections in line with SSP narratives. A future with a growing or steady level of inequality within or between regions will put the environmental transition out of reach because the public will not accept this policy. Conversely, if income convergence between countries is an option, the challenge of tackling climate change would be less insurmountable.

In the second part of the paper, we leave global macroeconomics to empirically study social inequality in the context of the transition risk in France. After disentangling the carbon footprint of French households using a domestic input-output framework and the household budget survey, we seek to understand the social and environmental impacts of introducing an *ad valorem* carbon tax on every product available in the economy.

We found a clear positive relationship between the absolute amount of CO_2e emitted by households and their standard of living. On average, households in the highest income decile emit 2.6 times more than those in the lowest income decile. Although emissions rise with income, growth in the carbon footprint trends is lower than income since expenditures tend to smooth as income grows. Indeed, when we compute the aggregate amount of CO_2e emitted per euro spent, we found a gap of 0.15 kg of CO_2e per euro spent between high- and low-income households. The volume effect (i.e., the greater the expenditures, the greater the emissions) tends to be softened by the structure effect (i.e., consumption patterns differ according to income groups). We estimate the carbon footprint elasticity of expenditures and income to understand their link to GHG emissions better. Three models have been estimated using direct, indirect, and total emissions to capture the whole picture of this metric. When considering total emissions, results suggest that elasticities vary from 0.55 to 0.61 for income and from 0.58 to 0.78 for expenditures. In short, there is a causal link between these three variables: the carbon footprint tends to grow less rapidly than expenditures, while expenditures increase less quickly than income. Although inelastic, results also suggest that elasticities are more sensitive to indirect than direct emissions. One potential explanation could be that carbon-intensive energy, mobility, and food consumption are more rapidly saturated as income grows. Therefore, a big spender has the choice not to be a big emitter.

After analyzing the carbon footprint distribution given socioeconomic characteristics, we implement a €100 per ton of CO_2e emitted carbon tax. We model households' behavioral response by constructing Engel curves with the QAIDS model of Banks *et al.* (1997). Unsurprisingly, without any compensation scheme, the carbon tax is regressive. On average, households included in the lowest income decile devote 12% of their equivalized income to the tax payment compared to barely 4% for high-income households. In order to compensate some households for the regressive nature of the carbon tax, we use a microsimulation model to test the efficiency of three redistribution schemes. The tax revenue is assigned to households either homogeneously (flat-recycling), based on socioeconomic factors of energy and transport vulnerability (tailored scheme), or poverty (social cushioning). We found that redistribution schemes make the carbon tax more proportional but not totally progressive. While each process helps reduce the initial tax burden, the social cushioning drastically reduces inequality between income groups, while the tailored scheme is better for reducing inequality within income groups.

In contrast with previous studies on the social impact of implementing a carbon tax, we also detail the environmental effects of such a policy, notably the potential backfire effect of emissions following lump-sum transfers. Although above zero, we found slight aggregated effects (between a 2.55% and 6.51% uptick in emissions with respect to the situation with the carbon tax). However, we observe that low-income households, likely to be compensated, are expected to increase their emissions substantially (0.57 kg of CO_2e per euro compensated). Meanwhile, the highest emitting households are less sensitive to price signals regarding emissions (-0.21 kg of CO_2e per euro lost). Nevertheless, we should acknowledge the efficiency of the tailored scheme to limit the backfire effect and to reduce social inequality across households. This result stresses the rationale to consider horizontal inequality in elaborating an environmental policy.

Overall, we acknowledge that considering social aspects in climate economic modeling is of paramount importance. The different results reviewed in this paper show how environmental optimality can be reversed when social inequality is adequately considered. The difficulty of the climate challenge will depend on the pathway the world is following. For now, the climate urgency is forcing practitioners to prioritize the environmental benefits of the transition while underestimating the induced social costs. Environmental policies that emerge in the coming years to combat climate change run the risk of not being accepted if the trade-off between social and environmental progress remains topical. An additional difficulty could arise from the potential backfire effect of reducing income inequality. Without the supply of green alternatives, any effort to reduce the vulnerability of the most affected by the transition could be wasted. The trade-off between social and environmental aspects is critical to the transition risk if net zero targets substantially reduce emissions.

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A Additional results

A.1 Tables

Table 9: Descriptive statistics of households by income decile

Income decile	Number of households	Disposal income	Expenditures	EIR‡	Number of person	Number of child	Number of worker	Consumption unit
1	1,218	12,638	17,669	1.40	2.49	1.14	0.84	1.62
2	1,266	19,909	19,955	1.00	2.53	1.11	0.84	1.63
3	1,258	23,288	22,454	0.96	2.36	0.90	0.90	1.57
4	1,220	26,660	24,292	0.91	2.33	0.80	0.95	1.57
5	1,216	30,285	25,985	0.86	2.35	0.77	1.02	1.58
6	1,181	33,515	29,575	0.88	2.30	0.68	1.07	1.56
7	1,162	38,282	31,942	0.83	2.37	0.69	1.16	1.60
8	1,169	43,553	35,631	0.82	2.35	0.62	1.19	1.60
9	1,192	51,075	39,658	0.78	2.30	0.56	1.23	1.59
10	1,199	77,974	53,442	0.69	2.28	0.52	1.26	1.58
Total	12,081	35,477	29,908	0.84	2.37	0.78	1.04	1.59

Source: BDF (2017), Insee, ENTD (2019), SDES.

‡ Expenditures to income ratio.

Table 10: Number of households without consumption by item and income decile

Income decile	1	2	3	4	5	6	7	8	9	10	Total
Food	93	55	48	31	29	28	27	19	14	10	354
Manufactured products	34	26	25	19	18	18	8	11	2	2	163
Market services	1	0	0	0	0	0	0	0	0	0	1
Energy	52	14	15	17	8	10	7	8	9	10	150
Non-market services	337	156	64	42	18	17	16	13	12	18	693
Transport	254	260	240	201	165	137	106	90	66	44	1563
Culture	26	23	8	3	2	2	0	3	0	0	67
Construction	1051	1056	987	931	896	792	745	697	689	646	8490
Rents	568	547	639	688	739	798	836	888	962	985	7650
Total	1189	1227	1205	1176	1166	1131	1117	1127	1159	1151	11648

Source: BDF (2017), Insee.

Table 11: Descriptive statistics of households by income decile (reduced sample)

Income decile	Number of households	Disposal income	Expenditures	EIR‡	Number of person	Number of child	Number of worker	Consumption unit
1	964	16,196	21,623	1.33	2.78	1.33	0.99	1.75
2	964	23,127	22,317	0.96	2.62	1.11	0.99	1.68
3	964	27,561	24,808	0.90	2.61	1.04	1.06	1.68
4	964	30,629	25,950	0.84	2.48	0.88	1.10	1.64
5	964	33,845	27,658	0.81	2.44	0.81	1.13	1.62
6	964	37,543	29,344	0.78	2.43	0.75	1.19	1.63
7	964	42,372	33,192	0.78	2.45	0.74	1.25	1.64
8	963	47,734	35,474	0.74	2.42	0.63	1.27	1.64
9	963	54,921	38,380	0.69	2.33	0.59	1.24	1.60
10	963	83,362	51,280	0.61	2.30	0.52	1.27	1.58
Total	9637	39,722	30,999	0.84	2.49	0.84	1.15	1.65

Source: BDF (2017), Insee.

‡ Expenditures to income ratio.

Table 12: Emissions converter of main energetic products in 2017

		Consumption price structure				Emission structure			
Item	Type	Unit	HTT	HTVA	TTC	Unit	Combustion	Upstream	Total
Transport	Gazole	€/ℓ	0.48	1.03	1.23	$kgCO_2e/\ell$	2.51	0.655	3.165
	SP98	€/ℓ	0.54	1.20	1.44	$kgCO_2e/\ell$	2.43	0.409	2.839
	SP95-E10	€/ℓ	0.49	1.13	1.35	$kgCO_2e/\ell$	2.43	0.409	2.839
	SP95	€/ℓ	0.49	1.15	1.38	$kgCO_2e/\ell$	2.43	0.409	2.839
	GPL	€/ℓ	0.53	0.62	0.74	$kgCO_2e/\ell$	1.60	0.262	1.862
House	Electricity	€/kWh	0.11	0.14	0.16	$kgCO_2e$/kWh	0.35	0.084	0.434
	Natural gas†	€/kWh	0.05	0.06	0.07	$kgCO_2e$/kWh	0.20	0.039	0.239
	Domestic fuel oil	€/ℓ	0.50	0.62	0.74	$kgCO_2e/\ell$	2.68	0.571	3.251
	Propane†	€/kWh	0.11	0.11	0.13	$kgCO_2e$/kWh	0.23	0.027	0.257
	Butane	€/kg	2.03	2.03	2.44	$kgCO_2e$/kg	2.95	0.487	3.437
	Coal	€/kg	-	0.15	-	$kgCO_2e$/kg	2.49	0.230	2.720
	Wood	€/kg	-	-	6.53	$kgCO_2e$/kg	0.01	0.016	0.030

Source: SDES and ADEME

† Expressed in kWh LCV (lower calorific value).

Note: The HTT price ("*hors toutes taxes*") excludes any taxes but integrates the cost of the commodity, the cost of refining, the cost of storage, and the cost of distribution. The HTVA price ("*hors taxe sur la valeur ajoutée*") is obtained by adding the national tax on energetic product consumption (TICPE). The TTC price ("*toutes taxes comprises*") encompasses the French value-added tax 20%.

Table 13: Carbon dependency and vulnerability factors

Dependency		Vulnerability	
Factor	Motive	Factor	Motive
Dwelling size	Large dwelling or houses	Tenure	Tenant households
Transport	The household requires the use of fossil fuel vehicle to work	Composition	Small households (CU <3) or large households (CU >3)
Energy system	Heating system using fossil fuel	Age	Either young (<35 years old) or old (>60 years old) households
Geographic location	Rural households and households living in the outskirts of big cities	Professional status	Either working or unemployed
		Precariousness	Households benefiting from state's aids

Source: Amundi Institute.

Table 14: Nomenclature table with some examples of consumption categories

Item	Theme	Product
Food	Food	Rice Beef Porc Fish
	Beverages and tobacco	Tea Water Wine Tobacco
Manu-factured products	Clothing	Shoes and other footwear Garments
	Furnishings, household equipment	Garden and camping furniture Lighting equipment Major kitchen appliances Kitchen utensils and articles Household cleaning and maintenance products
	Purchase of vehicles	New motor cars Second-hand motor cars Motorcycles
	Information and communication equipment	Fixed telephone equipment Mobile telephone equipment Computers, laptops, and tablets Software
	Recreation durables and personal care	Photographic and cinematographic equipment and optical instruments Boats, yachts, outboard motors, and other water sports equipment Equipment for sport Garden products Electric appliances for personal care
Market services	Insurance and financial services	Insurance connected with health Personal transport insurance Remittances fees
	Housing	Imputed rentals for housing Subscription to cable TV, satellite TV, IPTV, and Pay-TV Domestic services and household services
Energy	Water supply and miscellaneous services relating to the dwelling	Water supply Refuse collection Sewage collection
	Electricity, gas and other fuels	Electricity Natural gas through networks Liquefied hydrocarbons Liquid fuels Solid fuels

Table 15: Consumption items classification (continued)

Item	Theme	Product
Non-market services	Health	Medicines Treatment devices for personal use Pharmaceutical products Preventive care services Dental preventive services Inpatient long-term care services
	Transport services of goods	Postal and courier services
	Education services	Primary education Secondary education Tertiary education Tutoring
Transport	Operation of personal transport equipment	Fuels and lubricants for personal transport equipment Maintenance and repair of personal transport equipment Services for parking
	Passenger transport services	Passenger transport by railway Passenger transport by road Passenger transport by air Passenger transport by sea and inland waterway
Culture	Recreational services	Rental of game software and subscription to online games Recreational and sporting services Services provided by cinemas, theatres and concert venues Newspapers, books and stationery Package holidays
	Restaurants and accommodation services	Food and beverage serving services Accommodation services
Building	Construction	Renovation and construction for residence
Rent	Rent	Actual rentals for housing

Source: Amundi Institute.

Table 16: Compensated households and energy/transport tax burden in the tailored scheme

		Energy			Transport		Tax burden (in % of total)	
Income decile	N	Unemployed	Young	Retired	Mobility	Tailored scheme	Energy burden	Transport burden
1	964	91	63	10	342	475	40.05	30.03
2	964	59	71	16	404	521	40.68	29.11
3	964	19	60	20	494	555	36.57	30.24
4	963	4	66	30	500	568	34.19	30.49
5	963	4	64	22	453	520	35.25	31.73
6	963	1	47	19	198	255	31.08	32.60
7	963	3	36	23	13	74	32.30	37.73
8	963	1	44	21	0	66	30.17	-
9	963	0	34	28	0	62	29.76	-
10	963	0	24	28	0	52	34.18	-
Total	9,637	182	509	217	2,404	3,148	34.89	30.66

Source: Amundi Institute.

Table 17: Regression results for carbon footprint elasticity to income (v)

	Direct (e^{dir})			Indirect (e^{ind})			Total (e)		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Intercept	2.218***	1.427***	−3.914***	0.256**	0.163	−5.240***	2.110***	2.036***	−3.398***
	(0.132)	(0.155)	(0.111)	(0.137)	(0.157)	(0.116)	(0.220)	(0.267)	(0.080)
v	0.000***	0.000***		0.000***	0.000***		0.000***	0.000***	
	(0.000)	(0.000)		(0.000)	(0.000)		(0.000)	(0.000)	
v^2	−0.000***	−0.000***		−0.000***	−0.000***		−0.000***	−0.000***	
	(0.000)	(0.000)		(0.000)	(0.000)		(0.000)	(0.000)	
v^3		0.000***			0.000			0.000***	
		(0.000)			(0.000)			(0.000)	
$\log(v)$			0.537***			0.631***			0.551***
			(0.012)			(0.012)			(0.008)
l	1.071***	0.976***	0.178***	1.136***	1.121***	0.244***	2.115***	2.109***	0.188***
	(0.085)	(0.085)	(0.014)	(0.091)	(0.091)	(0.015)	(0.139)	(0.140)	(0.010)
Obs.	11,876	11,876	11,860	11,939	11,939	11,922	11,939	11,939	11,922
$\Re^2$	0.283	0.289	0.244	0.345	0.345	0.298	0.430	0.430	0.396
$\Re^2_c$	0.283	0.289	0.244	0.345	0.345	0.298	0.430	0.430	0.396

Source: Amundi Institute.

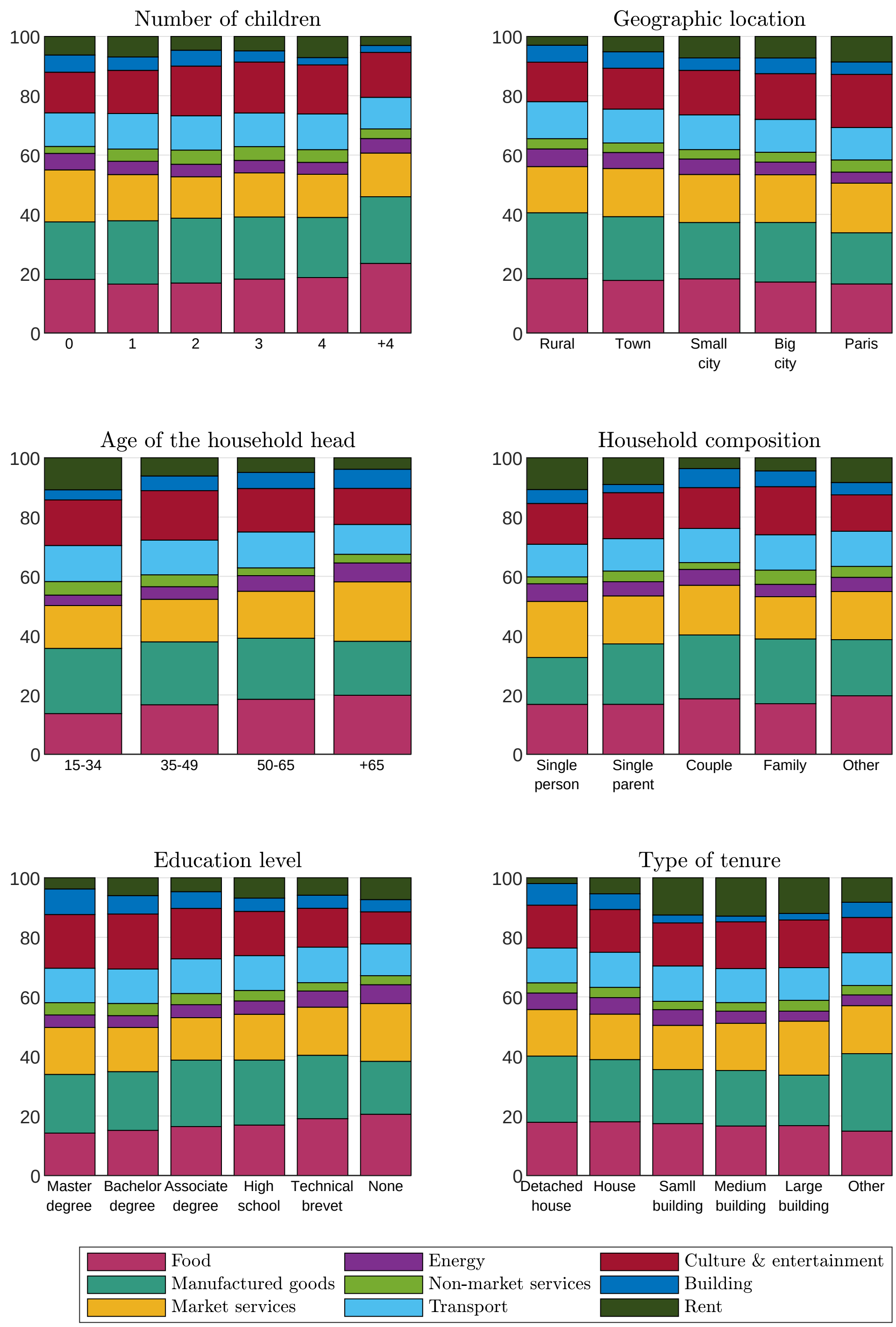
Table 18: Regression results for carbon footprint elasticity to expenditures (m)

	Direct (e^{dir})			Indirect (e^{ind})			Total (e)		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Intercept	2.745***	2.044***	−3.559***	−0.020	−1.025***	−8.836***	1.648***	−0.104	−4.968***
	(0.128)	(0.127)	(0.100)	(0.116)	(0.113)	(0.083)	(0.180)	(0.180)	(0.062)
m	0.000***	0.000***		0.000***	0.000***		0.000***	0.000***	
	(0.000)	(0.000)		(0.000)	(0.000)		(0.000)	(0.000)	
m^2	−0.000***	−0.000***		−0.000***	−0.000***		−0.000***	−0.000***	
	(0.000)	(0.000)		(0.000)	(0.000)		(0.000)	(0.000)	
m^3		0.000***			0.000***			0.000***	
		(0.000)			(0.000)			(0.000)	
$\log(m)$			0.494***			1.004***			0.710***
			(0.010)			(0.009)			(0.006)
l	2.024***	1.566***	0.218***	1.336***	0.726***	0.069***	2.418***	1.742***	0.125***
	(0.081)	(0.080)	(0.013)	(0.074)	(0.072)	(0.011)	(0.115)	(0.112)	(0.008)
Obs.	11,881	11,881	11,881	11,918	11,918	11,918	11,915	11,915	11,915
$\Re^2$	0.237	0.279	0.253	0.520	0.572	0.598	0.566	0.604	0.592
$\Re^2_c$	0.236	0.279	0.252	0.520	0.572	0.597	0.565	0.604	0.592

Source: Amundi Institute.

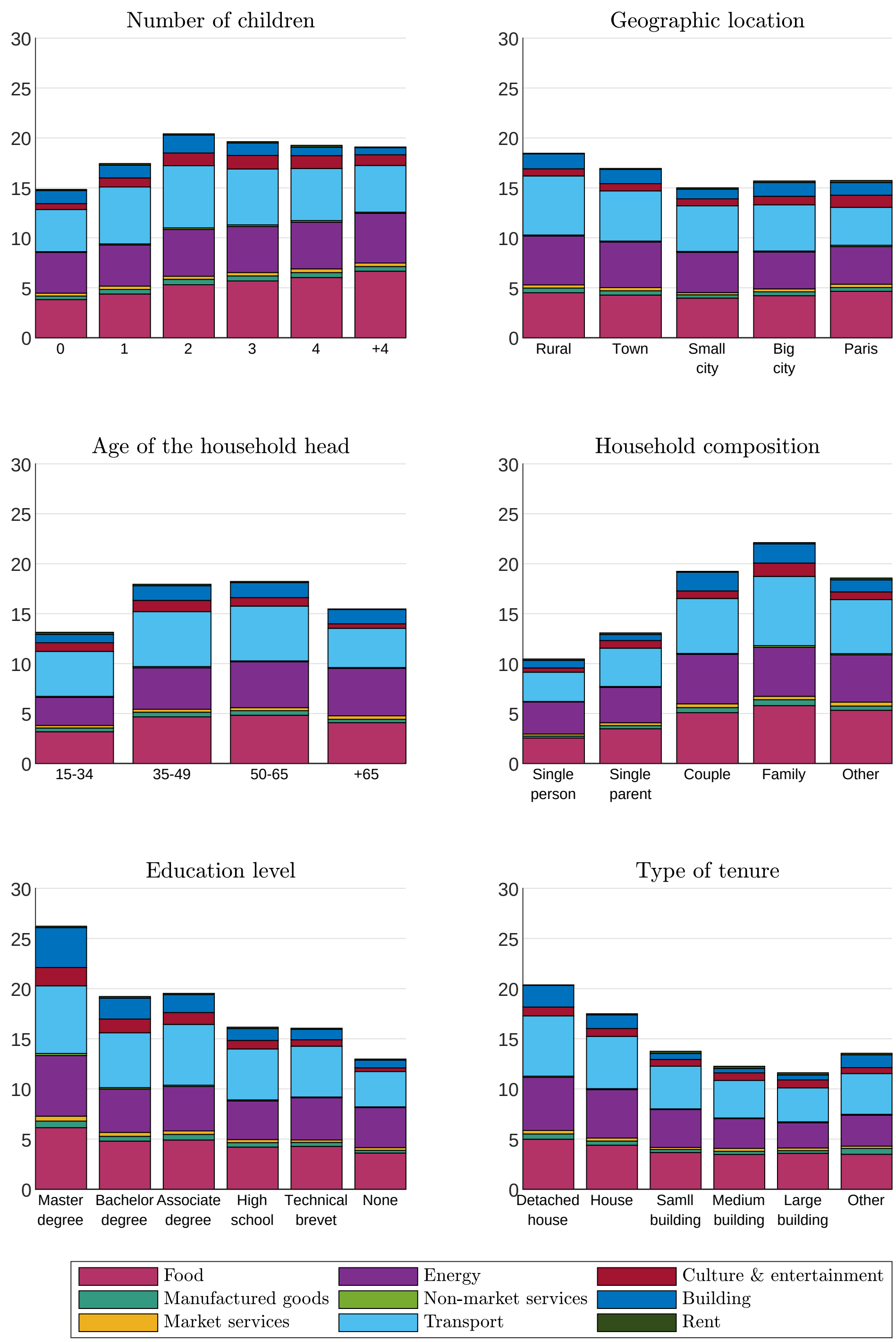
A.2 Figures

Figure 16: Households expenditures (in % of total) by item and characteristics



Source: BDF 2017, Insee, author's own calculations.

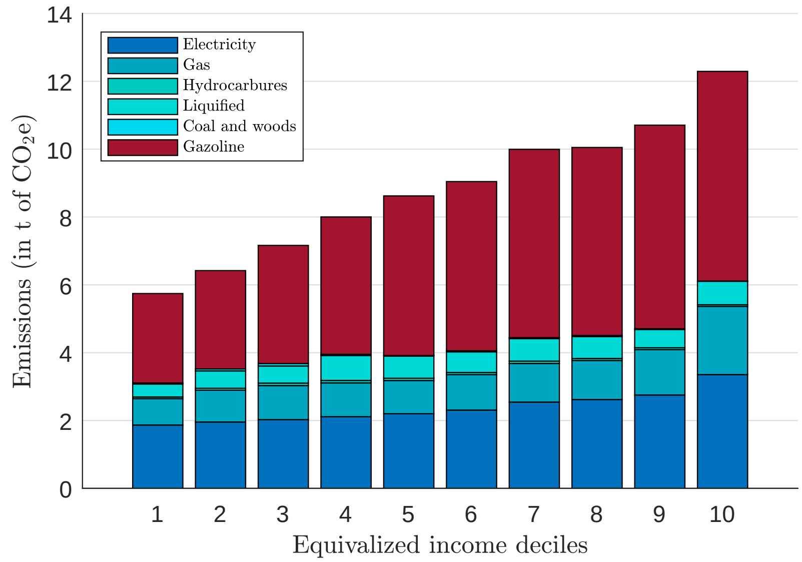
Figure 17: Average carbon footprint by item and characteristics



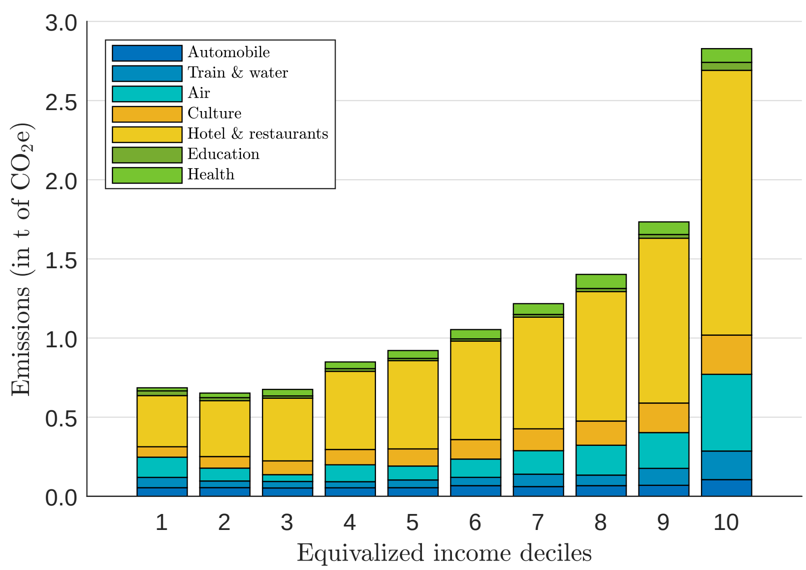
Source: BDF 2017, Insee, author's own calculations.

Figure 18: Average direct and indirect households carbon footprint by item and income decile

(a) Direct emissions

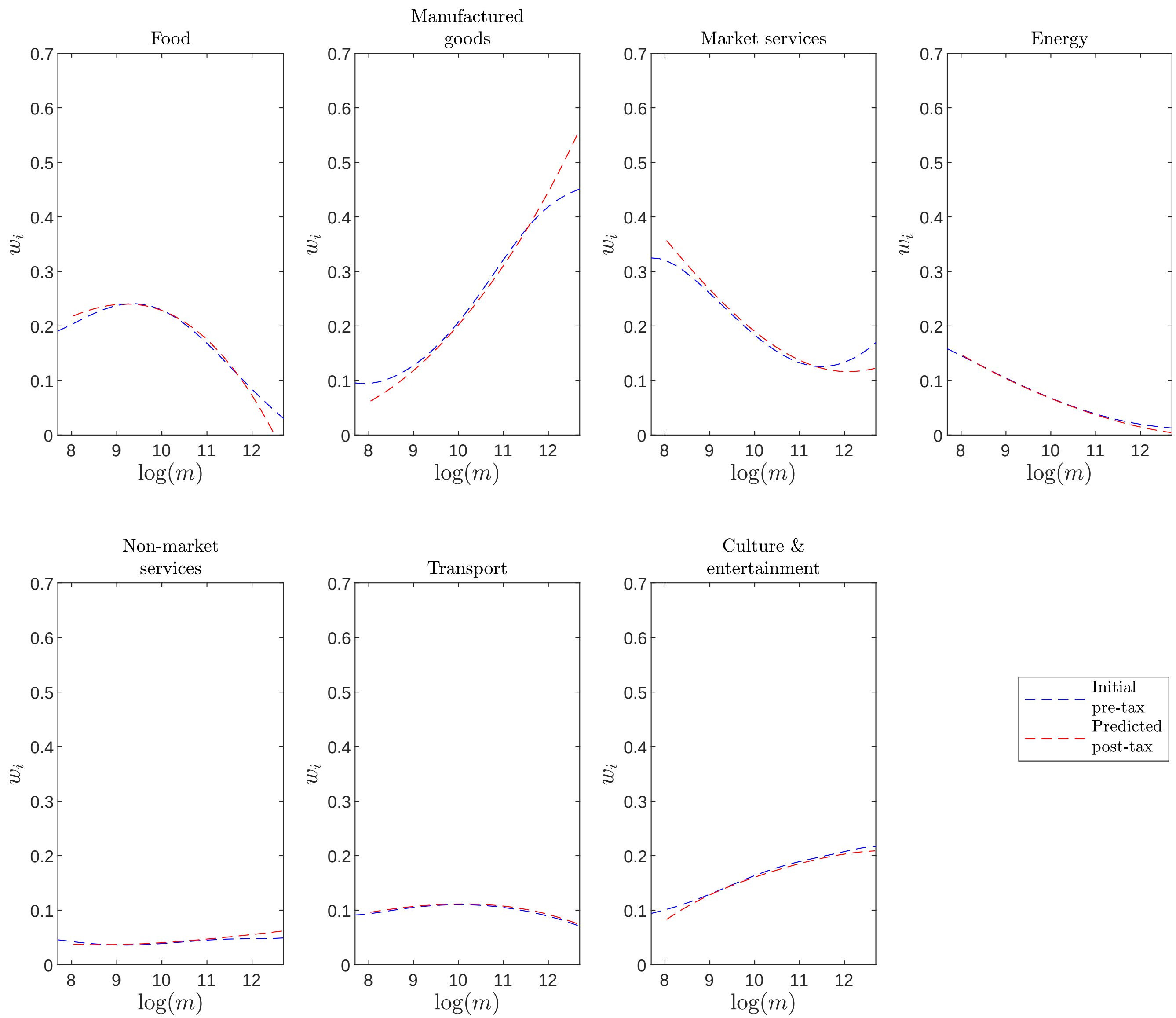


(b) Indirect emissions



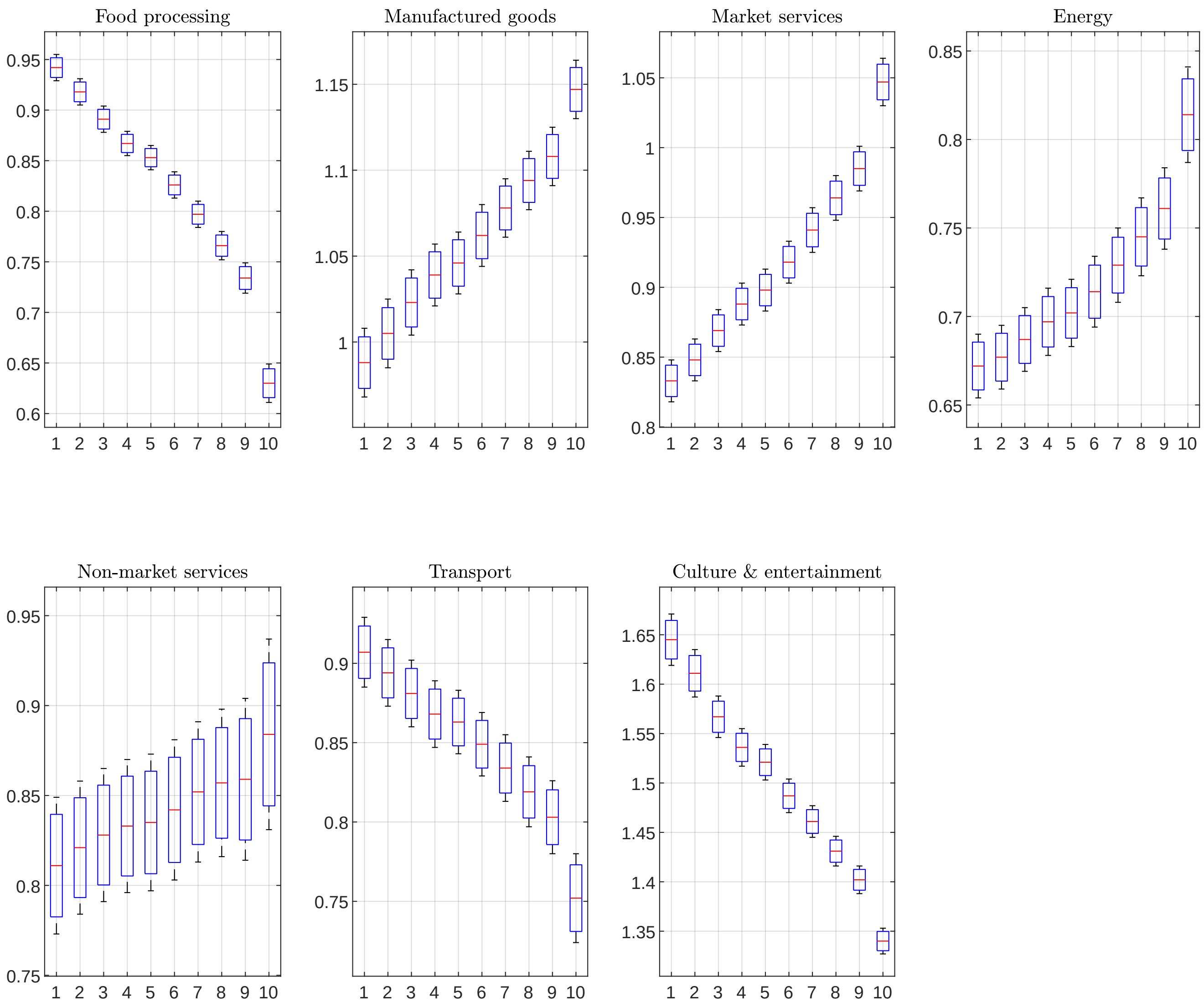
Source: BDF 2017, Insee, author's own calculations.

Figure 19: Engel curves before and after the implementation of the tax of €100 per CO_2e



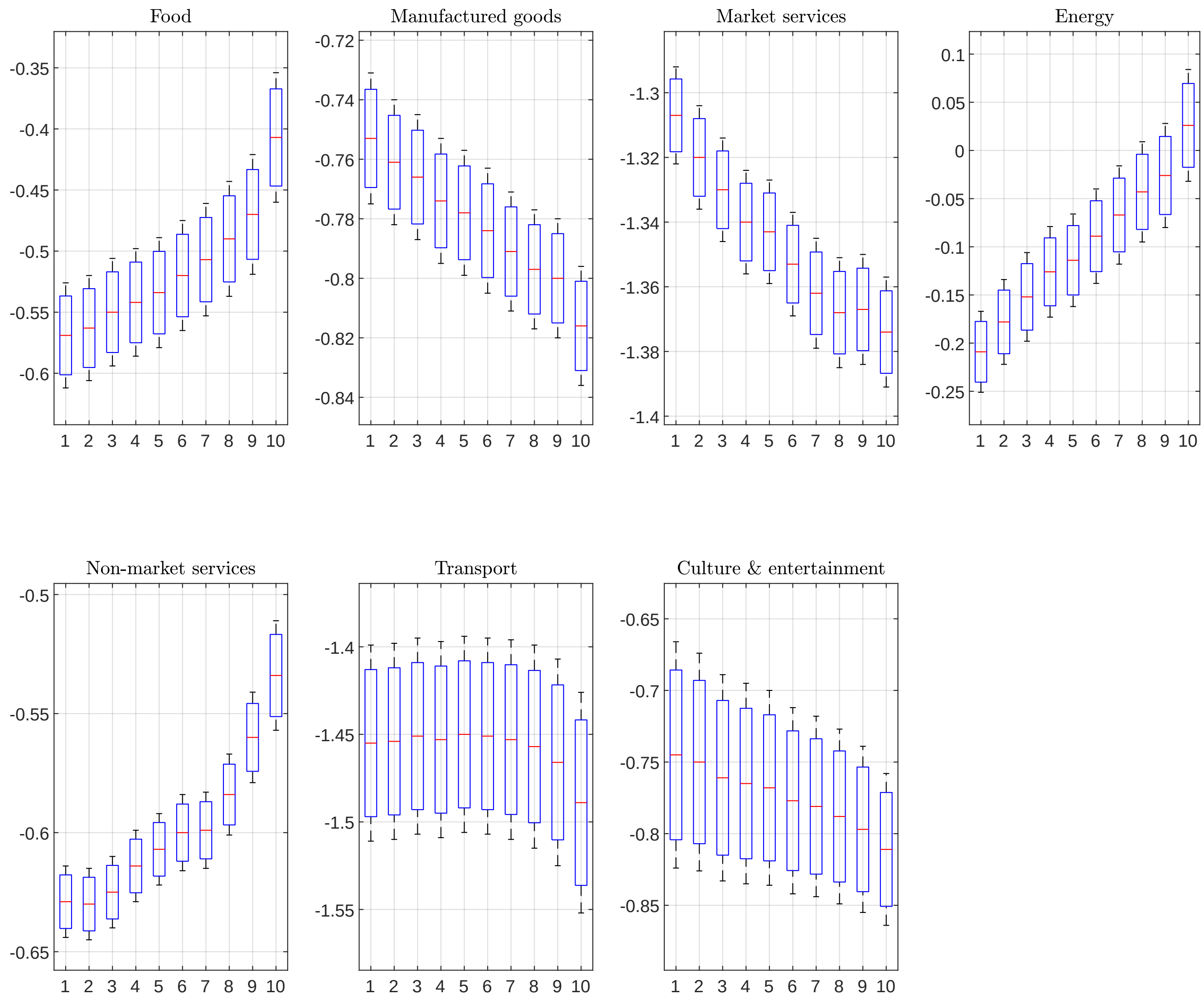
Source: Amundi Institute.

Figure 20: Budget elasticity of demand by item and income decile



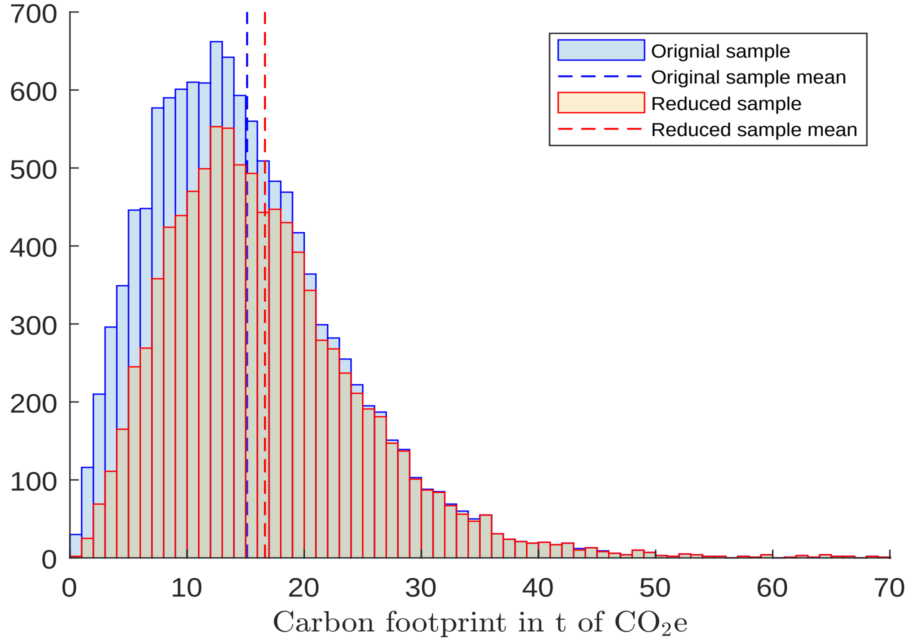
Source: Amundi Institute.

Figure 21: Uncompensated price elasticity of demand by item and income



Source: Amundi Institute.

Figure 22: Histogram of households carbon footprint by sample



Source: Amundi Institute.

B Technical appendix

B.1 An overview of the DICE and the RICE model

The DICE model Here, we give an overview of the revised model of Nordhaus (2017). The DICE model is based on the optimal growth model known as the Ramsey model, in which society invests in capital goods, reducing consumption today to increase consumption in the future. The DICE extends the original model by including climate investments, similar to capital investments. Here, we present the overall model revised by Nordhaus (2017). This framework will serve as a baseline model to integrate a social dimension as an input. The model maximizes a social welfare function ($\mathcal{W}^{\text{DICE}}$), which corresponds to the discounted sum of population-weighted utility of per capita consumption:

$$\mathcal{W}^{\text{DICE}} = \sum_{t=1}^{T} \mathcal{V}(\mathbf{c}_t,\ L_t)\ R_t = \sum_{t=1}^{T} U(\mathbf{c}_t)\ L_t\ R_t \tag{B.1}$$

$\mathcal{V}$ is the instantaneous social welfare function, U is the utility function, $\mathbf{c}_t$ is the per capita consumption, and L_t the population. The discount factor on welfare is $R_t = (1+\rho)^{-t}$, where ρ is the generational discount rate on welfare, which applies to the well-being of different generations (it is not observed). The function U has a constant elasticity with respect to per capita consumption of the form $U(c) = \mathbf{c}^{1-\eta}/(1-\eta)$. The parameter η is interpreted as the generational inequality aversion. The output equation is defined as the output net of damages and abatement:

$$\mathcal{Q}_t = \mathfrak{D}_t[1-\Lambda_t]\ \mathcal{Y}_t \tag{B.2}$$

where $\mathfrak{D}_t$ representing the damage function, Λ_t the abatement cost function, and $\mathcal{Y}_t$ the gross output expressed as a Cobb-Douglas function of capital, labor, and technology. The damage function is defined as:

$$\mathfrak{D}_t = \frac{D_t}{[1+D_t]} \tag{B.3}$$

where

$$D_t = \varphi_1 \mathcal{T}_t^{\text{AT}} + \varphi_2 \left[\mathcal{T}_t^{\text{AT}}\right]^2 \tag{B.4}$$

Equation (B.4) determines the impacts of climate change on the economy. The model takes average temperature change $\mathcal{T}_t^{\text{AT}}$ as the main statistic for climate damages. Here, damages are approximated by a quadratic function of temperature change above the pre-industrial level. Total CO_2 emissions E_t is a function of the level of carbon intensity σ_t, the gross output $\mathcal{Y}_t$ and an exogenous land-use emissions E_t^{Land}. It is expressed as:

$$E_t = \sigma_t \left[1-\mu_t\right]\ \mathcal{Y}_t + E_t^{\text{Land}} \tag{B.5}$$

where μ_t the emissions reduction rate. The geophysical equation $M_{j,t}$ links greenhouse gas emissions to the carbon cycle, radiative forcings, and climate change. The equation takes the following form:

$$M_{j,t} = \phi_{j,0} E_t + \phi_j^{\text{AT}}\ M_{t-1}^{\text{AT}} + \phi_j^{\text{UP}}\ M_{t-1}^{\text{UP}} + \phi_j^{\text{LO}}\ M_{t-1}^{\text{LO}} \tag{B.6}$$

where r illustrates the three reservoirs, namely the atmosphere (AT), upper oceans and the biosphere (UP), and the lower oceans (LO) that represent a sink for carbon. The parameter ϕ_j^{r} indicates the flow between reservoirs and periods. The relationship between the accumulation of GHG and increased radiative forcing is described as follows:

$$F_t = \kappa \left\{ \log\left[M_t^{\text{AT}}/M_{t=1750}^{\text{AT}}\right] \right\} + F_t^{\text{EX}} \tag{B.7}$$

where κ the radiative force equilibrium, F_t the change in total radiative forcings from anthropogenic sources (CO_2), F_t^{EX} is exogenous forcings, and the first term is the forcings due to atmospheric concentrations of GHG. The relationship between GHG accumulation and the increase in radiative forcing arises from empirical data and climate models. In this model, the climate system for temperatures is characterized by a simplified two-level system comprising the atmosphere and the mixed layer:

$$\mathcal{T}_t^{\text{AT}} = \mathcal{T}_{t-1}^{\text{AT}} + \psi_1 \Big\{ F_t - \psi_2 \; \mathcal{T}_{t-1}^{\text{AT}} - \psi_3 \left[\mathcal{T}_{t-1}^{\text{AT}} - \mathcal{T}_{t-1}^{\text{LO}} \right] \Big\}$$
$$\mathcal{T}_t^{\text{LO}} = \mathcal{T}_{t-1}^{\text{LO}} + \psi_3 \left[\mathcal{T}_{t-1}^{\text{AT}} - \mathcal{T}_{t-1}^{\text{LO}} \right]$$

where $\mathcal{T}_t^{\text{AT}}$ is the global mean surface temperature and $\mathcal{T}_t^{\text{LO}}$ is the mean temperature of the deep oceans at time t, ψ_1 is the thermal capacity of the atmosphere, ψ_2 is the climate feedback parameter and ψ_3 is the heat exchange coefficient.

In solving the previous equations by optimizing the social welfare function ($\mathcal{W}^{\text{DICE}}$), the SCC can be defined at time t as:

$$\text{SCC}_t = \frac{\partial \, \mathcal{W}^{DICE}}{\partial \, E_t} / \frac{\partial \, \mathcal{W}^{\text{DICE}}}{\partial \, C_t} \equiv \frac{\partial \, C_t}{\partial \, E_t} \tag{B.8}$$

Therefore, the SCC translates the economic impact of a one unit of CO_2 emission in terms of consumption. In other words, it is the economic cost associated with climate damages resulting from the emission of an additional ton of CO_2.

The RICE model More complexity can be introduced in AIM to differentiate equations for several regions. The Regional Integrated model of Climate and the Economy (RICE) model developed by Nordhaus and Yang (1996) and improved by Nordhaus (2011) in RICE-2011, is a sub-regional neoclassical climate-economy model[58]. There are twelve different regions[59] producing a single-good. The time dimension starts from 2005 to 2605 with a ten-year time steps. Nordhaus (2010) takes the conventional values for the pure rate of time preference and the elasticity of consumption to 1.5% and two, respectively, as in the DICE.

The RICE methodology consists of solving the Ramsey saving problem for the twelve regions given the previous equations. The model is solved in two steps. The first step consists of estimating the optimal saving rates, $s_{i,t}^*$ in the absence of mitigation ($\mu_{i,t} = 0$). These optimal saving rates permit to estimate the optimal consumption in this baseline run:

$$c_{i,t}^* = \frac{(1 - s_{i,t}^*) \; \mathcal{Q}_{i,t}}{L_{i,t}} \tag{B.9}$$

Then, the relative weights of the welfare function are estimated. They are defined as the inverse of the marginal utility of consumption at the baseline consumption level:

$$\mathbf{v}_{i,t} = \frac{U'(c_{i,t}^*)^{-1}}{\sum_i^I U'(c_{i,t}^*)^{-1}} \tag{B.10}$$

where $\mathbf{v}_{i,t}$ are the time-varying Negishi weights. In the second step, the mitigation policy is estimated, given these weights, by the Bergson-Samuelson social welfare type function:

$$\mathcal{W}_i^{RICE} = \sum_{t=1}^{T} \left(\frac{1}{1+\rho} \right)^t \sum_{i=1}^{I} \mathbf{v}_{i,t} L_{i,t} U(c_{i,t}) \tag{B.11}$$

[58] The RICE model has been developed since 1996 and thoroughly improved. Here we present the RICE-2011 version (Nordhaus, 2011).

[59] The regions are the United States, the European members of OECD, Japan, Russia, non-Russia Eurasia, China, India, Middle East, Africa, Latin America, Other High-income countries, and non-OECD Asia.

The optimal policy is chosen when the marginal cost of mitigation is equalized across regions. Given a carbon tax τ_t, the mitigation rate for each region i is defined by:

$$\mu_{i,t} = \left(\frac{\tau_t \sigma_{i,t}}{\theta^1_{i,t} \theta_2} \right)^{\frac{1}{\theta_2 - 1}} \tag{B.12}$$

Setting the region i's population in period t by $L_{i,t}$, the gross output $\mathcal{Y}_{i,t}$ for region i in period t depends on capital ($K_{i,t}$) and labor ($L_{i,t}$) endowments as in the neoclassical production function. The net output is the gross net of climate damages and abatement costs similar to equation (B.2) with regional subscript. Regional CO_2 emissions are proportional to gross output but depend on the carbon intensity of the different economies $\sigma_{i,t}$ as in equation (B.5) with regional distinction. The abatement costs $\Lambda_{i,t}$ expresses the fraction of emissions abated to the fraction of output delivered to mitigate. It is defined by the convex function of the mitigation rate $\mu_{i,t}$:

$$\Lambda_{i,t} = \theta^1_{i,t} \mu^{\theta_2}_{i,t} \tag{B.13}$$

where $\theta_2 = 2.8$ and $\theta^1_{i,t}$ are exogenous parameters, decreasing across time at a rate to equalize the marginal cost of the last unit of mitigation with the estimated price of backstop technology. This yields the efficiency of the abatement technology. Backstop technology is an innovation representing a ceiling of carbon emission but might take time to deploy globally. To reach this technology, each region pays a different price, more or less accessible, depending directly on the carbon price established. The greater the carbon price, the quicker the backstop technology's availability. The regional damages functions $\mathcal{D}_{i,t}$ link the atmospheric temperatures above the pre-industrial mean with damages by a quadratic function as in the DICE model. The temperature is determined by a simple climate module in which the concentration of atmospheric greenhouse gases is connected to temperature change.

B.2 The household demand system

The QAIDS model Let us consider a consumer's demand for a set of k items given the budget m_h, which represents, in our case, the total amount of expenditures of households h on the i item. The Quadratic Almost Ideal Demand System (QAIDS) from Banks *et al.* (1997) is derived from the standard indirect utility function:

$$\ln V_h = \left[\left\{ \frac{\ln m_h - \ln \mathbf{a}_h(p)}{\mathbf{b}_h(p)} \right\}^{-1} + \pi_h(p) \right]^{-1} \tag{B.14}$$

where $\pi_h(p)$ is a differentiable, homogeneous function of degree zero of prices p that can be written:

$$\pi_h(p) = \sum_{i=1}^{k} \pi_{i,h} \ln p_i \tag{B.15}$$

The fraction inside braces represents the indirect utility function of a demand system where budget shares are linear in log total expenditures. $\ln \mathbf{a}_h(p)$ is the transcendental logarithm function, defined as follows:

$$\ln \mathbf{a}_h(p) = \alpha_0 + \sum_{i=1}^{k} \alpha_{i,h} \ln p_i + \frac{1}{2} \sum_{i=1}^{k} \sum_{j=1}^{k} \gamma_{i,j} \ln p_i \ln p_j \tag{B.16}$$

where $\mathbf{p}_i$ is the price of good i for $i = 1, ..., k$. $\mathbf{b}_h(p)$ is the Cobb-Douglas price aggregator:

$$\mathbf{b}_h(p) = \prod_{i=1}^{k} p_i^{\beta_{i,h}} \tag{B.17}$$

The QAIDS model is defined by equations (B.14), (B.15), (B.16) and (B.17). All the parameters (π_i, $\gamma_{i,j}$, $\alpha_{i,h}$ and $\beta_{i,h}$), except α_0, have to be estimated. α_0 could be estimated jointly with the other parameters, but it will be computationally difficult. Therefore, it has to be set arbitrarily, although Deaton and Muellbauer (1980) suggest fixing it at the lowest value of $\ln m_h$ observed in the sample. We follow this method. As in economic theory, the parameters of the demand function must satisfy some properties:

$$\sum_{i=1}^{k} \alpha_{i,h} = 1, \quad \sum_{i=1}^{k} \beta_{i,h} = 0, \quad \sum_{i=1}^{k} \pi_{i,h} = 0, \quad \sum_{i=1}^{k} \gamma_{i,j} = 0, \quad \text{and} \quad \gamma_{i,j} = \gamma_{j,i} \quad \forall i \neq j$$

where the four-firsts on the left side refer to the adding-up (i.e., $\sum w_{i,h} = 1$) and homogeneity. The last one is the Slutsky symmetry (i.e the matrix of second derivatives with respect to prices should be symmetric).

Let $q_{i,h}$ represent the quantity of good or service i consumed by household h and p_i its price. Then, we obtain $w_{i,h} = q_{i,h} p_i / m_h$ the expenditures' share allocated to the good or service i. By applying Shephards Lemma's identity, the budget shares are given by:

$$w_{i,h} = \alpha_{i,h} + \sum_{j=1}^{k} \gamma_{i,j} \ln p_j + \beta_{i,h} \ln \left\{ \frac{m_h}{\mathbf{a}_h(p)} \right\} + \frac{\pi_i}{\mathbf{b}_h(p)} \left[\ln \left\{ \frac{m_h}{\mathbf{a}_h(p)} \right\} \right]^2 \tag{B.18}$$

We follow the methodology of Banks *et al.* (1997) to compute the budget, own-price elasticity, and cross-price elasticity.

Budget elasticity To compute expenditures elasticity from the QAIDS model, we differentiate equation (B.18) with respect to $\ln m_h$. Then, we obtain the budget elasticity of shares:

$$\Gamma_{i,h} \equiv \frac{\partial w_{i,h}}{\partial \ln m_h} = \beta_{i,h} + \frac{2\pi_{i,h}}{\mathbf{b}_h(p)} \left[\ln \left\{ \frac{m_h}{\mathbf{a}_h(p)} \right\} \right] \tag{B.19}$$

Knowing that:

$$\frac{\partial w_{i,h}}{\partial \ln m_h} = \frac{\partial w_{i,h}}{\partial m_h} \frac{\partial m_h}{\partial \ln m_h} = \frac{\partial w_{i,h}}{\partial m_h} m_h \tag{B.20}$$

and that:

$$\frac{\partial w_{i,h}}{\partial m_h} = \frac{\partial \left(\frac{p_i q_{i,h}}{m_h}\right)}{\partial m_h} = -\frac{p_i q_{i,h}}{m_h^2} + \frac{p_i}{m_h} \frac{\partial q_{i,h}}{\partial m_h} = -\frac{w_{i,h}}{m_h} + \frac{w_{i,h}}{q_{i,h}} \frac{\partial q_{i,h}}{\partial m_h}$$

By plugging the previous equation into equation (B.20), we have:

$$\frac{\partial w_{i,h}}{\partial \ln m_h} = \left(-\frac{w_{i,h}}{m_h} + \frac{w_{i,h}}{q_{i,h}} \frac{\partial q_{i,h}}{\partial m_h} \right) m_h = -w_{i,h} + m_h \frac{w_{i,h}}{q_{i,h}} \frac{\partial q_{i,h}}{\partial m_h}$$

Since the expenditures-elasticity is expressed as:

$$\varepsilon_{i,h} = \frac{\partial q_{i,h}}{\partial m_h} \frac{m_h}{q_{i,h}}$$

we obtain:

$$\Gamma_{i,h} = w_{i,h}(\varepsilon_{i,h} - 1)$$

After rearranging, we obtain:

$$\varepsilon_{i,h} = \frac{\Gamma_{i,h}}{w_{i,h}} + 1 \tag{B.21}$$

Own-price elasticity To compute own-price elasticity, we differentiate equation (B.18) with respect to $\ln p_i$. We obtain:

$$\Gamma_{i,i,h} = \gamma_{i,j} - \Gamma_{i,h} \left(\alpha_{i,h} + \sum_j \gamma_{i,j} \ln p_j \right) - \frac{\pi_{i,h} \beta_{h,i}}{\mathbf{b}_h(p)} \left[\ln \left(\frac{m_h}{\mathbf{a}_h(p)} \right) \right] \tag{B.22}$$

Knowing that:

$$\frac{\partial w_{i,h}}{\partial \ln p_i} = \frac{\partial w_{i,h}}{\partial p_i} p_i$$

and that:

$$\frac{\partial w_{i,h}}{\partial p_i} = \frac{\partial \left(\frac{p_i q_{i,h}}{m_h}\right)}{\partial p_i} = \left(q_{i,h} + \frac{\partial q_{i,h}}{\partial p_i} p_i \right) \frac{1}{m_h} = \left(1 + \frac{\partial q_{i,h}}{\partial p_i} \frac{p_i}{q_{i,h}} \right) \frac{q_{i,h}}{m_h}$$

Since the uncompensated own-price elasticity is defined by:

$$\varepsilon^u_{i,i,h} = \frac{\partial q_{i,h}}{\partial p_i} \frac{p_i}{q_{i,h}}$$

we obtain:

$$\frac{\partial w_{i,h}}{\partial \ln p_i} = \left(1+\varepsilon^u_{i,i,h}\right)\frac{q_{i,h}}{m_h}p_i = \left(1+\varepsilon^u_{i,i,h}\right)w_{i,h}$$

After rearranging, we finally obtain:

$$\varepsilon^u_{i,i,h} = \frac{\Gamma_{i,i,h}}{w_{i,h}} - 1 \tag{B.23}$$

Cross-price elasticity To compute cross-price elasticity, we differentiate the equation (B.18) with respect to $\ln p_j$. We obtain:

$$\Gamma_{i,j,h} = \gamma_{i,j} - \Gamma_{i,h}\left(\alpha_{j,h} + \sum_k \gamma_{i,k}\ln p_k\right) - \frac{\pi_{i,h}\beta_{i,h}}{\mathbf{b}_h(p)}\left[ln\left(\frac{m_h}{\mathbf{a}_h(p)}\right)\right] \tag{B.24}$$

Applying the same methodology as before, the uncompensated cross-price elasticity is expressed as:

$$\varepsilon^u_{i,j,h} = \frac{\Gamma_{i,j,h}}{w_{i,h}}$$

Therefore, the uncompensated cross- and own-price elasticity can be written as:

$$\varepsilon^u_{i,j,h} = \frac{\Gamma_{i,j,h}}{w_{i,h}} - \delta_{i,j} \tag{B.25}$$

where $\delta_{i,j}$ is the Kronecker delta given by $\delta_{i,j} = 0$ for all $i \neq j$ and $\delta_{i,i} = 1$ for all i. Using the Slutsky equation, we derive the compensated Hicksian price elasticities, which integrate the substitution and the income effect together:

$$\varepsilon^c_{i,j,h} = \varepsilon^u_{i,j,h} + \varepsilon_{i,h}w_{j,h} \tag{B.26}$$

Model estimation Two major issues are still affecting the estimations. Firstly, as mentioned by Blundell *et al.* (1994) and Blundell and Robin (2000), a significant source of endogeneity might arise from the regressions since total expenditures m is related to expenditures' shares w_i. Secondly, there is an estimation bias in the model since a large number of goods and services are not consumed by households. The occurrence of zeros could arise from "*infrequent purchases, choice of not consuming particular goods given current prices and households budget constraint, as well as, they may represent misreporting or mis-measurement*" (Pudney, 1989). Therefore, results can be both biased and overestimated.

To overcome the endogeneity issue, we can integrate the impact of demographic characteristics in the system[60]. The demand for goods and services depends predominantly on the household's size and composition. Without these characteristics, the model assumes no household consumption behavior variability. To take into account those sources of heterogeneity, socioeconomic and sociodemographic characteristics integrate the model through the α's, which are modeled as linear combinations of a set of characteristics variables, namely the type of tenure, the number of children, the age of the head of the household and the geographical location. Thus, the model integrates this translating approach developed by Pollak and Wales (1981). It allows the level of demand to be related to some socioeconomic and sociodemographic factors and preserves the conditional linearity of the model.

[60] See Lecocq and Robin (2015) for more details on the methodology adopted.

The socioeconomic factors enter the model in equation (B.18) and also in equation (B.16). Thus, an additional adding-up condition must be incorporated into the model to keep demand theory consistent. We are also using an instrumental variable method developed by Hausman (1978). Income enters the model as an instrumental variable in the reduced form model. Then, the predicted residuals computed in the standard form enter the model as an additional explanatory variable. The demand system is estimated using iterated linear least-squares (ILLS). A series of seemingly unrelated regressions (SUR) is performed to obtain unbiased estimates of parameters. Standard errors of all parameters are simultaneously calculated using the asymptotic variance-covariance matrix as in Blundell and Robin (1999).

The censoring issue can be solved using a censored demand system following a two-step procedure developed by Shonkwiler and Yen (1999). In the first step, a maximum-likelihood heteroskedastic probit model is estimated to consider the consumption choice. Then, it is used to predict the standard cumulative distribution and probability density functions. In the second step, cumulative distribution functions augment independent variables in the system, while probability density functions are included as additional explanatory variables. Such a methodology would directly affect the QAIDS framework. Moreover, this method constrains the model to reject the cross-price elasticities. The censored system can be avoided since we keep a significant share of our sample even with censoring.

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