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# Three essays on macroeconomics of low-carbon transition

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# Abstract

If climate change can be seen as the greatest threat humankind is facing, reaching a net zero emission neutrality by the end of the $XXI^e$ century might be its greatest challenge. Low-carbon transition is a macroeconomic issue crossed by numerous redistributive effects that are not fully known yet and implies a keen understanding of its mechanisms. Macroeconomic models, especially computable general equilibrium (CGE) models, can help frame the obstacles and serve as a powerful tool for public policy design. My thesis explores different dimensions associated with macroeconomic modeling and how to better integrate heterogeneity into their framework. The first chapter is dedicated to the question of emissions accounting and assessing the distribution of carbon footprint within the population. Built upon the results of the first chapter, the second one contributes to the debate on the regressivity of carbon pricing by proposing a general equilibrium analysis of redistributive effects using a CGE model in which several groups of households are represented, with heterogeneous behavior in price response. The third and last chapter focuses on the question of the incidence of the calibration of production function parameters on CGE simulation results. We perform econometric regressions on 54 large panels, each associated with a sector of activity, to estimate the elasticities of substitutions between production inputs. We show how nested Constant Elasticity of Substitution (CES) production functions lead to opposite estimated results compared to a more general production function we use as a benchmark: The Variable Output Elasticity - Cobb Douglas (VOE-CD).

# Résumé

Si le changement climatique peut sans doute être considéré comme la plus grande menace à laquelle l'humanité est confrontée, atteindre la neutralité carbone d'ici la fin du $XXI^e$ siècle pourrait être son plus grand défi. La transition vers une économie neutre en carbone est un enjeu macroéconomique qui est traversé par de nombreux effets redistributifs encore mal connus et qui implique une compréhension fine des mécanismes qui l'entourent. Les modèles macroéconomiques, et en particulier les modèles d'équilibre général calculable (EGC), peuvent aider à cerner les obstacles et aider à la conception des politiques publiques. Ma thèse explore différentes dimensions associées à la modélisation macroéconomique et la manière de mieux intégrer l'hétérogénéité dans leur cadre d'analyse. Le premier chapitre est consacré à la question de la comptabilisation des émissions et à l'évaluation de la distribution de l'empreinte carbone au sein de la population. S'appuyant sur les résultats du premier chapitre, le deuxième contribue au débat sur la régressivité de la tarification du carbone en proposant une analyse d'équilibre général des effets redistributifs à l'aide d'un modèle EGC dans lequel plusieurs groupes de ménages sont représentés, avec un comportement hétérogène dans leurs réponses aux variations de prix. Le troisième et dernier chapitre se concentre sur la question de l'incidence de la calibration des paramètres de la fonction de production sur les résultats de simulations faites avec un modèle EGC. Nous effectuons des régressions économétriques sur 54 jeux de données de panels, chacun associé à un secteur d'activité, pour estimer les élasticités de substitutions entre les facteurs de production. Nous montrons comment des fonctions de production imbriquées Constant Elasticity of Substitution (CES) conduisent à des résultats estimés opposés par rapport à une fonction de production plus générale que nous utilisons comme référence : la fonction Variable Output Elasticity - Cobb Douglas (VOE-CD)

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# Introduction

*Should we need to control such things as the production of energy and $CO_2$ in the world, we will face an economic and political resource allocation problem of unprecedented difficulty and complexity*

Allen V. Kneese (1971)

The threat that climate change represents to humans' well-being is becoming more and more precise, tangible, and alarming, as exposed by the latest publications of the International Panel on Climate Change (IPCC, 2022) or by the increase in the frequency of extreme weather events such as heatwaves, droughts, hurricanes, floods or storms we recorded in the recent years. After almost 30 years of international negotiations, starting officially in 1992 with the Summit of Rio, the international community eventually agreed in 2015 on pledges to limit the increase of temperatures by the end of the century to 1.5°C, well below 2°C. This ambitious target was a sign of relief that world leaders could put global interest ahead of private interests, even if the pathways to achieve it remain unclear. Indeed, the current state of national pledges, reenacted in 2021 at the COP 26, would lead to an increase in temperatures of 2.1° C (within a range of ± 0.5° C) and *current policies & actions* to 2.7° C (within a range of ± 0.9° C) (UNEP, 2021), which remains well above what parties agree on in the first place. The expected reduction in emissions required to limit climate change is considerable. According to UNEP, to meet the 1.5° C target, emissions must globally decrease at an average yearly rate of 7.6% and at least 4.5% for a 2°C target[1]. Looking at developed countries that have pledged to reach net-zero emissions by 2050[2], the expected trend is even steeper.

Regardless of the evolution of the international macroeconomic context, the world economies, and first and foremost, developed countries must lead a steady, permanent and significant reduction of their emissions. However, such an objective can only be achieved through a solid and comprehensive roadmap that can overcome

[1]By comparison, $CO_2$ emissions yearly grown at a 1.4% rate during the decade 2010-2019 and reached its historical peak in 2019 with 36.81 $GtCO_2$.

[2]At this date, EU member states, United Kingdom, Japan Canada, and New Zealand legally committed to reaching carbon neutrality by 2050 (Retrieved from Net Zero Tracker).

the problem of the *tragedy of horizons*[3].

Economically, Climate Change results from an intertemporal misallocation of resources that falls under the inability of private markets to *correctly* price the negative externalities that greenhouse gases cause to human well-being. To correct this misallocation, the most cost-effective climate policy, widely promoted among economists, would be to impose a Pigovian tax (Pigou, 1932) on carbon emissions, reflecting the Social Cost of Carbon (SCC). The SCC, and therefore the optimal price of this carbon tax, is an estimate of the present value of the damage, expressed in economic value, of emitting one additional ton of carbon dioxide into the atmosphere. This tax increases the price of fossil fuels in proportion to the carbon they emit and therefore incentivizes economic agents to shift their resource allocation to the new relative prices, eventually reaching the social optimum (the so-called first-best outcome). It should be noted that this mechanism takes different forms in carbon policies: indirect tax on energy products, a cap-and-trade system associated with emission permits, or internal price in investment decision-making.

Increasing the cost of fossil fuels would also stimulate investment in less carbon-intensive activities and therefore change the structure of the capital stock, substituting carbon-intensive capital with less carbon-intensive capital. From a purely technical point of view, it means: investing in several technologies and actions, such as ramping up renewable energy sources in power production, retrofitting residential and business buildings, developing public transport systems, or accelerating the electrification of the vehicle fleet. This decarbonization process is generally referred to as the *energy transition*, as it involves a change in energy consumption, either through energy effi-

[3]The tragedy of horizons refers to a speech given by the former Governor of England Mark Carney in 2015 on how the catastrophic impact of climate change will impose a cost on future generations that the current generation has no incentive to fix.

ciency measures or through the gradual elimination of fossil fuels from the energy mix. In order to acknowledge the existence of other non-energy sources of emissions (such as specific industrial processes in the cement and steel industries, land use choices, or certain agricultural practices), we refer to *low-carbon transition*.

Carbon pricing is also an idiosyncratic shock where economic agents are heterogeneously affected by climate policy. For firms, the impact depends primarily on their sector specificities regarding the activity, production function, and capital structure, which determines their energy use (Martin et al., 2014; Dechezleprêtre and Sato, 2020). Concerning households, the impact of a climate policy will differ according to their consumption structure and the average carbon intensity of goods covered by a carbon tax. The literature shows that these effects are regressive with income level (Ohlendorf et al., 2021), but also that heterogeneity arises from other factors such as places of residence and work or their housing tenure status.

Macroeconomics began to address the profound implications of a decarbonization policy on economic activity in the late 1960s (Ayres and Kneese, 1969). A wide range of macroeconomic model classes have been developed to study the economics of climate (Farmer et al., 2015). In particular, Integrated Assessment Models (IAMs) models have been widely used in the work of the IPCC to produce scenario analyses. They play a central role in determining Social Socioeconomic Pathways (SSPs), which are scenarios that examine contrasting narratives of socioeconomic trends that could shape future society and are intended to cover the range of plausible futures (Riahi et al., 2017). In contrast to these IAMs, which can become very complex because of the numerous combinations between economic and technical modules, *simple* IAMS - such as PAGE (Hope, 2006), used for the Stern Review (Stern, 2006), FUND (Waldhoff et al., 2014) and DICE model (Nordhaus, 1991, 2013) are often used to calculate the SCC and inform about the intertemporal carbon policy to be pursued to maximize the intertemporal welfare.

As appealing as these tools for public policy can be, several prominent voices have risen to criticize their use in the design of public policies. A part of the economics profession, while still recognizing their scientific interest in the qualitative evaluation of their dynamics, considers them too uncertain and sensitive to hypotheses to provide reliable quantitative indications and therefore ill-suited to assess and serve climate policies (Arrow et al., 1996; Heal, 2017; Pindyck, 2020; Stern and Stiglitz, 2022).

Therefore, how can we, as economists, determine a carbon price that can serve public action and the low-carbon transition process? The issue of measuring this carbon price that captures the trade-off between economic development and respect for environmental protection can be resolved using two approaches. The first one inherently linked to IAMs is the Benefit-Cost Analysis (BCA), which adopts a normative approach. It measures the carbon price that equalizes the marginal benefits it brings (reducing the damages from climate change by lowering the carbon emissions) to its marginal cost (the price increase on carbon-intensive goods and services). The second approach, called Cost-Effectiveness Analysis (CEA), is more positive and does not embed welfare analysis, especially intergenerational welfare, and therefore does not require the evaluation of discounted damages from climate change dynamics. On the contrary, it examines what carbon price would be necessary to trigger a reduction in emissions based on their marginal abatement cost (alternatively, the shadow cost of the carbon constraint) and the overall emission reduction (or limitation of temperature increase) target as given. The publication of world carbon budgets (IPCC, 2018) compatible with targets of 1.5°C and 2°C [4], as the enactment of national low-carbon pathways and strategies corresponds to this approach and allows for a focus on multiple technical and social dimensions. The complexity of the economic interactions between the economic agents and their heterogeneity raises several questions.

How to increase the accuracy and operationality of macroeconomic models in the

[4]In order to account for uncertainty, carbon budgets estimations are associated with a probability distribution of likelihood to stay under a threshold of maximum temperature increase.

context of a decision support tool for implementing low-carbon transition? What information is needed to integrate the interdependence of a national economy with its economic environment? How can we better represent the heterogeneity that characterizes an economy between households and activities and their respective expected behaviors to implement carbon policies? Which complementary policies could be implemented to moderate the distortions they induce and ensure a fair repartition of the cost?

These questions are ultimately part of the problem of choosing the relevant representative framework for the analysis of transition policies. This framework should be able to integrate general equilibrium effects and interactions between production and consumption activities while guaranteeing a sufficient representation of heterogeneity.

Today, climate macroeconomics is at a crossroads. IAMs models are becoming more tractable and accurate, continue to feed the work of the IPCC, and are particularly useful in building climate scenarios. Furthermore, by framing the low-carbon transition in a cost-benefit analysis, economists have shifted the debate to the optimal social cost of carbon, with all its limitations. Cost-effectiveness analysis, to which the Computable General Equilibrium (CGE) literature contributes, appears well-suited to assist the economy's progressive transformation on a path consistent with carbon budgets.

CGE models, in that perspective, offer an interesting framework. Extending on the Input-Output Model from Leontief (1937) and adopting a general equilibrium setting (Johansen, 1960a), they seek to numerically solve the problem for the supplies, demands, and prices that support equilibrium across a specified set of markets. Instead of identifying environmentally optimal policies, they are more interested in comprehending and quantifying the effects of specific economic policy decisions. The extension of the general equilibrium framework to environmental issues can be traced back to Maler (1974), but CGE models started in the 1990s to integrate these di-

mensions (Wing, 2009) into their analytical framework. Notable examples of CGE models are OECD ENV-Linkages multi-country (Château et al., 2014) ; Centre for Global Trade Analysis (Corong et al., 2017); GEM-E3 (Capros et al., 2013); and the multiregional RHOMOLO (Brandsma et al., 2015).

Despite having a more granular representation of the economy with a wide sectoral decomposition, national accounts on which these *top-down* models are calibrated do not offer a sufficient representation of energy-intensive sectors and, therefore, cannot encompass the heterogeneity of technologies, which is essential to integrate a decarbonization pathway through energy sources substitution. In this sense, it argues for the hybridization of economic models (Hourcade et al., 2006; Böhringer and Rutherford, 2008), whether to improve technical knowledge of the production process or between the macroeconomic and microeconomic dimensions to assess the existing heterogeneity fully. Hybridization seeks to complete the economic richness of top-down models with a more detailed representation of specific economic activities key in the analysis of transition scenarios that *bottom-up* models provide. It has been mostly developed for coupling engineering models describing energy supply from primary sources with CGE models (Fortes et al., 2014) and used on different applications such as energy systems, transport (Helgesen et al., 2018) or residential sector (Drouet et al., 2005). More generally, these developments aim to represent more precisely the marginal abatement costs of energy-related technologies to pin down heterogeneous substitution effects. Providing robust estimates for the parameters of the production function depends not only on the richness of the representation of technologies that allows hybridization across models but also on the choice of the form of the production function, which is retained in CGE models. Constant elasticity substitution (CES) production functions (Arrow et al., 1961) have been widely used for this purpose because they can represent a continuum of substitution possibilities between inputs while relying on consistent theoretical foundations. However, additional assumptions

must be made about the nesting structure (Sato, 1967) to fully represent the production processes associated with the use of a large number of inputs, which in turn affects the results of econometric estimates of substitution elasticities (van der Werf, 2008).

As important as it is for these developments to specify the interrelationships between energy supply and use and their economic translation, it is also essential to integrate the heterogeneity that characterizes the components of final demand and households, in particular, to account for distributional effects induced by carbon policies. In this fashion, several methodologies of coupling between a CGE and a microsimulations models have been proposed in the literature (Cockburn et al., 2014) to exploit the individual heterogeneity into an integrated framework. Indeed, one of the key issues in analyzing the effects of carbon policies is the heterogeneity of consumption and production behaviors. Households differ in income and other important characteristics, such as their location of residence, type of mobility, or familial structure, leading them to differ in their consumption patterns. Thus, it is essential to draw a clear picture of the actual heterogeneity of their carbon emissions and their substitution behavior between consumer products when relative prices vary. From a methodological point of view, this amounts to enriching the CGE models by adding bottom-up models (with a finer representation of production technologies or a distinction of households into several groups), but also to associate a calibration of behavioral parameters (substitution elasticities in the production function, price elasticities of households final consumption) that reflect this heterogeneity.

Moreover, as illustrated by the impact on the global economic framework of Russia's war on Ukraine, the evolution of energy prices is prone to uncertainty and could completely obliterate our understanding of the macroeconomic context. Recent geopolitical developments, whether related to the pandemic or the armed conflict in Ukraine, underline the need to have tools that can integrate short-term dynamics

and inform public decision-making in an uncertain and fragile context. Any shock in the world economy can significantly alter the conclusions of a cost-effectiveness analysis, whether it is a sudden change in international energy prices, a disruption in the supply chain, or a lack of skilled labor in certain sectors. Henceforth, the journey to a low-carbon economy should be considered more a steeplechase than a traditional middle-distance race. Unexpected obstacles can cause course changes, and the necessity to consider sudden and unpredictable shocks is inevitable.

In this sense, it seems essential that a sufficiently complex and responsive evaluation framework emerges in the coming years to adapt to shocks that are generally difficult (if not impossible) to anticipate. Taking these potential obstacles into account, together with the uncertainty surrounding the contribution of technical progress to the reduction of emissions, considerably reduces the conclusions to be drawn for a long-term horizon. Restricting the analysis to short- and medium-term impacts associated with intermediate steps on the path to net zero emissions seems more pragmatic and preferable. It would require updated assessments, incorporating new information to update model calibration on statistical data and parameter calibration. A thorough analysis of low-transition requires extensive empirical knowledge: of the structure of the capital stock, the availability of abatement technologies, their current state, and their potential for development, a precise mapping of the emission flows within the economy, the structure of production at an adequate level, and the heterogeneity that characterizes our economies, both on the productive and consumers side. I attempt to contribute to this research by providing empirical evidence on two specific research lines directly linked to the macroeconomic assessment of a low-carbon transition within a CGE framework.

Hence, in the first Chapter, I discuss different metrics related to carbon accounting and provide estimations of individual carbon footprint indicators, taking the case of France. Studying heterogeneity of carbon footprint at a country level induced by a

worldwide production process pins down the importance of the international value chain in the heterogeneity of carbon footprint indicators at the individual level and, therefore, relative exposures to price shock.

In the second Chapter, I extend this analysis by exploring the distributional effects on households induced by carbon taxation. I conduct an analysis using micro-simulations and a CGE model that enables me to explore the main concerns regarding the choice of the tax base, the redistribution pattern, the specific behaviors of agents, and the supply-side contribution that eventually sheds light on the equity-efficiency nexus.

Finally, in the last Chapter, I address the question of the dynamics of change that we could expect from the production side of carbon policies using estimated parameters and draw conclusions on the importance of these parameters regarding the decarbonization pathways.

In this thesis, these different chapters aim to answer the same question: How can empirical research help better grasp a low-carbon transition's effects, considering the different dimensions that influence it?

**Chapter 1: Quantifying the global and distributional aspects of the French carbon footprint.**

In this first Chapter, I am interested in questions related to carbon accounting, particularly in measuring France's carbon footprint and population distribution. Indeed, considerations related to climate justice that animate part of the scientific debate, particularly that of the responsibility for emissions require a deeper understanding on the different accounting approaches . First and foremost, this requires collecting knowledge about the circuit of emissions along the global value chain and the final consumption with which they are associated (Steininger et al., 2016). Ultimately, the underlying question is whether a decoupling (at least in relative terms) between the level of emissions and the level of income can be observed (Churchill et al., 2018) and to what extent these two variables are correlated. I rely on the consumption-based reference methodology for carbon accounting of emissions (Peters, 2008) associated with the multi-regional input-output database EXIOBASE (Stadler et al., 2018) from which I determine a set of carbon intensity indicators for several products and according to several scopes of emissions covering. Through this mapping, I show that the heterogeneity of carbon footprint depends on the emission sources, whether they result from the consumption of goods or services (indirect emissions) or the direct use of energy products (direct emissions). The distribution of emissions among the population leads to two main conclusions. The first one is that the inequalities in carbon footprint are less critical than the inequalities of income. Hence carbon taxation instruments are regressive. I find an elasticity between direct emissions and income of 0.533 versus 0.455 between indirect emissions and income. This hierarchy is reversed when looking at the elasticities of emissions with the expenditures, in which case the direct emissions are less elastic than indirect emissions (0.693 for direct emissions versus 0.762 for indirect ones). I also show that there is less horizontal heterogeneity for

indirect emissions among the same income class than for direct emissions, for which dimensions such as the type of residence or the ownership of a private vehicle are significantly more correlated.

## Chapter 2: A distributional analysis of carbon taxing in France: from micro-simulations to a general equilibrium framework

In the second Chapter of this dissertation, I focus on the distributional effects of carbon pricing policies on French households under different frameworks of analysis. The acceptability of carbon pricing policies has been widely studied in the literature, with a focus generally limited to direct emissions and not systematically addressing the general equilibrium effects at plays (Rausch et al., 2011). It is well known that carbon pricing policies tend to be regressive with income in developed countries (Ohlendorf et al., 2021) and therefore are prone to increase the risk of public rejection (Klenert et al., 2018). Redistribution schemes through direct rebates can attenuate these regressive impacts (Pomerleau and Asen, 2019) but are less efficient than other recycling schemes (Rausch et al., 2011; Rausch and Reilly, 2015; Klenert et al., 2018), showing a clear trade-off between efficiency and equity. How does integrating general equilibrium effects affect the results associated with the redistributive impacts of carbon pricing policies? Beforehand, I conduct micro-simulations and show the differential effects of a tax on direct and indirect emissions. I then introduce several mechanisms for redistributing the tax revenues, depending on whether they are lump-sum, associated with the household's income class, and finally, according to its income. I also introduce the effects associated with taking into account the price response of households depending on whether their behavior is considered similar for the whole population or income class dependent. To this end, I show that a redistribution policy based on an income criterion can reverse the initial regressivity and be considered sufficiently targeted by taking the income criteria for classes of households. Adopting a CGE framework, I integrate a distinction of households into several income classes. Using an Almost Ideal Demand System model (Deaton and Muellbauer, 1980) of microdata, I estimate specific reactions by class of income and

for a set of differentiated products. I show that a direct rebate redistribution mechanism can offset the short-term regressive effects associated with the introduction of a carbon tax but that in the long run, technological changes in the productive sector and households' adaptation to the new price system cancel them out.

**Chapter 3: Empirical estimates of the elasticity of substitution of a KLEM production function without nesting constraints: The case of the Variable Output Elasticity-Cobb Douglas.**

In the third and final Chapter of this thesis, I explore the issue of the empirical estimation of input substitutability within the production function and its impact on CGE model simulation results. In this Chapter, I attempt to expose the bias that the choice of a specific nested production function brings to the results of econometric estimates of elasticities of substitution and, consequently, to the results from simulations conducted with a CGE and calibrated on these parameters. Indeed, CGE model results are highly sensitive to assumptions made on the distribution of exogenous parameters, notably elasticities of substitution between energy and other inputs (Jacoby et al., 2006; Antimiani et al., 2015). A body of applied econometric studies has attempted to provide empirical estimates of the level of substitution between factor inputs using different production function forms, such as Translog (Koetse et al., 2008) or, more recently, CES forms (Lagomarsino, 2020). The CES framework has the advantage of being consistent with macroeconomics theory but requires imposing how inputs are nested within the production function. The choice of the nesting structure remains left up to the author's discretion and his own assumption, which leads us to ask ourselves which form is preferable.

In order to overcome this limit, we adopt a generalized form of the production function called the Variable-Output Elasticity Cobb-Douglas (Reynès, 2019). It is a flexible form of the Cobb-Douglas production function, which provides a generalization of the CES functional form to the case where the Elasticity of Substitution (ES) between each pair of inputs is not equal (McFadden, 1963). Using an original and consistent panel dataset from the WIOD 2016 Release and from which all the variables (prices and quantities) used in the estimation are derived, we perform

econometric regressions for different production nesting structures, one unconstrained and two constrained nests of the production function. Our results shed additional light on the controversy over the substitutability between capital and energy by the contribution of the VOE-CD production function in econometric estimations of ES between inputs for several specifications of a KLEM production in relaxing the constraint imposed by the CES on the choice of the applied nest structure. When applied to energy and carbon policy simulations, the results diverge substantially according to the calibration of the model. In this regard, the VOE-CD specification could be considered a relevant alternative for CGE models to calibrate their parameters of ES between inputs.

# Chapter 1

# Quantifying the global and distributional aspects of the French carbon footprint

## 1.1 Introduction

The scientific recognition of Climate Change as a significant concern for humanity's well-being eventually led in the past decades to a progressive mobilization of the international community, which pledged in 2015 to stabilize the temperature increase at the end of the century between 1.5 °and 2 °C compared to the prior-industrial era with the Paris agreement. This ambitious goal could ultimately only be achieved by phasing out or compensating with carbon sinks every source of anthropogenic Greenhouse Gases (GHG) emissions between 2044 and 2100, depending on the target and the uncertainty range associated with the scenario (Tollefson, 2018). The shortness of the time frame and the unprecedented effort to bring down emissions calls for a high level of coordination between the different parties, which can only be achieved through a shared view on the measure of the emissions in order to track their evolution, and therefore adapt climate policies. Mitigation measures adoption and tracking rely on the existence of an effective and transparent information system for carbon accounting.

Carbon accounting mainly emerged in the wake of the Earth's summit in 1992 and has been enhanced by the Kyoto protocol signature in 1997, which states that the Annex-A countries must submit National Emissions Inventories (NEI) in a consistent and harmonized framework. These national emissions inventories integrate territorial emissions, and their scope is evolving in the function of the knowledge and the technologies to monitor emissions of different types and from different sources.[1]

This main accounting framework for GHG emissions is elaborated from a Producer-Based (PB) approach, which considers allocating emissions to the territory where they occur. It has since been widely developed (Eggleston et al., 2006) and, through the annual publication of inventories, serves as the leading indicator to

[1]The 2006 IPCC guideline was refined in 2019 with several improvements brought to the data collection process, the methodologies used for specific sectors, and the revision of some emissions factors based on up-to-date scientific observations.

track the effectiveness of climate policy measures implemented at the national level. However, this approach is incomplete in investigating several issues, such as the bulk of emissions associated with international trade or the contribution of final consumers' modifications in their preferences and consumption pattern to global emissions.

The Consumer-Based (CB) approach, which adopts the viewpoint of the final demand, would be more adapted to answer such questions since it proceeds to allocate emissions to the final consumers. It is generally called *carbon footprint* [2]. Whether this opposition raises ethical issues regarding the responsibility of the different agents (Steininger et al., 2014), it firstly aims at establishing a consistent accounting framework between consumption behaviors and their impacts on the level of GHG emissions. It also induces a technical challenge in that CB emissions accounting supposes an additional data set to map the international flows of emissions worldwide (Peters, 2008).

These two approaches should be considered extreme cases of emissions allocations, and it exists a continuum of possible allocations between them (Ferng, 2003; Gallego and Lenzen, 2005; Rodrigues et al., 2017). It is noted that besides these approaches, other alternative methodologies of emissions allocation among economic agents are possible. One possible way would be to allocate the GHG emissions from the fossil fuels combustion to the extractor countries, independently of the global value chain in which they are entangled (Davis et al., 2011). Another way would be to privilege an income formation criterion and how the added value is shared between labor, capital owners, and government or other economic agents (Marques et al., 2012). *In fine*, the possibilities of allocation are numerous and highlight different viewpoints of allocation methodologies. Choosing one over another in framing public policies or defending a position in international negotiations depends more on political and

[2] According to the fourth report from the Intergovernmental Panel on Climate Change (IPCC) *"there is no single accepted carbon footprinting methodology (...), nor is there one widely accepted definition of carbon footprint"* (Eggleston et al., 2006)[p 306]. For a more elaborate discussion, see Wiedmann and Minx (2007).

operational motivations than methodological ones (Steininger et al., 2016).

The development of Environmentally Extended Multi-Regional Input-Output (EE-MRIO) is a way to overcome these obstacles by providing a global framework constructed on the Supply-Use table of the world economy, which can distinguish countries or regions of countries, activities of production, and products. These databases allow for accounting for the carbon footprint by acknowledging the global value chain structure and, therefore, could discern emissions by geographical origin, product type, and consumer use. Several EE-MRIOs projects have been implemented in the past decade, the most developed being EXIOBASE (Stadler et al., 2018; Tukker et al., 2009), WIOD (Timmer et al., 2015), EORA (Lenzen et al., 2013) and GTAP (Andrew and Peters, 2013). These databases differ between their sectoral decomposition, the environmental satellite stressors associated, the base year, the geographical coverage, or how they proceed to solve the data inconsistencies. However, some flaws, such as their *black box* structure, prevent it from being a sound and consensual tool even if we currently observe convergences and ongoing harmonization in this field (Moran and Wood, 2014). Nevertheless, it proposes a unified and integrated accounting framework in which several allocation methodologies can be associated and helps to frame the space of negotiations of the GHG emissions reduction effort sharing. This question regularly addressed during the Conference of Parties and representing the bulk of the international negotiations, directly summons the concept of climate justice. The recognition of *common and differentiated responsibilities and respective capabilities* (CBDR-RC) enshrined in the 1992 UNFCCC treaty serves as a basis to acknowledge global warming being an ethical and political issue beyond its climatic and environmental features.

Many studies and research have addressed the link between income and emissions inequalities both from theoretical and empirical approaches. The concept of *"Environmental Kuznets Curve"* (EKC) originally proposed by Grossman and Krueger

(1991) states that decoupling between environmental pressure and income can be observed up to a certain level of income per capita[3].

Ravallion (2000) integrates within-country inequalities into the cross-study empirical analysis of the EKC conjecture and finds a non-linear concave relationship across countries between carbon emissions and average income, suggesting for middle-to high-income levels a declining trend of emissions. This study, among others (Heerink et al., 2001) provides some empirical elements of the possibility of the EKC at an individual level, even if the results in cross-countries analysis remain mixed (Jorgenson et al., 2016; Grunewald et al., 2017). This question of the household's carbon emissions' infra-country distribution has been addressed in several studies mobilizing micro-data on households. The first strain of the literature focuses on the distribution of direct emissions since they are directly encompassed in NEI and do not require mapping the international emissions flows. For France, we can cite the papers by Douenne (2020a) regarding direct emissions associated with transportation and by Berry (2019) broadening the range to direct emissions associated with residential heating purposes.

The second branch, developed more recently, aims to map a complete set of emissions induced by the households' final consumption and integrate indirect emissions resulting from production activities in the analysis. It started with the initial study proposed by Wier et al. (2001) that incorporates an estimate of indirect emissions factors to final consumption[4] and has sensibly grown in the past years with publications on this topic for a wide range of countries[5]. Among the numerous publications

[3]The EKC states that the relationship between emissions and income per capita follows an inverted U-shape, increasing with income up until a certain point and decreasing afterward. This concept is differentiated between a *strong* version where environmental pressure per head is reduced in absolute terms and a *weak* version where this decoupling is only observed in relative terms. If the *strong* version remains a surmise, some countries have experienced a relative decoupling of their emissions with their income level in the past decades (Churchill et al., 2018). For an extensive review, see Stern (2004).

[4]There is no distinction of households distribution in this analysis.

[5]The reader can refer to the survey of literature conducted by Pottier (2021).

on this subject, we can highlight the study of Weber and Matthews (2008), which was the first to propose such an analysis segmenting the population into different classes and provide estimates of the carbon footprint for each of them. Authors found an average estimate of 50 $tCO_2$ per US household with a carbon footprint-income elasticity[6] of 0.52. These results echo another study on Swiss households (Girod and de Haan, 2010), which finds a GHG emissions-expenditures elasticity of 0.94 when taking expenditures and 0.53 when taking directly functional units (such as person kilometers, housing surface, and Kg of food). This last study raises the question of the best variable to infer emissions and raises the debate between top-down and bottom-up estimations methods. On the one hand, top-down economic variables are more tractable and benefit from a more widespread diffusion of statistics. On the other hand, bottom-up-based estimates have the advantage of disentangling the environmental impacts of products from their market price and therefore are more capable of providing more sound estimates of their impact on GHG emissions. However, this latest approach supposes applying such methodology thoroughly for each identified product and process of production, which in the case of a general mapping of emissions flows, is tedious to apply systematically.

Regarding the French case, Pottier et al. (2020) estimate the distribution of the carbon footprint for households, using official intensity factors issued by the public administration for the indirect emissions and combining Households Budget Statistics micro-data with specific micro-data sets on transportation and energy uses. On our side, we proceed to calculate these intensity factors for indirect emissions from an EE-MRIO rather than using the decomposed national input-output methodology[7] (Pasquier, 2016) carried on by the office of statistics of the french environment

[6]The carbon emissions-income elasticity states by how much the emissions increase with the income. An elasticity of 0.5 states that the carbon emissions increase by 0.5% when the household's income increases by 1%.

[7]In a recent publication (Malliet, 2020), we highlighted the biases that this methodology bears on the estimation of these intensity factors with respect to a multi-regional input-output analysis.

minister[8] in charge of the production of these estimates.

The issue of the carbon footprint and, more generally, the mapping of emissions from an international perspective toward a final individual imputation is important in identifying the abatement potential from shifting consumption patterns and assessing emissions inequalities between countries and among its population.

The objective of this paper is twofold, first, assessing the structure of international flows of emissions induced by the aggregate French consumption, and second, how this carbon footprint is distributed within the population depending on different socio-economic criteria.

The first section presents the methodology applied to compute the aggregated carbon footprint and how individual carbon footprints are calculated. Then, we present the data sources used to proceed with the calculations for the case of France. In the third section, we present results and descriptive statistics. In the fourth section, we proceed to econometric estimations of elasticities of emissions with respect to different variables. The fifth section concludes.

[8]Service de la donnée et des études statistiques (SDES) - Ministère de la Transition Écologique et Solidaire.

## 1.2 Methodology & data

In the following section, we define and explain the scope of the carbon footprint we consider in this study, the input-output methodology applied to calculate it, and its link with the micro-data related to the households' expenditures.

### General approach

The total carbon footprint reflects the consumption-based emissions principle and consists of two components: (i) indirect emissions and (ii) direct emissions. Indirect emissions are those generated throughout the value chain of a product, from the extraction of raw materials and the production of intermediary goods to transportation toward the final consumer. Indirect emissions occur at a source owned or controlled by another identity. Direct emissions include emissions generated by the final consumer through the combustion of energy products.

We also bring another component to this dichotomy between direct and indirect emissions by breaking down indirect emissions into two components. Production emissions are the indirect emissions induced by the final good production process. In contrast, grey emissions are indirect emissions, which are not emitted by the final good production activity but are induced by upstream activities onto the global value chain.

Three main approaches exist to estimate carbon footprint; (i) the monetary approach, which relies on monetary flows associated with emissions multipliers, (ii) the physical approach, sometimes referred to as life-cycle assessment, which uses estimates of the physical units of good and services consumed, associated with emissions multiplier per physical unit, (iii) a hybrid approach combining the first two. We rely in this study on a monetary approach to calculate the carbon footprint, using monetary flows associated with emissions intensity factors determined through

an environmental extended input-output model. Whereas the physical approach excels in the measurement of emissions intensity ratios, the advantage of the monetary approach is to map the inter-relations with other economic actors and ensures consistent results with the accounting framework. One limitation of this approach is that it does not encompass a *quality effect* since carbon emissions are inferred by the level of expenditures (Girod and de Haan, 2010).

We can express the household's $h$ total carbon footprint $f_h^{CF}$ as the full extent of the climatic pressure that the consumption of a product and the use of services (both public and private) causes. It includes direct emissions, which can be characterized by spatial and temporal synchronicity with the combustion of fossil fuel energy products, generally serving transportation and heating purposes. Indirect emissions $f_h^{indirect}$ result from the combination of different actors from different countries.

In the scope of the indirect emissions, we also consider the ones induced by the consumption from the public administration $f_h^{public}$. Since these latest provide services that benefit all the citizens of a country and therefore are tedious to be individualized, we equally split this *collectivized* carbon footprint between all households. Finally, we consider that the total carbon footprint is the sum of all the emissions that are related to the consumption of a commodity $c$[9]

Using the notation from Isaksen and Narbel (2017), we can express the total carbon footprint of a household such as:

$$f_h^{CF} = \sum_c f_{h,c}^{direct} + \sum_c f_{h,c}^{indirect} + \sum_c f_{h,c}^{public} \tag{1.1}$$

We express the footprint as the product of an intensity factor $e_c$ defined as the ratio between the volume of emissions induced by the consumption of one monetary unit of the good $x_c$, and this for all sources (direct, indirect, public).

$$e_c = \frac{f_c}{x_c} \tag{1.2}$$

[9]The distinction by commodities allows highlighting the differences of consumption structure on the final carbon footprint

Which yields:

$$f_h^{CF} = \sum_c (e_c^{direct} + e_c^{indirect} + e_c^{public})\ x_{h,c} \tag{1.3}$$

The indirect emissions intensity factor $e_c^{indirect}$ can also be further break-downed to take into account (i) the country where the emissions are located and (ii) at which stage on the global value chain they are released. We can disentangle the indirect emissions $f_{c,h,o}^{production}$ which result from the production process of the final good $c$, produced in the country $o$ and consumed by the household $h$ to the emissions resulting from all the upstream activities which have been indirectly required in this process of production and that we denote $f_{c,h,o}^{gray}$. Formally and combining these two dimensions (geographical and stage of the global value chain), we can express the intensity factor of indirect emissions such as:

$$e_c^{indirect} = \sum_o e_{c,o}^{indirect} = \sum_o (e_{c,o}^{production} + \sum_o e_{c,o}^{gray}) \tag{1.4}$$

**The indirect emissions**

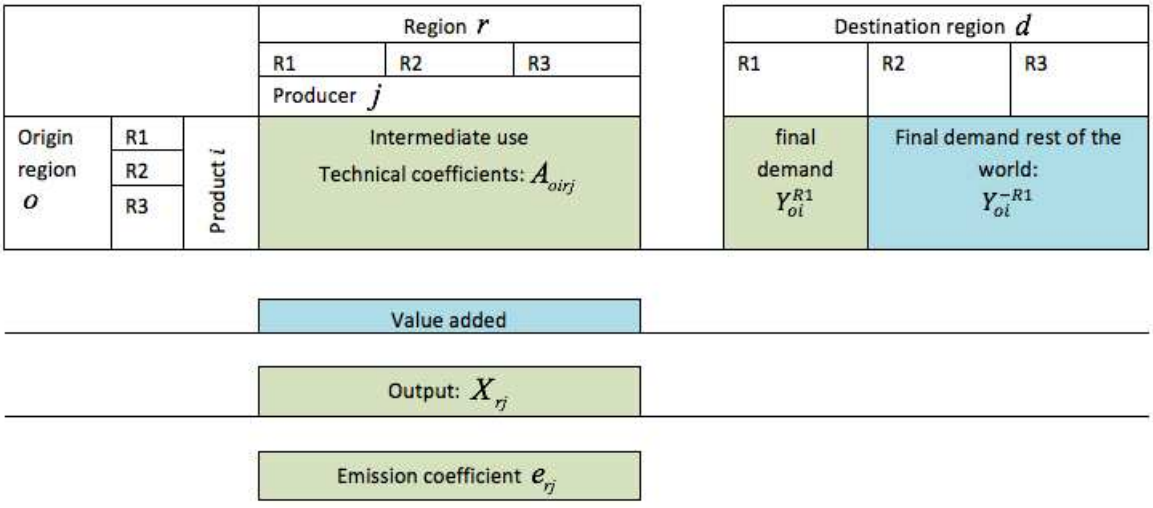
We use the Leontief input-output model extended to environmental analysis (Leontief, 1970; Lipnowski, 1976) to calculate these intensity factors for the indirect emissions. The main distinction that brings a MRIO with respect to a national Input-Output Table (IOT) is in its representation of the rest of the world economy, which is fully mapped in terms of inter-industrial and inter-country relations. The MRIO enumerates the vector of total annual sales ($X$) of different regions $r$ representing the world economy and decomposes in several sectors $j$ to either an intermediate demand from the supply-side $Z$ or the $k$ group of final consumers represented in the matrix of the demand-side $Y$:

$$X = Z + Y \tag{1.5}$$

where element $X_{rj}$ from output vector $X$ stands for the output production in the region $r$ and sector $j$, $Z_{oi,rj}$ from intermediate use matrix stands for the use by the

sector from region $o$ producing $i$ and using inputs from sector $j$ of the region $r$, and with element $Y_{oi,k}$ of the vector $Y$ stands for the final consumption of product[10] $i$ from origin region $o$ and by the group $k$. We can express this accounting identity by calling $A$ the technical coefficient matrix composed of the elements $A_{oirj}$, which denotes the share of input by origin region $o$ and product $i$ in total output of producer $j$ in the region $r$ such that:

Figure 1.1: Schematic overview of a MRIO table




$$X = A.X + Y \tag{1.6}$$

Rearranging the terms yields the well-known Leontief Input-Output model equation where $(1 - A)$ is the Leontief matrix:

$$X = (1 - A)^{-1} Y = L Y \tag{1.7}$$

The environmental satellite element $S_{rj}^{s}$ from matrix $S$ expresses the total emissions output of the greenhouse gas $s$ induced by the activity of production $X_{rj}$. Using the vector of emissions intensity per unit of output $e^{s}$ :

$$e^{s} = S^{s} \hat{X}^{-1} \tag{1.8}$$

[10]We adopt here a different notation for the products index, namely $i$ than in the equation 1.1 because the nomenclature of products is different than from the households expenditures.

We can derive the coefficient vector representing emissions $f^s$ induced by the final consumption of one unit of a product. through the Leontief matrix and the matrix $\hat{e}^s$ obtained by diagonalization[11] of the vector $e^s$

$$f^s = \hat{e}^s \; L \; Y = \hat{e}^s \; (1 - A)^{-1} \tag{1.9}$$

Where element $e^s_{rj}$ in emission coefficient vector $e$ denotes the multiplier of emissions of type $s$ in kg per euro of output by region $r$ and sector $j$. Finally, we can derive the emissions induced by the final demand of a country $d \in r$ on the total emissions for the world economy.

$$F^{s,d} = \hat{e}^s \; L \; \hat{Y} = \hat{e}^s \; (1 - A)^{-1} \; \hat{Y}^d \tag{1.10}$$

where element $F^{s,d}_{rj,oi}$ in the emissions footprint matrix $F^{s,d}$ stands for the emissions of source $s$ emitted (due to the destination country $d$ consumption) by sector $j$ from region $r$ to produce $i$ in region $o$.

To obtain the indirect emissions footprint per product $i$ from country $r$ and consumed in the country $d$, we sum over the rows for regions and over the rows for sectors in the Input-Output matrix:

$$F^{s,d,indirect}_{ri} = \sum_{oj} F^{s,d}_{rj,oi} \tag{1.11}$$

Alternatively, we can allocate the indirect emissions to the last exporting region by summing the matrix over the rows for both products and regions:

$$F^{s,d,indirect}_{oi} = \sum_{rj} F^{s,d}_{rj,oi} \tag{1.12}$$

The distinction between production and gray emissions relies on the economic interrelations between firms, which will be captured in the inter-industrial transaction matrix. A Taylor's series expansion can approximate the Leontief matrix by adding

[11] matrix diagonalization yields $\hat{B} = IB$.

to the identity matrix $I$ the technical coefficient matrix $A$, successively raised to increasing powers:

$$L = I + A + A^2 + A^3 + \cdots + A^n \tag{1.13}$$

The production emissions are those induced by the intermediate consumption of the sections, which are the direct requirements for the production and, therefore, can be determined from equation 1.13 by applying an expansion of the series to the power one.

$$L^P = I + A \tag{1.14}$$

Replacing the Leontief matrix in equation 1.10 yields:

$$F^{P,s,d} = \hat{e}^s \; L^P \; \hat{Y}^d \tag{1.15}$$

Reversely, gray emissions are upstream on the global value chain and correspond to the difference between the total footprint $F^{s,d,indirect}$ and the emissions due to the production of the final good $F^{P,s,d}$.

$$F^{G,s,d} = F^{s,d} - F^{P,s,d} \tag{1.16}$$

### The direct emissions

The carbon intensity factor for direct emissions can be determined in two ways. Either from a bottom-up approach, by taking emissions factors associated with physical units of energy products, or from a top-down angle, by taking the monetary amount of sales of energy products and the aggregate emissions associated with their use. We rely here on the second approach, taking calculating the ratio between the direct emissions $E_i^{s,direct}$ and the final demand $X^d$.[12]

[12]Energy products induced both direct emissions from their consumption and indirect emissions from their production.

**The emissions accounting**

The total carbon footprint is the sum of the emissions by source $s$ (expressed in physical units) and translated in $CO_2$ equivalent metric ($CO_2e$) according to their Global Warming Potential(GWP) ratio to $CO_2$. This ratio is defined as the warming impact on the climate of a greenhouse gas relative to the one induced by a Kg of $CO_2$ and for a 100 years horizon. This ratio is denoted $\zeta^s$, and we rely on official data from the IPCC $4^{th}$ report.

$$F_i = \sum_s F_i^s \, \zeta^s \tag{1.17}$$

Conversely, the relation holds for the carbon emissions factors:

$$e_i = \sum_s e_i^s \, \zeta^s \tag{1.18}$$

The relation between the aggregate carbon footprint at the country level and the household footprint will depend on the assumption that the regional composition of households' final consumption is the same for every household. There is no heterogeneity in terms of emissions intensity factor by product between the households. It means that households' heterogeneity in carbon footprint will depend on the structure of their expenditures and their level.

By ensuring the accounting consistency between the macroeconomic variables, and the aggregation of the micro-data, we can directly apply these emissions factors to each household's expenditures as stated in the equation 1.1. In the next part, we will clarify the features of the data sets we use and how we combine them to produce estimators of individual footprints.

## Data

### The emissions factors

As mentioned in the previous part, we rely on the Environmental Extended Multi-Regional Input-Output database EXIOBASE[13] (Stadler et al., 2018) to calculate the carbon footprint factor for indirect and public emissions. The core of the model is an Input-Output table representing the flow of 200 goods and services (products) throughout the global economy segmented into 49 regions[14] from which 44 are identified countries.[15] The associated environmental satellite accounts for 60 types of substance or environmental impacts, from which we extract climate impacts classified in 23 indicators indexed by their type of GHG ($CO_2, CH_4, N_2O, SF_6, HFCandPFC$). We cover the year from 2000 to 2018 and specify our analysis concerning the infra-country distribution for the year 2011[16].

### The households' expenditures

$e_c^{direct}$ is obtained by using the National Accounting Matrix Including Environmental accounts (NAMEA) table for the year 2011 for France, divided by the aggregate households' final consumption expenditures. (Commission, 2010). It provides us with an average carbon intensity of one EUR of expenditures for energy products used for transportation and heating purposes. In order to calculate the carbon footprint of French households, we use the Household Budget Survey (INSEE,2011), which provides representative data on households' expenditures, among other socioeconomic variables.

Before matching it with the GHG emissions factors computed in the previous

[13]We used the 3.8 version, which can be retrieved from this repository: https://doi.org/10.5281/zenodo.3533196.

[14]The term *region* in this paper covers a delimited territory, when existing which corresponds to a country, or the aggregation of several countries.

[15]Together these 44 countries account for approximately 89% of global gross domestic product (GDP) and between 80% and 90% of the trade flow by value within Europe.

[16]All results are in $MtCO_2e$ and millions of euros.

sections, we first proceed to a rescaling of the aggregate consumption by COICOP groups computed from the national accounting value survey. Several possible biases result from the confrontation of survey data and national accounting that could result from differences in concepts (methods of the collection), differences in perimeter ( choice of product nomenclature), and differences in the field (territory and households concerned)(André et al., 2016).

Following Ruiz and Trannoy (2008), we proceed to a correction of this aggregate consumption calculated from the weighted sum of the sample of observations at the COICOP 2 level (37 products) with the national accounts expenditures data. It is a crucial step if we want to keep consistent the carbon intensity factor derived from the MRIO with the individual expenditures in the Households Budget Survey. Table 1 exposes the relative differences observed in consumption expenditures.

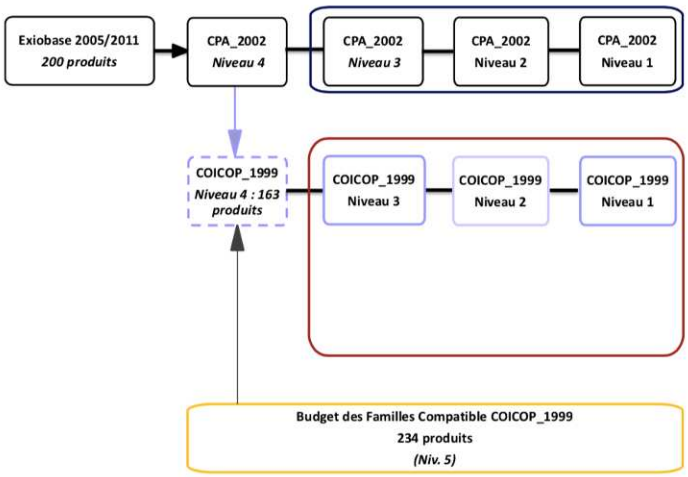
Table 1.1: Correction of consumption expenditures data

| | Products | Amount of National Accounting | Amount of BdF | Rate of coverage (in %) |
|---|---|---|---|---|
| 1 | Food and non-alcoholic beverages | 124.18 | 138.20 | 0.90 |
| 2 | Alcoholic beverages and Tobacco | 22.44 | 35.64 | 0.63 |
| 3 | Clothing and footwear | 38.04 | 42.63 | 0.89 |
| 4 | Housing, water, gas, electricity and other fuels | 118.17 | 119.41 | 0.99 |
| 5 | Furnishing, household equipment and routine maintenance of the house | 44.55 | 55.37 | 0.80 |
| 6 | Health | 13.65 | 16.86 | 0.81 |
| 7 | Transport | 131.10 | 140.88 | 0.93 |
| 8 | Communications | 25.10 | 34.78 | 0.72 |
| 9 | Recreation and culture | 72.20 | 94.46 | 0.76 |
| 10 | Education | 5.00 | 8.95 | 0.56 |
| 11 | Restaurants and hotels | 49.22 | 69.03 | 0.71 |
| 12 | Miscellaneous, goods and services | 110.51 | 121.96 | 0.91 |

The French Household Budget Survey dataset contains information on 234 different goods and services classified in a nomenclature compatible with the UN Classification of Individual Consumption by Purpose (COICOP). These expenditures are segmented into 12 divisions, subdivided into groups (37 products), classes (86 products), and sub-classes (161 products). On the other hand, the EXIOBASE database and the corresponding emissions multipliers are classified under the European classification CPA 2002. Since we need to bridge the EXIOBASE CPA-based categories to COICOP 1999, we construct a bridging matrix using the correspondence tables provided by the Reference and Management of Nomenclatures (RAMON) service

provided by EUROSTAT and assume a proportional to added-value ventilation of products from CPA 2002 to COICOP 1999.[17]

Figure 1.2: Bridging structure between the products classification nomenclatures




Finally, to reduce potential biases, we perform this matching at level 4 of CPA (224 products) with COICOP classes of household expenditures (161 products).

[17]The statistical service EUROSTAT does not provide weights of each subgroup of expenditure in this upper-level of classification. Therefore we have to rely on some assumptions that could weaken the precision of the indirect emissions estimation.

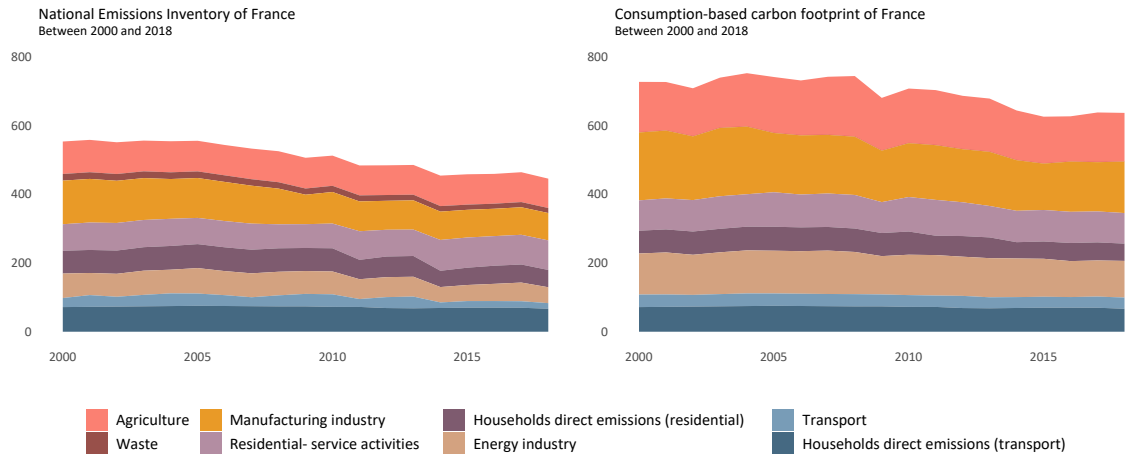
## 1.3 Results and descriptive statistics

This section presents emissions results by applying the methodology exposed in the previous section. The first part is dedicated to analyzing the national carbon footprint regarding regional and sectoral composition. We keep an activity nomenclature to present the results and be compatible with the CPA. In the second part, we focus on the distributional aspect and how is allocated this carbon footprint between the different classes of households. For this reason, we privilege a decomposition by functions of consumption adapted to the COICOP reference nomenclature.

### Aggregate results

France is structurally a net importer of emissions, with a carbon footprint higher than its territorial emissions for the whole period covered by the data (2000-2018). Whereas territorial emissions have steadily declined from 535 Mt in 2000 to 419 Mt in 2018 (a 28% decrease), a trend is less obvious to sketch regarding the carbon footprint. The emissions have remained between 751 and 624 Mt $CO_2$e, and after reaching a plateau above 700 Mt $CO_2$ between 2000 and 2011, they started to decline afterward steadily and reached 635 Mt CO2 in 2018.

Figure 1.3: Evolution of the French carbon footprint from 2000 to 2018 by main sectors



We can observe that the shares of imported emissions (for indirect emissions only) remained stable over the years and have fluctuated between 55.9% and 59.5% (see Figure 1.5). Breaking down into main sectors, it appears that agriculture products represented the largest share of imported emissions (69.4%) and have constantly been growing from 2000 when it was 58.1%. The manufacturing industry is the second largest sector in imported emissions, with a 68.3% share in 2018. Contrarily to the agricultural sector, this share has slightly decreased over the past fifteen years since its highest value was 72% in 2003. Structurally, Manufacturing industries largely depend on international suppliers and agricultural goods, for which a trend of globalization seems at stake. The production of these goods is embedded into the global value chains. Transport, Residential-services activities, and the Energy industry have a carbon footprint that is more dependent on domestic activities. Residential services activities imported emissions share has decreased, from 49% in 2003 (up to 52.5% in 2008) to 43.4% in 2018. The energy industry and transport experienced an inversed trend, with a growing share of the indirect emissions coming from abroad. Despite being slightly less than 40 % of indirect emissions in 2000, these imported emissions from the energy industry have constantly been growing since to reach 51.1% in 2018. A similar trend can be observed for transport, with a share of imported emissions increasing from 40.9% in 2000 to 47.1% in 2018.

Looking specifically to the year 2011, which is the same as in the households budget survey data, we find a total carbon footprint for France of 732 Mt $CO_2$e, for which 17.5% are direct emissions, 35.3% are domestic indirect emissions, and 47.2% are imported indirect emissions. These results are in line with official estimations using a different methodology of imported emissions accounting (Pasquier, 2016) issued by the French public administration (CGDD, 2015) The

The

The first region of imported emissions is the European Union (EU) with 73.7 Mt

Figure 1.4: Ratio between imported emissions and domestic emissions for the main sectors

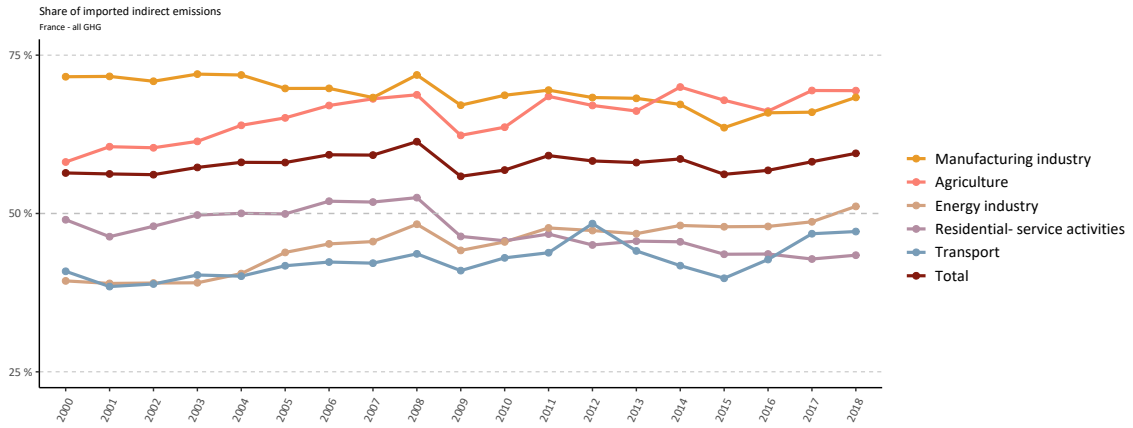
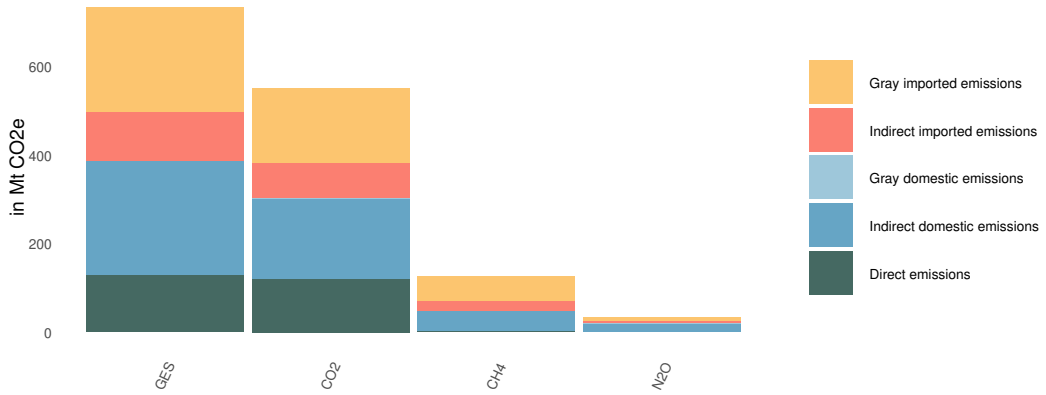



Figure 1.5: Total carbon footprint for France in 2011 by type of GHG

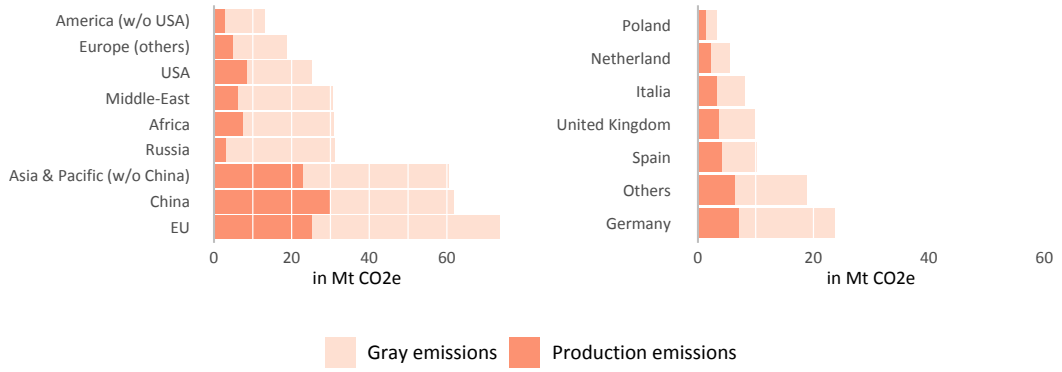



$CO_2e$ (21.36% of the total imported emissions), closely followed by China with 61.6 Mt $CO_2e$ (17.9%) and the rest of Asia with 60.5 Mt $CO_2e$. The breakdown between the production and the grey emissions for the different countries is worth noticing.

China, for instance, has the highest ratio between production and grey emissions, pinning it down as a manufacturing country (and, in a less measure, the rest of Asia and the EU). Other regions, on the contrary, have a much lower ratio stating that their emissions are mostly from upstream activities, especially for Russia and Middle-East

countries, which are the main exporters of oil and gas.

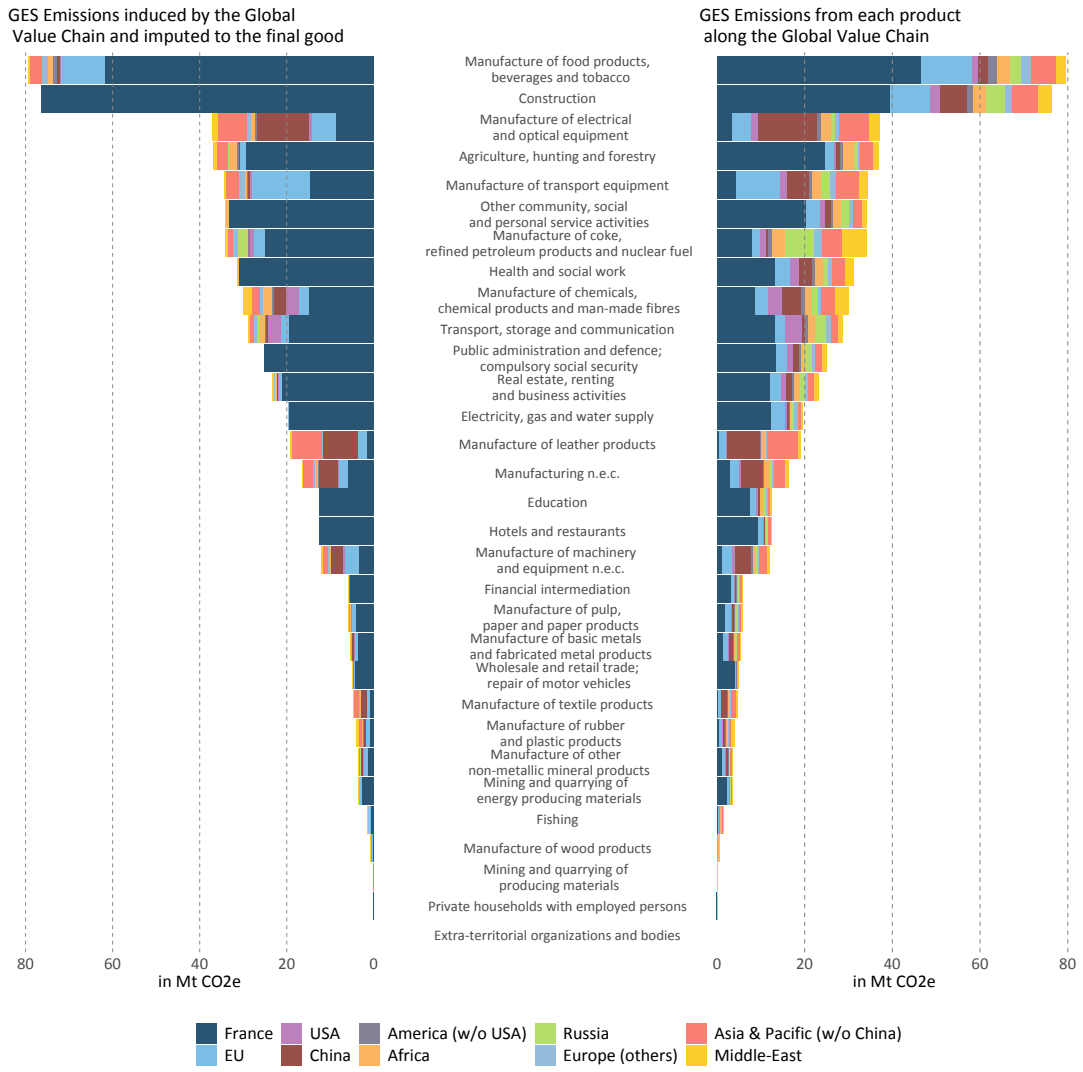
Figure 1.6: Imported GHG emissions by regional source




Looking specifically at the European countries, it appears that Germany is the primary source of imported emissions with 23,6 Mt, slightly more than twice compared to the second and third countries, Spain and Great Britain.

A significant share of France's carbon footprint comes from the food industry and the construction sector. Breaking down the structure of imported emissions by product and country provides an interesting view of the international carbon circuit, at least from the perspective of France. For electronic devices, Asia is the leading region of emissions, whereas emissions from the transport industry (car manufacturers, train builders, aeronautic industry) are much more issued from European countries. Figure 1.7 highlights that the imported emissions are mainly concentrated on some key products when accounting for the final consumption criteria, for which the tertiary sector activities constitute a significant part. It is noticeable that the primary sources of emissions, when imputed to the final goods, lead the services to represent the major share of emissions, though they are not necessarily associated with highly emitting activities. Real estate activities, professional, collective, and personal services represent nearly half the carbon footprint when one accounts for this emissions imputation. Besides services, agricultural, agro-products, steel, and metallurgy are

Figure 1.7: France Carbon footprint in 2011 decomposed by product




the other primary sources of emissions, with steel and metallurgy an import share of 63%.

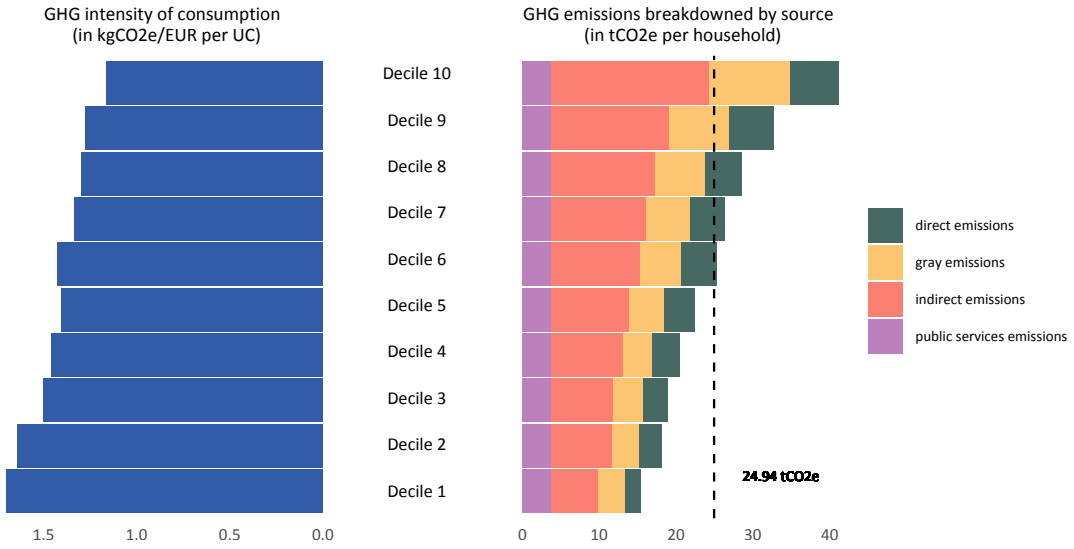
In the aggregate economy, these emissions account for 73.2% of the total indirect emissions, with some heterogeneity across sectors. For some of them (construction, public services, education), the imported emissions only result from domestic producers' final goods and services. On the contrary, for some specific goods, their final consumption is mostly imported by the consumers (Electrical and optical equipment or leather products).

The difference in the geographical origin of emissions between the two parts of Figure 1.7 pins down that the direct importations of goods and services represent a fringe of the whole carbon footprint, the final demand being mostly satisfied by domestic producers. It would indicate that the main leverages on carbon emissions reduction are on the economy's supply side. Imported emissions are a major concern nationwide, with a strong heterogeneity between sectors, and also stating the participation of French firms in a global value chain, at the European level for some specific industries, but relies even more on Asia suppliers (tables are reported in Appendix A).

## Households footprints

For the second part of this section, we will focus on the distributional aspects of the carbon footprint. Based on a reduced sample of 15007 French households[18], we use the carbon intensity factors determined from the input-output dataset per product (in a CPA nomenclature) and, through a bridging matrix, compute them on the COICOP nomenclature. The direct emissions are calculated as the product of the emissions factors and the household's expenditures for transport and heating fuels. We also add to the household carbon footprint the carbon emissions induced by the public state expenditures, equally shared among households. In a sense, we consider that the ultimate beneficiaries of the public services are its population, and for that reason, these emissions should be accounted within the households' carbon footprint scope.

Figure 1.8: Carbon footprint by decile of standard of living



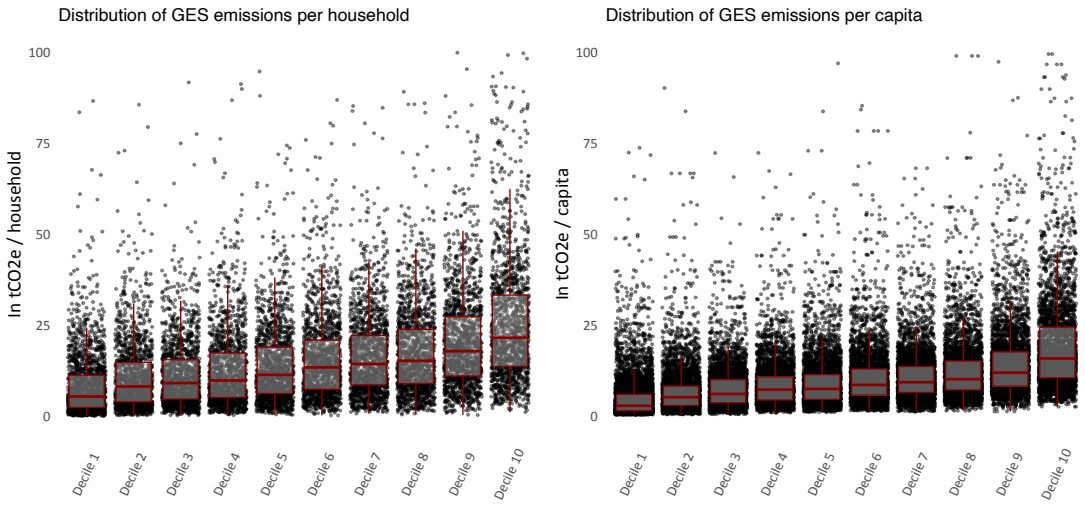

For the year 2011, we find a mean carbon footprint of 24.5 $tCO_2$ (22.9 $tCO_2$ without the emissions from the public spending) per household and 11.3 $tCO_2e$ per capita. The range starts from 15.2 $tCO_2e$ for the households in the first decile up to

[18]The original sample contains 15797 observations, we perform a census at the 2.5% threshold at the two tails to keep 95% of the observations from the original sample.

40.4 $tCO_2e$ for those in the last one (see Figure 1.8).

However, these observations with classes of income of standard of living[19] hide a firm vertical heterogeneity within each decile (see Figure 1.9 below), indicating that other dimensions could also explain this dispersion beyond the level of income. The household structure partly explains this difference since the number of Unities of Consumption [20] (UC) is strictly decreasing with the level of consumption.

Figure 1.9: Distribution of the carbon footprint by decile of the standard of living




The distribution per capita (calculated by dividing the household footprint by the number of people in each household) is slightly more homogeneous than the household distribution. The difference in the household demographic structure partly explains it. On average, low-income households are younger and more numerous than the average population.

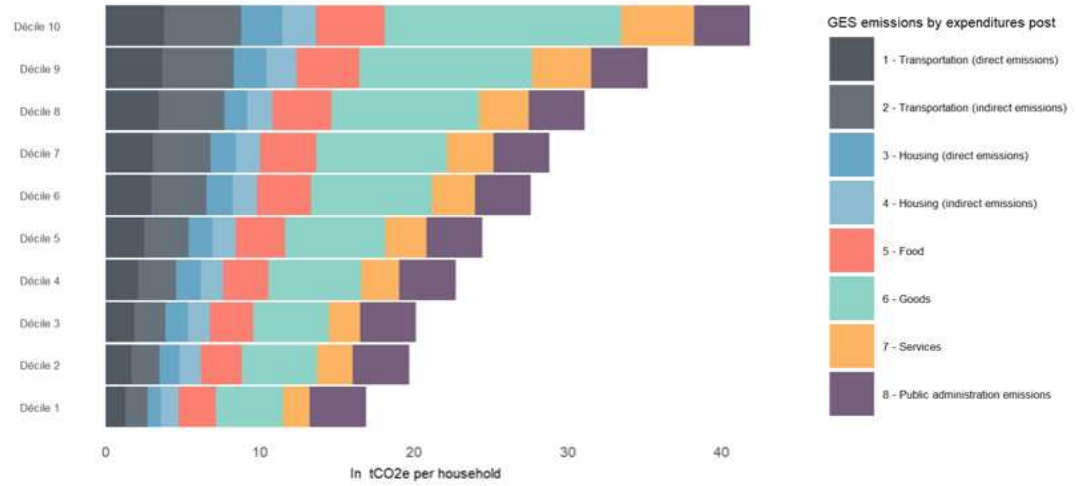
A composition effect of the expenditures in the carbon footprint structure is also at play, as shown by the left part of the figure 1.8. The households' consumption tends to

[19]For the presentation of the results, we will for the income classes adopt a segmentation by the standard of living, which is defined as the household disposable income divided by the number of unities of consumption (UC).

[20]Unity of consumption is a metric based on factors conversion applied to household members depending on their position. A first adult accounts for 1, a second adult or a child above 15 years accounts for 0.5, and a child accounts for 0.3.

become relatively less carbon-intensive with the increase in income, independently of the structure of the household. The primary goods, such as food, housing, or energy, covering basic needs are the most carbon-intensive, whereas services and recreation goods, on the other side, are among the less carbon-intensive and represent a higher share of the expenditures among the high-income households.

Figure 1.10: Decomposition of the carbon footprint by products




Looking at the decomposition by products in Figure 1.10, we find that indirect emissions are mostly due to goods consumption (this category is quite heterogeneous since it includes both equipment goods and everyday non-food related expenses). Emissions associated with transportation (both direct and indirect) are the second most important emission item with 5.13 $tCO_2e$, followed by food products with 3.35 $tCO_2e$ and housing with 3.2 $tCO_2e$. Private services represent 2.88 $tCO_2e$, whereas public services emissions account for 3.6 $tCO_2e$ (about 15% of the total carbon footprint)

The level of consumption (and indirectly the level of income) partly explains the heterogeneity of carbon footprint among the households since we also observe a wide dispersion within the standard of living income deciles. Other socioeconomic variables, such as the localization of residence or the household demographic structure,

highlight differences among the population, as shown in other studies (Nässén et al., 2015).

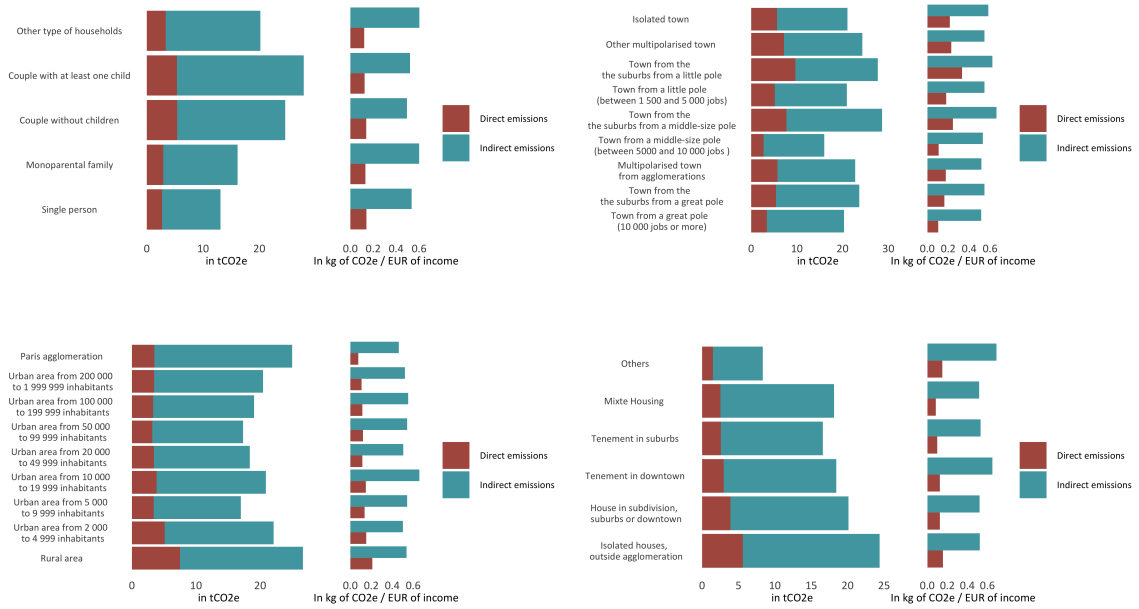
Regarding the localization of housing, several studies have addressed its impact on the carbon footprint. One of the main results is a reversed U-shaped relationship between the level of emissions and the distance to the center of an urban center (Gill and Moeller, 2018; Jones and Kammen, 2014).

For the French case, taking as the explanatory variable the size of the urban area to explain the total level of carbon footprint (direct and indirect sources of emissions), one observes a U-shaped relationship (non-reversed). Emissions decrease with the urban area's size up to towns with a lesser population than 100 000 inhabitants (except for the town with a population between 10 000 & 20 000 inhabitants). For the cities with a greater population, the emissions per household start increasing. This relation seems to be more explained by the direct emissions relative to the level of income, strictly decreasing with the size of the urban area, whereas we do not observe such a trend.

In the Household Budget Survey, there is an alternative spatial variable to the urban area's size, which is the type of area defined according to the distance of the urban agglomeration center (and for different sizes of agglomeration). For instance, a suburb city of an agglomeration with a population larger than 100 000 inhabitants will be differently coded than another city with the same population but being the center of an agglomeration. This distinction is useful since it introduces a decomposition of the urban structure relative to an agglomeration's spatial organization rather than its administratively defined population and better captures specific patterns induced by the agglomeration structure.

Figure 1.11 shows a different relationship with the carbon footprint than the previous one—the areas where the highest emissions per household are the small and middle-sized cities of an urban pole. Contrarily, households in the greatest and middle

Figure 1.11: Distribution of the carbon footprint by type of urban area of residence




pole cities have lower emissions.

The heterogeneity of carbon footprints, according to the household structure, is essential. The direct emissions vary only with the number of adults in the household (for couples with and without children), whereas the indirect emissions only vary with the total number of household members. Regarding the emissions per euro of income, on the other hand, we do not observe differences across the type of households meaning that the composition effect of the expenditures remains homogeneous across the type of households.

## 1.4 Econometric Estimations

### Cross-sectional OLS

In this section, we perform a cross-sectional econometric regression based on a multivariate log-log OLS regression modeling of GHG indirect and GHG direct emissions from French households. Formally we are going to estimate the following equations with $f$ being the GHG emissions from source $s$ (either direct or indirect); $Y_h$ the total annual income of household $h$, $EXP_h$ its annual expenditures, and $H_h$ is the household size. $Z_1$ to $Z_n$ is a set of dummy variables regarding the location of residence.:

$$\log(f_h^s) = C + \alpha^s \ \log(Y_h) + \beta^s \ \log(H_h) + \eta_1^S \ Z_h + \eta_2^S \ Z_{2,h} + ... + \eta_n^s \ Z_{n,h} + \epsilon_h \quad (1.19)$$

$$\log(f_h^s) = C + \alpha^s \ \log(EXP_h) + \beta^s \ \log(H_h) + \eta_1^I \ Z_h + \eta_2^s \ Z_{2,h} + ... + \eta_n^s \ Z_{n,h} + \epsilon_h \quad (1.20)$$

The regression coefficient $\alpha$ is the elasticity of GHG emissions with respect to household income $Y$, and $\beta$ is the elasticity of GHG emissions with respect to household size. The dummy variables can be interpreted such that when a dummy $Z$ is 1, then the exponential function of its regression coefficient ($e^{\eta}$) is a multiplier of $f$ about the reference case where $Z$ is 0.

The set of dummy variables is as follows:

- $Z_car$ takes the value of 1 when the household has at least one car and 0 otherwise
- $Z_zone_1$ takes the value of 1 when the household lives in the center of an agglomeration
- $Z_zone_2$ takes the value of 1 when the household lives in a suburb of an agglomeration
- $Z_zone_3$ takes the value of 1 when the household lives in the suburbs of a multi-centers agglomeration

The reference case is areas located outside of an agglomeration. Integrating these dummies could be reversed and based on other variables, such as the size of the urban area. From the previous section, we saw that the heterogeneity in carbon footprints was specific to this segmentation, so we integrated them into the regression. To check for endogeneity, we compute the correlation matrix and find no strong correlation between the explanatory variables.

We perform a variance inflation factor (VIF) for the two model specifications to test the collinearity between the quantitative variables. The VIF measures how much the variance of an estimated regression coefficient increases because of collinearity. It is generally recommended to drop variables for which the VIF is higher than 10. From Table 1.2, we can see that all quantitative variables ($\log Y$, $\log C$, $\log H$) are below this threshold and therefore do not induce excluding one of them from the regression.

Table 1.2: Variance Inflation factor test

| | log.Y | log.D | Z_car | Z_zone1 | Z_zone2 | Z_zone3 |
|---|---|---|---|---|---|---|
| Specification with income | 1.46 | 1.16 | 1.32 | 5.29 | 4.35 | 2.68 |
| Specification with expenditures | 1.37 | 1.14 | 1.26 | 5.30 | 4.35 | 2.68 |

The following table summarizes the estimation for these two specifications. The estimated parameters are almost all significant at the 1% threshold except for the spatial dummies in some cases. $Z_zone_1$ (living in centers of agglomeration) is non-significant in the specification explaining the indirect emissions in the consumption function, whereas $Z_zone_2$ (living in suburb areas) is only significant regarding the indirect emissions when related to both income and consumption. The four specifications exhibit a positive elasticity between GHG emissions and the level of consumption and income. When the consumption increases by 1% (respectively to the income), the direct emissions increase by 0.69% and the indirect emissions by 0.76% (respectively of 0.53% for the direct emissions and 0.45% for the indirect emissions) when controlling for the zone of residence and the ownership of a private vehicle. It is noted that

direct emissions are much less explained by the dependent variables selected in this regression than for the indirect emissions, its $R^2$ being within 0.26 and 0.29 (resp. for income and consumption explanatory variables). In contrast, the $R^2$ for indirect emissions is within 0.42 and 0.73 (resp. for income and consumption explanatory variables).

Table 1.3: Estimation for the regressions on the full sample

| | *Dependent variable:* | | | |
|---|---|---|---|---|
| | log.f_ED | log.f_EI | log.f_ED | log.f_EI |
| | (1) | (2) | (3) | (4) |
| log.C | 0.693*** | 0.762*** | | |
| | (0.021) | (0.005) | | |
| log.Y | | | 0.533*** | 0.445*** |
| | | | (0.024) | (0.008) |
| log.D | 0.182*** | 0.206*** | 0.293*** | 0.411*** |
| | (0.044) | (0.010) | (0.045) | (0.015) |
| Z_car | 1.669*** | 0.227*** | 1.795*** | 0.475*** |
| | (0.038) | (0.009) | (0.040) | (0.014) |
| Z_zone1 | −0.283*** | 0.008 | −0.203*** | 0.124*** |
| | (0.072) | (0.017) | (0.073) | (0.025) |
| Z_zone2 | −0.060 | 0.047*** | −0.036 | 0.099*** |
| | (0.077) | (0.018) | (0.078) | (0.027) |
| Z_zone3 | 0.079 | 0.017 | 0.080 | 0.044 |
| | (0.085) | (0.020) | (0.087) | (0.030) |
| Constant | −0.970*** | 1.529*** | 0.351 | 4.253*** |
| | (0.200) | (0.047) | (0.231) | (0.079) |
| Observations | 15,007 | 15,007 | 15,007 | 15,007 |
| $R^2$ | 0.285 | 0.734 | 0.257 | 0.422 |
| Adjusted $R^2$ | 0.285 | 0.734 | 0.257 | 0.422 |
| Residual Std. Error (df = 15000) | 1.784 | 0.421 | 1.819 | 0.621 |
| F Statistic (df = 6; 15000) | 998.248*** | 6,912.048*** | 864.557*** | 1,823.694*** |
| *Note:* | | | | *p<0.1; **p<0.05; ***p<0.01 |

To differentiate the effects by income, we perform the same regression on the standard of living income subgroups. The results are presented in the tables below.

Table 1.4: Elasticities for indirect emissions by decile of income

| | *Dependent variable:* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | log.f_EI | | | | | | | | | |
| | Decile 1 | Decile 2 | Decile 3 | Decile 4 | Decile 5 | Decile 6 | Decile 7 | Decile 8 | Decile 9 | Decile 10 |
| log.C | 0.819*** | 0.843*** | 0.782*** | 0.729*** | 0.717*** | 0.684*** | 0.616*** | 0.656*** | 0.643*** | 0.665*** |
| | (0.010) | (0.016) | (0.017) | (0.017) | (0.017) | (0.017) | (0.017) | (0.017) | (0.018) | (0.020) |
| log.D | 0.153*** | 0.168*** | 0.241*** | 0.238*** | 0.213*** | 0.306*** | 0.375*** | 0.342*** | 0.287*** | 0.245*** |
| | (0.022) | (0.029) | (0.031) | (0.033) | (0.034) | (0.035) | (0.036) | (0.039) | (0.039) | (0.047) |
| Z_zone1 | 0.017 | −0.003 | −0.014 | −0.069 | −0.034 | 0.015 | 0.046 | −0.048 | −0.007 | 0.081 |
| | (0.041) | (0.045) | (0.047) | (0.043) | (0.051) | (0.055) | (0.055) | (0.065) | (0.069) | (0.091) |
| Z_zone2 | 0.048 | 0.077 | 0.052 | −0.051 | −0.009 | 0.087 | 0.073 | 0.048 | 0.012 | 0.038 |
| | (0.044) | (0.050) | (0.052) | (0.048) | (0.055) | (0.058) | (0.058) | (0.068) | (0.072) | (0.094) |
| Z_zone3 | −0.001 | −0.034 | 0.047 | −0.021 | 0.015 | 0.054 | 0.062 | −0.005 | −0.022 | 0.040 |
| | (0.054) | (0.056) | (0.055) | (0.053) | (0.059) | (0.063) | (0.063) | (0.075) | (0.078) | (0.103) |
| Z_car | 0.210*** | 0.188*** | 0.161*** | 0.221*** | 0.244*** | 0.236*** | 0.183*** | 0.202*** | 0.158*** | 0.132*** |
| | (0.021) | (0.024) | (0.024) | (0.026) | (0.028) | (0.031) | (0.035) | (0.037) | (0.042) | (0.046) |
| Constant | 1.041*** | 0.755*** | 1.333*** | 1.871*** | 1.962*** | 2.231*** | 2.924*** | 2.632*** | 2.885*** | 2.703*** |
| | (0.095) | (0.147) | (0.157) | (0.156) | (0.161) | (0.170) | (0.176) | (0.179) | (0.190) | (0.217) |
| Observations | 2,682 | 1,563 | 1,515 | 1,483 | 1,519 | 1,557 | 1,573 | 1,546 | 1,569 | 1,168 |
| $R^2$ | 0.813 | 0.753 | 0.710 | 0.711 | 0.683 | 0.668 | 0.605 | 0.624 | 0.574 | 0.604 |
| Adjusted $R^2$ | 0.813 | 0.752 | 0.709 | 0.710 | 0.682 | 0.666 | 0.603 | 0.622 | 0.573 | 0.602 |
| *Note:* | | | | | | | | | | *p<0.1; **p<0.05; ***p<0.01 |

Consumption is a significant variable in explaining households' direct and indirect emissions for all income classes. The size of the household is also a significant variable for all classes of income regarding the indirect emissions but not for direct emissions, where it is not the case for the deciles $2^{nd}$,$3^{rd}$ and $4^{th}$ deciles (and only at the 95% threshold for the $5^{th}$ decile and the 90% threshold for the $10^{th}$ decile).

The households' residence location appears not to be significant in explaining the indirect emissions and slightly explains the direct emissions for some of the income

Table 1.5: Elasticities for direct emissions by decile of income

| | *Dependent variable:* | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | log.f_ED | | | | | | | | | |
| | Decile 1 | Decile 2 | Decile 3 | Decile 4 | Decile 5 | Decile 6 | Decile 7 | Decile 8 | Decile 9 | Decile 10 |
| log.C | 0.704*** | 0.848*** | 0.778*** | 0.686*** | 0.542*** | 0.594*** | 0.474*** | 0.641*** | 0.566*** | 0.509*** |
| | (0.043) | (0.077) | (0.075) | (0.072) | (0.074) | (0.070) | (0.070) | (0.072) | (0.069) | (0.079) |
| log.D | 0.213** | −0.039 | −0.102 | 0.088 | 0.300** | 0.376*** | 0.602*** | 0.621*** | 0.409*** | 0.331* |
| | (0.094) | (0.140) | (0.137) | (0.145) | (0.152) | (0.141) | (0.144) | (0.161) | (0.150) | (0.185) |
| Z_zone1 | −0.495*** | −0.146 | −0.314 | −0.383** | −0.459** | −0.075 | −0.041 | −0.410 | −0.234 | −0.311 |
| | (0.177) | (0.217) | (0.210) | (0.186) | (0.230) | (0.224) | (0.220) | (0.270) | (0.265) | (0.356) |
| Z_zone2 | −0.434** | 0.302 | 0.196 | −0.207 | −0.286 | 0.239 | 0.121 | −0.148 | −0.084 | −0.128 |
| | (0.189) | (0.240) | (0.233) | (0.207) | (0.247) | (0.237) | (0.232) | (0.281) | (0.276) | (0.370) |
| Z_zone3 | −0.099 | −0.004 | 0.224 | 0.047 | 0.086 | 0.144 | 0.150 | 0.030 | 0.147 | 0.186 |
| | (0.230) | (0.270) | (0.250) | (0.229) | (0.265) | (0.256) | (0.253) | (0.311) | (0.299) | (0.404) |
| Z_car | 1.818*** | 1.500*** | 1.752*** | 1.552*** | 1.668*** | 1.635*** | 1.393*** | 1.538*** | 1.273*** | 0.980*** |
| | (0.091) | (0.116) | (0.106) | (0.111) | (0.124) | (0.124) | (0.139) | (0.155) | (0.163) | (0.182) |
| Constant | −1.021** | −2.467*** | −1.733** | −0.665 | 0.590 | −0.167 | 1.137 | −0.449 | 0.700 | 1.664* |
| | (0.409) | (0.707) | (0.707) | (0.679) | (0.724) | (0.693) | (0.705) | (0.745) | (0.729) | (0.850) |
| Observations | 2,682 | 1,563 | 1,515 | 1,483 | 1,519 | 1,557 | 1,573 | 1,546 | 1,569 | 1,168 |
| $R^2$ | 0.366 | 0.252 | 0.300 | 0.271 | 0.231 | 0.240 | 0.165 | 0.196 | 0.140 | 0.105 |
| Adjusted $R^2$ | 0.364 | 0.249 | 0.297 | 0.268 | 0.228 | 0.237 | 0.162 | 0.193 | 0.136 | 0.100 |
| *Note:* | | | | | | | | | | *p<0.1; **p<0.05; ***p<0.01 |

classes. The relationship between them and the fact of living in the center of an agglomeration (coded $zone_1$) is significantly negative (with values of elasticity between -0.5 and 0.-38) only for the households from the $1^{st}$, $4^{th}$ and $5^{th}$ decile when compared to the households of their income class living outside agglomeration.

These results would suggest that only these households (and, to the latest extent, those from the $1^{st}$ decile living in the suburbs) exhibit a significant difference in their consumption behavior with respect to the households within the same class of income. It seems to indicate that the localization of residence only partially plays a role in explaining the direct emissions within the same income class, whereas it is the case when the population is taken globally. Without a more comprehensive dataset regarding the mobility of households (such as the distance driven by car and other transportation means), it is hazardous to explain what causes these differences within the deciles.

We find that the level of emissions, both direct and indirect, is well explained by consumption level but with some differences. Regarding indirect emissions, the elasticity value is globally decreasing with the class of income. The first two deciles have an elasticity greater than 0.8, the three following ($3^{rd}$ decile to $5^{th}$ decile) between 0.7 and 0.8, and the last five ($6^{th}$ decile to $10^{th}$ decile) between 0.7 and 0.6. Regarding direct emissions, the interpretation of the results is much less straightforward. At the same time, we observe that the 40% poorest households have an elasticity of direct emissions with their consumption between 0.69 and 0.85, in contrast to the elasticity values for the 60% wealthiest households, which are between 0.51 and 0.64. Moreover, its value is not strictly decreasing with the class of income. It suggests that income level can explain the consumption behavior of energy goods and that the decreasing carbon intensity observed in all the emissions (see Table 3) does not necessarily hold for direct emissions.

## 1.5 Conclusion

This chapter applies an environmentally expanded input-output analysis to develop consumption-based GHG inventories and estimate French households' carbon footprint for different population categories. First of all, France is in a situation of net importer of emissions when applying the consumption-based accounting criteria. More than half of its indirect emissions have come from over countries since 2000. Furthermore, there is no clear trend in reducing imported emissions in relative terms; on the contrary, some activities such as transport, agriculture, and the energy industry have a growing share of their imported emissions.

Another characteristic of the imported emissions in France is that they result from firms' decisions since 73.2% of them result from imported intermediate inputs of domestic production. From these findings, we can derive the following recommendations: The carbon footprint reduction would necessarily come from transforming the global value chain by adopting less-emitting production processes, either domestically or abroad. By the law, aiming at reducing imported emissions, the levers shall apply to firms since they are responsible for the bulk of the global imported emissions. The decision by the European Commission to establish a border-carbon adjustment mechanism starting in 2023 appears to answer this issue, even if the emissions covered by this mechanism represent only a fringe of indirect emissions. Even if the consumption-based accounting approach emphasizes the final consumer behavior, the firms have the keys to unlocking the low-carbon transition and reducing the emissions from their upstream global value chain.

The distribution of emissions among the population leads to two main conclusions. The first one is that the inequalities in carbon footprint for the particular case of France are less critical than the inequalities of income. The economic consequence is that carbon taxation instruments are regressive. We find an elasticity between direct emissions and income of 0.533 versus 0.455 between indirect emissions and income.

However, this hierarchy is reversed when looking a the elasticities of emissions with the expenditures, in which case the direct emissions are less elastic than indirect emissions (0.693 for direct emissions versus 0.762 for indirect ones). We also show that there is less horizontal heterogeneity for indirect emissions among the same income class than for direct emissions and that the log-log model relating indirect emissions to consumption has a better fit.

Finally and more importantly, it should be kept in mind that carbon footprint indicators, either macroeconomic or microeconomic, are not fully reliable since they are calculated from worldwide economic flows proxies and through a data construction process that fatally embodies their uncertainty, reflecting the initial imperfect measurement from national statistics. Wood et al. (2019) performed a systematic comparison of the main MRIO and found inter-variation of 5-10% for main economic regions and up to 30-40% for individual countries (France's carbon footprint estimates were among the least dispersed with an inter-variation of 1-6.1%).On the micro-level, our results also hide the intra-variability within a range of similar products, for which significant differences could arise from the producer's choice. The potential for carbon footprint reduction would likely arise from substitution at this level rather than between classes of commodities. A possible extension of this work would be to assess the dispersion of indirect emissions relative to the dispersion of expenditure prices.

Despite these flaws, consumption-based carbon accounting remains a useful indicator. It provides relevant information on which public policies aiming at reducing carbon emissions can be designed, domestically and abroad, and can help raise concerns among the population over their consumption pattern and eventually could proceed to its empowerment.

# 1.A Appendix A: Carbon footprint decomposition

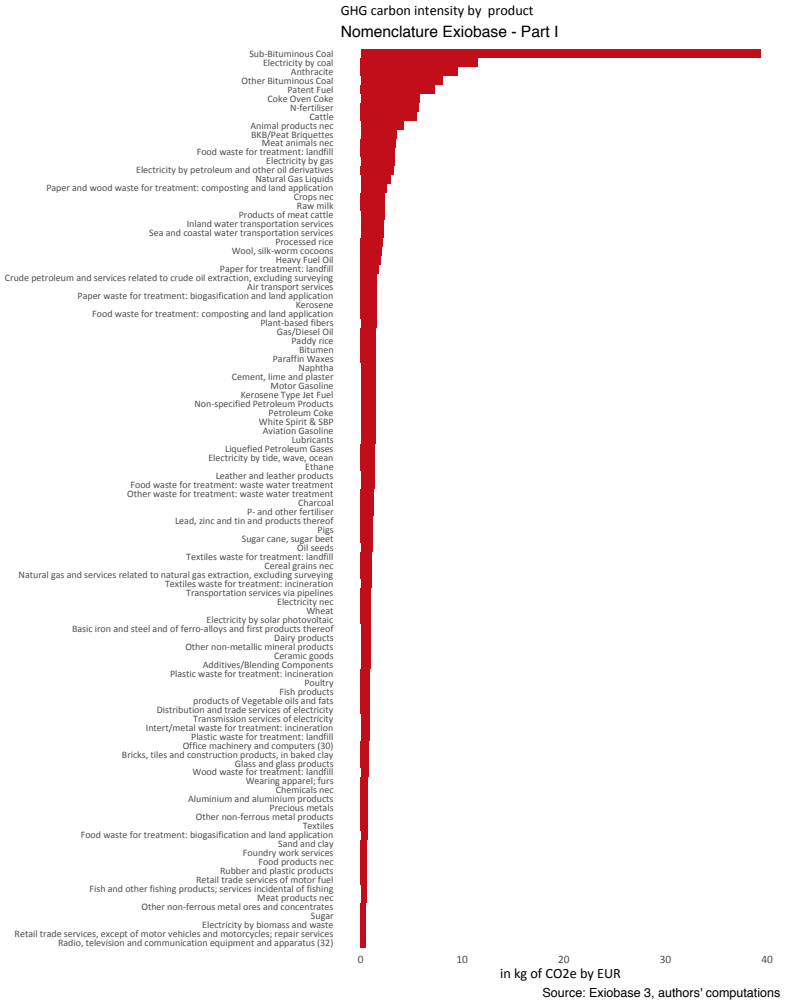
Table 1.6: Carbon intensity of consumption by decile of income of standard of living

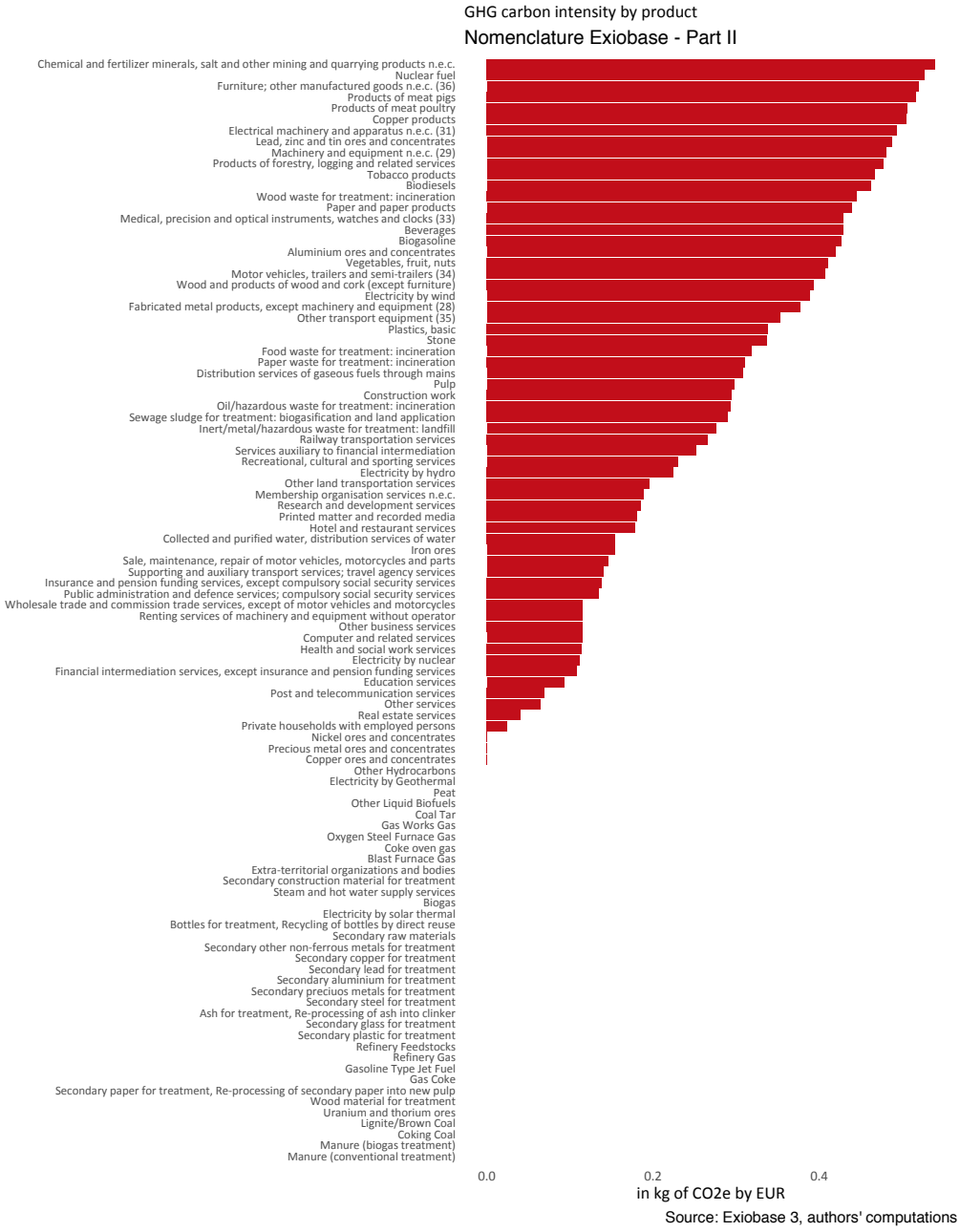
| Deciles | Decile 1 | Decile 2 | Décile 3 | Decile 4 | Decile 5 | Decile 6 | Decile 7 | Decile 8 | Decile 9 | Decile 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Carbon intensity of consumption (in $KgCO_2e/EUR$) | 1.701 | 1.640 | 1.503 | 1.457 | 1.403 | 1.429 | 1.336 | 1.300 | 1.277 | 1.161 |
| Number of u.c | 1.893 | 1.773 | 1.674 | 1.658 | 1.675 | 1.685 | 1.668 | 1.642 | 1.606 | 1.540 |

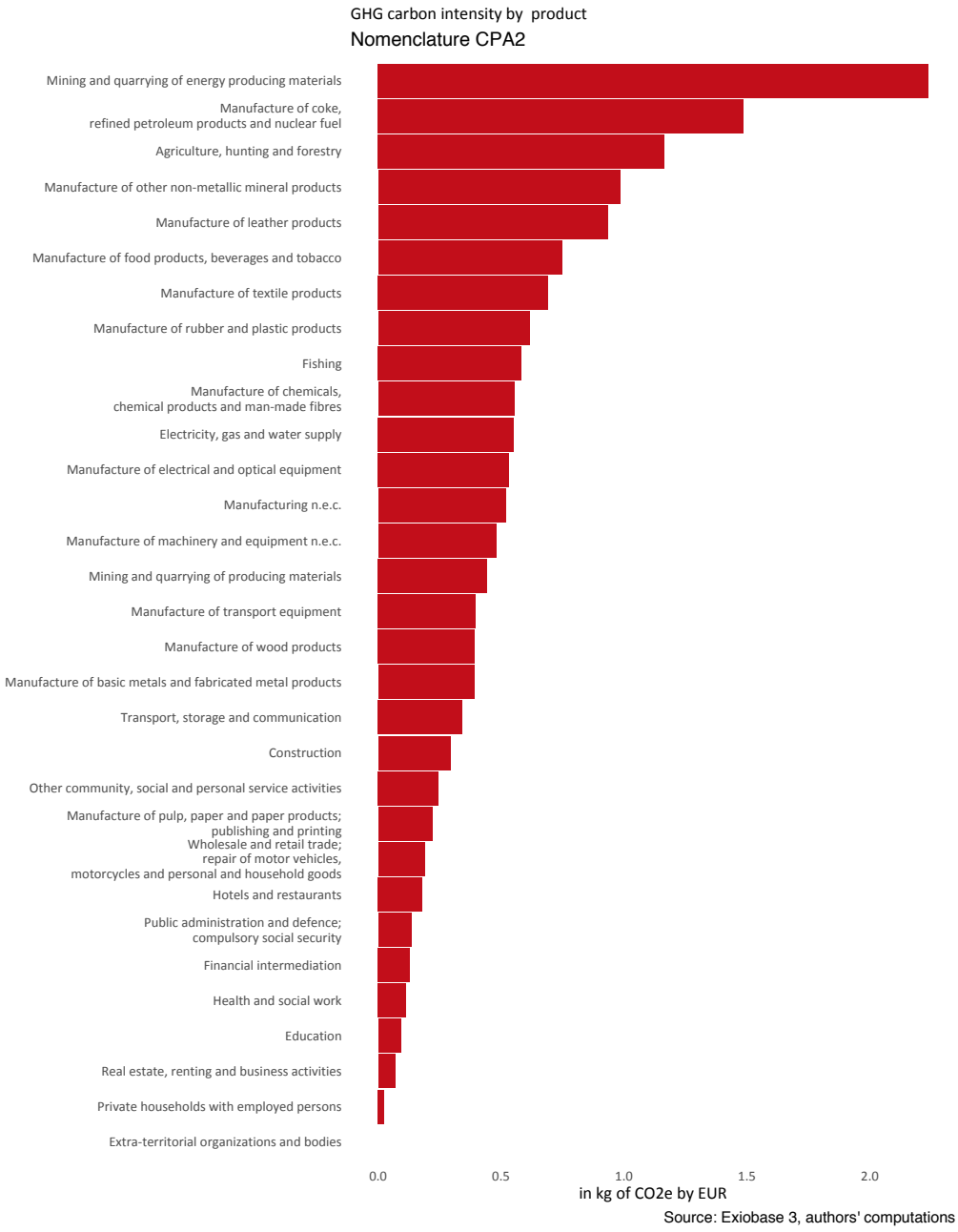
Table 1.7: Carbon emissions origin by product and region (in Mt $CO_2e$)

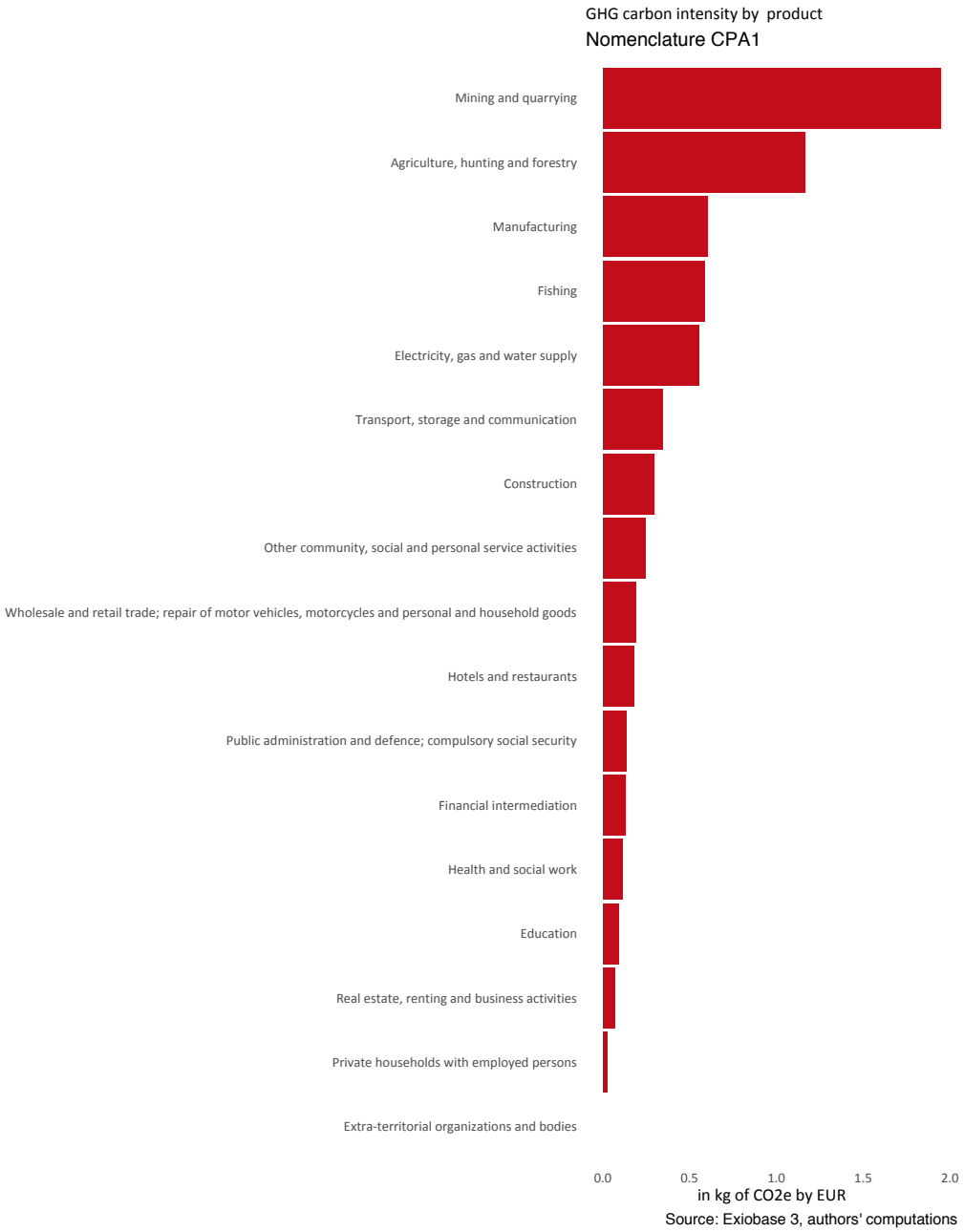
| | products | France | EU | US | Chine | Amérique du Nord | Amérique du Sud | Afrique | Russie | Europe (autres) | Asie | Moyen-Orient | Océanie | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Agriculture, hunting and forestry | 24.80 | 2.08 | 0.47 | 0.69 | 0.11 | 0.74 | 2.39 | 0.85 | 0.55 | 2.85 | 1.27 | 0.06 | 36.86 |
| 2 | Fishing | 0.37 | 0.29 | 0.06 | 0.07 | 0.01 | 0.03 | 0.09 | 0.10 | 0.27 | 0.14 | 0.07 | 0.01 | 1.53 |
| 3 | Mining and quarrying of energy producing materials | 2.39 | 0.55 | 0.03 | 0.05 | 0.01 | 0.01 | 0.04 | 0.04 | 0.16 | 0.13 | 0.04 | 0.03 | 3.50 |
| 4 | Mining and quarrying of producing materials | 0.06 | 0.02 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.02 | 0.01 | 0.00 | 0.14 |
| 5 | Manufacture of food products, beverages and tobacco | 46.73 | 11.42 | 1.48 | 2.19 | 0.43 | 1.56 | 3.12 | 2.49 | 2.28 | 5.59 | 2.25 | 0.21 | 79.74 |
| 6 | Manufacture of textile products | 0.30 | 0.57 | 0.15 | 1.42 | 0.03 | 0.07 | 0.40 | 0.14 | 0.13 | 1.19 | 0.35 | 0.05 | 4.80 |
| 7 | Manufacture of leather products | 0.56 | 1.50 | 0.36 | 7.54 | 0.07 | 0.22 | 0.70 | 0.35 | 0.26 | 6.89 | 0.76 | 0.12 | 19.32 |
| 8 | Manufacture of wood products | 0.13 | 0.16 | 0.02 | 0.09 | 0.01 | 0.02 | 0.04 | 0.06 | 0.02 | 0.10 | 0.03 | 0.00 | 0.68 |
| 9 | Manufacture of paper products; publishing and printing | 1.97 | 1.24 | 0.24 | 0.48 | 0.05 | 0.07 | 0.38 | 0.40 | 0.22 | 0.48 | 0.29 | 0.02 | 5.85 |
| 10 | Manufacture of coke, refined petroleum products and nuclear fuel | 8.10 | 1.88 | 1.20 | 0.36 | 0.27 | 0.85 | 2.96 | 6.62 | 1.83 | 4.44 | 5.63 | 0.04 | 34.17 |
| 11 | Manufacture of chemicals, chemical products and man-made fibres | 8.76 | 2.83 | 3.35 | 4.22 | 0.48 | 0.56 | 1.38 | 1.41 | 0.85 | 3.08 | 3.11 | 0.20 | 30.23 |
| 12 | Manufacture of rubber and plastic products | 0.56 | 0.64 | 0.12 | 0.66 | 0.02 | 0.05 | 0.44 | 0.12 | 0.11 | 0.54 | 0.79 | 0.01 | 4.07 |
| 13 | Manufacture of other non-metallic mineral products | 1.06 | 0.89 | 0.17 | 0.54 | 0.03 | 0.04 | 0.18 | 0.14 | 0.07 | 0.31 | 0.18 | 0.01 | 3.60 |
| 14 | Manufacture of basic metals and fabricated metal products | 1.36 | 1.27 | 0.20 | 0.97 | 0.04 | 0.07 | 0.25 | 0.34 | 0.22 | 0.54 | 0.24 | 0.04 | 5.54 |
| 15 | Manufacture of machinery and equipment n.e.c. | 1.12 | 2.39 | 0.65 | 3.77 | 0.11 | 0.14 | 0.61 | 0.54 | 0.44 | 1.51 | 0.70 | 0.07 | 12.04 |
| 16 | Manufacture of electrical and optical equipment | 3.41 | 4.52 | 1.41 | 13.63 | 0.33 | 0.48 | 2.23 | 1.03 | 0.88 | 6.64 | 2.56 | 0.18 | 37.29 |
| 17 | Manufacture of transport equipment | 4.38 | 9.98 | 1.77 | 4.85 | 0.34 | 0.46 | 2.10 | 1.85 | 1.56 | 4.71 | 2.39 | 0.19 | 34.58 |
| 18 | Manufacturing n.e.c. | 3.06 | 2.08 | 0.52 | 4.82 | 0.13 | 0.22 | 1.31 | 0.53 | 0.51 | 2.47 | 0.75 | 0.07 | 16.47 |
| 19 | Electricity, gas and water supply | 12.41 | 3.27 | 0.33 | 0.41 | 0.06 | 0.13 | 0.34 | 0.61 | 1.04 | 0.63 | 0.33 | 0.08 | 19.64 |
| 20 | Construction | 39.60 | 9.19 | 2.08 | 6.10 | 0.42 | 0.92 | 3.15 | 4.26 | 1.75 | 5.31 | 3.53 | 0.32 | 76.63 |
| 21 | Wholesale and retail trade; repair of motor vehicles | 4.04 | 0.21 | 0.19 | 0.04 | 0.05 | 0.02 | 0.09 | 0.09 | 0.05 | 0.15 | 0.06 | 0.01 | 5.00 |
| 22 | Hotels and restaurants | 9.50 | 1.02 | 0.18 | 0.20 | 0.05 | 0.10 | 0.26 | 0.29 | 0.21 | 0.49 | 0.22 | 0.02 | 12.55 |
| 23 | Transport, storage and communication | 13.17 | 2.48 | 3.75 | 0.81 | 0.21 | 0.38 | 1.73 | 2.32 | 1.22 | 1.47 | 1.21 | 0.08 | 28.83 |
| 24 | Financial intermediation | 3.32 | 0.50 | 0.39 | 0.21 | 0.04 | 0.07 | 0.34 | 0.29 | 0.18 | 0.32 | 0.20 | 0.02 | 5.87 |
| 25 | Real estate, renting and business activities | 12.27 | 2.35 | 1.16 | 1.36 | 0.19 | 0.25 | 1.35 | 1.19 | 0.68 | 1.41 | 1.08 | 0.08 | 23.36 |
| 26 | Public administration and defence; compulsory social security | 13.62 | 2.54 | 1.20 | 1.45 | 0.19 | 0.28 | 1.05 | 1.32 | 0.76 | 1.61 | 1.06 | 0.08 | 25.16 |
| 27 | Education | 7.67 | 1.31 | 0.39 | 0.43 | 0.07 | 0.14 | 0.50 | 0.68 | 0.37 | 0.64 | 0.40 | 0.04 | 12.64 |
| 28 | Health and social work | 13.37 | 3.34 | 2.06 | 2.97 | 0.33 | 0.44 | 1.61 | 1.29 | 0.93 | 2.88 | 2.08 | 0.14 | 31.44 |
| 29 | Other community, social and personal service activities | 20.36 | 3.19 | 1.20 | 1.29 | 0.20 | 0.35 | 1.79 | 1.70 | 1.05 | 1.84 | 1.20 | 0.12 | 34.27 |
| 30 | Private households with employed persons | 0.02 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.02 | 0.00 | 0.00 | 0.09 |
| 31 | Extra-territorial organizations and bodies | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 32 | Total | 258.47 | 73.71 | 25.14 | 61.63 | 4.27 | 8.66 | 30.86 | 31.04 | 18.59 | 58.39 | 32.78 | 2.31 | 605.86 |

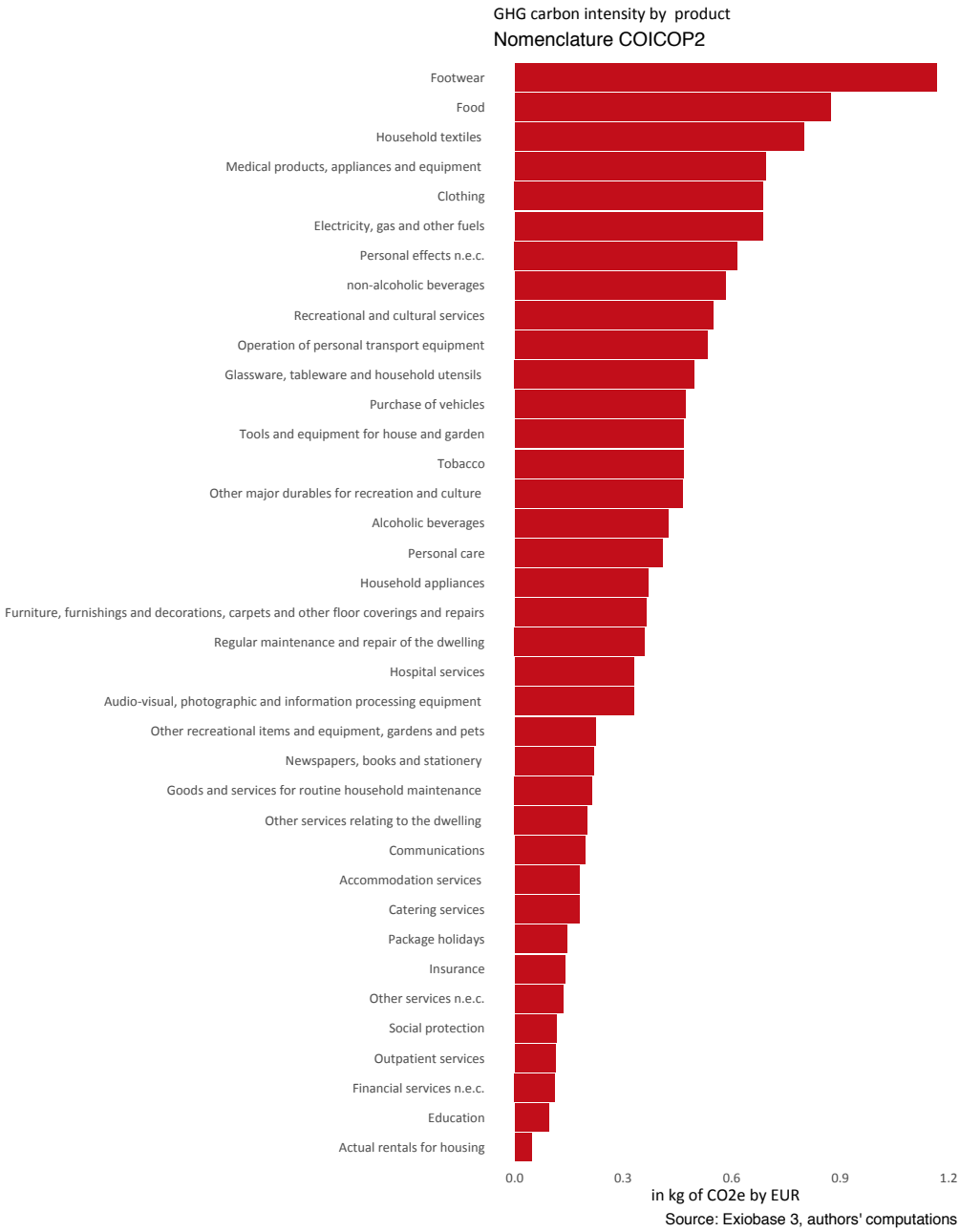
# 1.B Appendix B: Carbon intensity of products

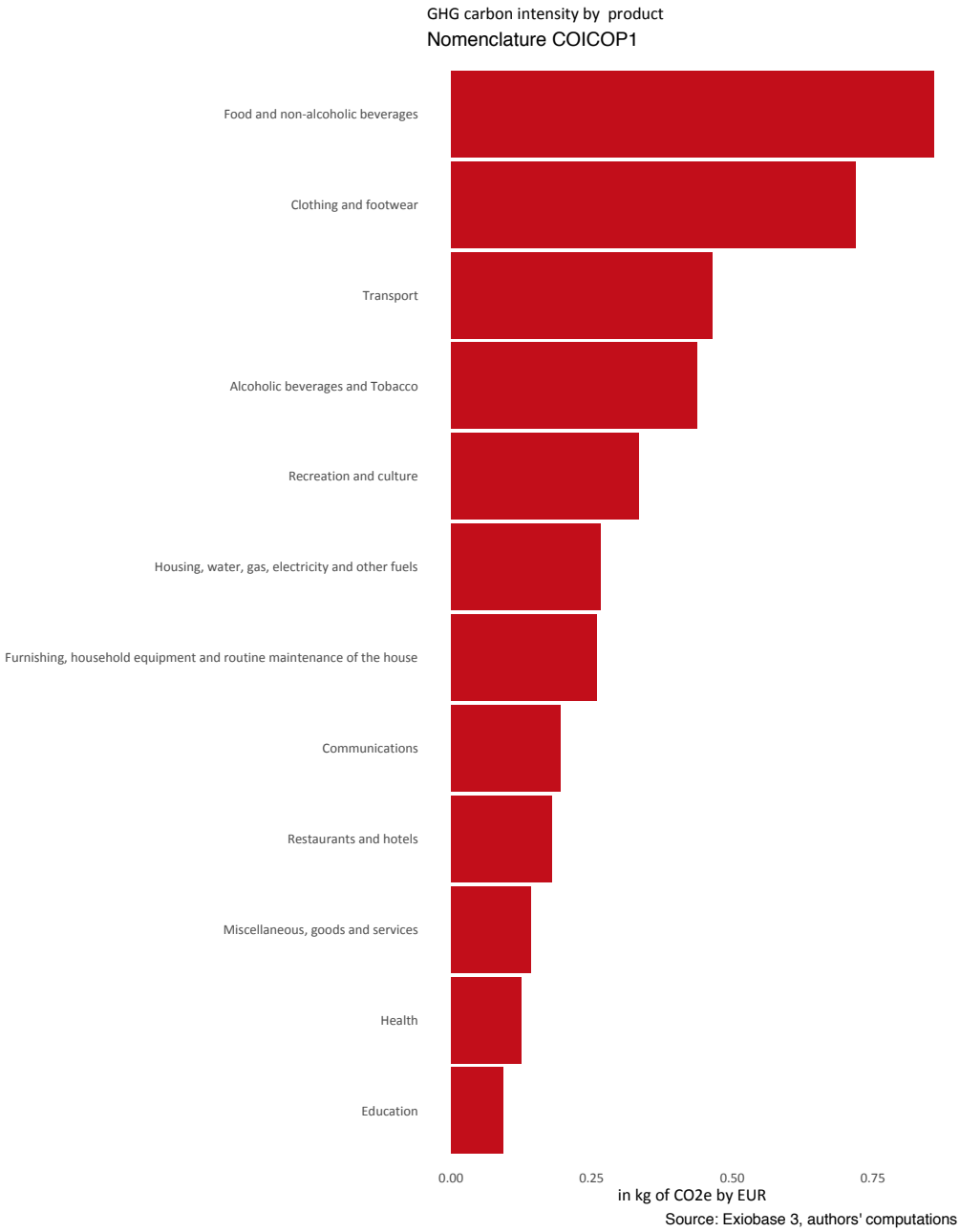



GHG carbon intensity by product
Nomenclature Exiobase - Part II
Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.
Nuclear fuel
Furniture; other manufactured goods n.e.c. (36)
Products of meat pigs
Products of meat poultry
Copper products
Electrical machinery and apparatus n.e.c. (31)
Lead, zinc and tin ores and concentrates
Machinery and equipment n.e.c. (29)
Products of forestry, logging and related services
Tobacco products
Biodiesels
Wood waste for treatment: incineration
Paper and paper products
Medical, precision and optical instruments, watches and clocks (33)
Beverages
Biogasoline
Aluminium ores and concentrates
Vegetables, fruit, nuts
Motor vehicles, trailers and semi-trailers (34)
Wood and products of wood and cork (except furniture)
Electricity by wind
Fabricated metal products, except machinery and equipment (28)
Other transport equipment (35)
Plastics, basic
Stone
Food waste for treatment: incineration
Paper waste for treatment: incineration
Distribution services of gaseous fuels through mains
Pulp
Construction work
Oil/hazardous waste for treatment: incineration
Sewage sludge for treatment: biogasification and land application
Inert/metal/hazardous waste for treatment: landfill
Railway transportation services
Services auxiliary to financial intermediation
Recreational, cultural and sporting services
Electricity by hydro
Other land transportation services
Membership organisation services n.e.c.
Research and development services
Printed matter and recorded media
Hotel and restaurant services
Collected and purified water, distribution services of water
Iron ores
Sale, maintenance, repair of motor vehicles, motorcycles and parts
Supporting and auxiliary transport services; travel agency services
Insurance and pension funding services, except compulsory social security services
Public administration and defence services; compulsory social security services
Wholesale trade and commission trade services, except of motor vehicles and motorcycles
Renting services of machinery and equipment without operator
Other business services
Computer and related services
Health and social work services
Electricity by nuclear
Financial intermediation services, except insurance and pension funding services
Education services
Post and telecommunication services
Other services
Real estate services
Private households with employed persons
Nickel ores and concentrates
Precious metal ores and concentrates
Copper ores and concentrates
Other Hydrocarbons
Electricity by Geothermal
Peat
Other Liquid Biofuels
Coal Tar
Gas Works Gas
Oxygen Steel Furnace Gas
Coke oven gas
Blast Furnace Gas
Extra-territorial organizations and bodies
Secondary construction material for treatment
Steam and hot water supply services
Biogas
Electricity by solar thermal
Bottles for treatment, Recycling of bottles by direct reuse
Secondary raw materials
Secondary other non-ferrous metals for treatment
Secondary copper for treatment
Secondary lead for treatment
Secondary aluminium for treatment
Secondary preciuos metals for treatment
Secondary steel for treatment
Ash for treatment, Re-processing of ash into clinker
Secondary glass for treatment
Secondary plastic for treatment
Refinery Feedstocks
Refinery Gas
Gasoline Type Jet Fuel
Gas Coke
Secondary paper for treatment, Re-processing of secondary paper into new pulp
Wood material for treatment
Uranium and thorium ores
Lignite/Brown Coal
Coking Coal
Manure (biogas treatment)
Manure (conventional treatment)
0.0
0.2
0.4
in kg of CO2e by EUR
Source: Exiobase 3, authors' computations


GHG carbon intensity by product
Nomenclature CPA2
Mining and quarrying of energy producing materials
Manufacture of coke, refined petroleum products and nuclear fuel
Agriculture, hunting and forestry
Manufacture of other non-metallic mineral products
Manufacture of leather products
Manufacture of food products, beverages and tobacco
Manufacture of textile products
Manufacture of rubber and plastic products
Fishing
Manufacture of chemicals, chemical products and man-made fibres
Electricity, gas and water supply
Manufacture of electrical and optical equipment
Manufacturing n.e.c.
Manufacture of machinery and equipment n.e.c.
Mining and quarrying of producing materials
Manufacture of transport equipment
Manufacture of wood products
Manufacture of basic metals and fabricated metal products
Transport, storage and communication
Construction
Other community, social and personal service activities
Manufacture of pulp, paper and paper products; publishing and printing
Wholesale and retail trade; repair of motor vehicles, motorcycles and personal and household goods
Hotels and restaurants
Public administration and defence; compulsory social security
Financial intermediation
Health and social work
Education
Real estate, renting and business activities
Private households with employed persons
Extra-territorial organizations and bodies
0.0
0.5
1.0
1.5
2.0
in kg of CO2e by EUR
Source: Exiobase 3, authors' computations


GHG carbon intensity by product
Nomenclature CPA1
Mining and quarrying
Agriculture, hunting and forestry
Manufacturing
Fishing
Electricity, gas and water supply
Transport, storage and communication
Construction
Other community, social and personal service activities
Wholesale and retail trade; repair of motor vehicles, motorcycles and personal and household goods
Hotels and restaurants
Public administration and defence; compulsory social security
Financial intermediation
Health and social work
Education
Real estate, renting and business activities
Private households with employed persons
Extra-territorial organizations and bodies
0.0
0.5
1.0
1.5
2.0
in kg of CO2e by EUR
Source: Exiobase 3, authors' computations


GHG carbon intensity by product
Nomenclature COICOP2
Footwear
Food
Household textiles
Medical products, appliances and equipment
Clothing
Electricity, gas and other fuels
Personal effects n.e.c.
non-alcoholic beverages
Recreational and cultural services
Operation of personal transport equipment
Glassware, tableware and household utensils
Purchase of vehicles
Tools and equipment for house and garden
Tobacco
Other major durables for recreation and culture
Alcoholic beverages
Personal care
Household appliances
Furniture, furnishings and decorations, carpets and other floor coverings and repairs
Regular maintenance and repair of the dwelling
Hospital services
Audio-visual, photographic and information processing equipment
Other recreational items and equipment, gardens and pets
Newspapers, books and stationery
Goods and services for routine household maintenance
Other services relating to the dwelling
Communications
Accommodation services
Catering services
Package holidays
Insurance
Other services n.e.c.
Social protection
Outpatient services
Financial services n.e.c.
Education
Actual rentals for housing
0.0
0.3
0.6
0.9
1.2
in kg of CO2e by EUR
Source: Exiobase 3, authors' computations


GHG carbon intensity by product
Nomenclature COICOP1
Food and non-alcoholic beverages
Clothing and footwear
Transport
Alcoholic beverages and Tobacco
Recreation and culture
Housing, water, gas, electricity and other fuels
Furnishing, household equipment and routine maintenance of the house
Communications
Restaurants and hotels
Miscellaneous, goods and services
Health
Education
0.00
0.25
0.50
0.75
in kg of CO2e by EUR
Source: Exiobase 3, authors' computations

# Chapter 2

# A distributional analysis of carbon taxing in France: from micro-simulations to a general equilibrium framework

## 2.1 Introduction

The economist profession mainly presents pricing carbon as the cornerstone, if not the silver bullet, of a cost-effective strategy to mitigate greenhouse gas emissions (GHG) and thus help prevent global warming[1]. Dwelling on the fundamental work brought by Pigou on externalities, the theoretical principle behind carbon pricing at first remains relatively simple. Since some economic activities that generate negative externalities (greenhouse gas emissions responsible for climate change, air pollution, pollutant discharges) are not regulated by market mechanisms, the introduction of market-based instruments that distort the prices of activities or goods that create this externality would reduce the demand for these products and thus the level of the negative externality.

The scale of the Yellow Vests movement in 2018, initiated by the scheduled increase in the carbon component of the tax on energy products, finally led the French government to agree to implement measures to defend purchasing power, including freezing the price trajectory of the carbon tax. At the same time, most people in developed countries have expressed their willingness to contribute to reducing emissions by changing their consumption behavior. How to explain this discrepancy between citizens' aspirations and the obstacles to implementing a carbon tax?

How to explain this gap when at the same time, the population from developed countries expresses in majority their willingness to contribute to emissions reduction by shifting their consumption behavior[2]?

The first set of plausible arguments is associated with the public perception of the incapacity of public authorities to ensure fairness in the deployment of carbon pricing instruments (Bennear and Stavins, 2007; Bristow et al., 2010; Douenne and Fabre,

[1] In 2019, the US Climate Leadership Council and the European Association of Environmental and Resource Economists (EAERE) issued both a statement advocating for the deployment of a carbon tax. More than 5000 economists have signed one of these two statements.

[2] According to a Pew Research Center survey, 80% of respondents in 17 advanced economies are willing to change the way they live or work to help fight climate change. (Center, 2021).

2022). More precisely, on the carbon tax, its regressivity constitutes an obstacle to its implementation (Baumol et al., 1988; Parry, 2015; Beiser-McGrath and Bernauer, 2019; Chiroleu-Assouline, 2022). According to Dechezleprêtre et al. (2022), two main factors contribute to ensuring public support for climate policies. First, the policy leads to an effective reduction in emissions and does not have adverse distributional impacts on the poorest households. Fullerton (2011) listed six distributional effects induced by environmental policy: (1) higher prices of carbon-intensive products, (2) changes in relative returns to factors like labor, capital, and resources, (3) allocation of scarcity rents from a restricted number of permits, (4) distribution of the benefits from improvements in environmental quality, (5) temporary effects during the transition, and (6) capitalization of all those effects into prices of land, corporate stock, or house values.

These redistributive effects will heterogeneously affect households if we consider that their preferences are not homothetic and, thus, that their structure of income and consumption evolves accordingly to their level. Since carbon-intensive products are more associated with basic needs (such as heating, cooking, or commuting), the more the household is poor, the higher its share is in its total expenditures. Therefore carbon tax generally turns out to be regressive with the income level in developed countries[3] (Parry, 2004; Fullerton et al., 2011).

However, some scholars argue that this regressivity might also be overestimated. Building on the permanent income hypothesis[4] Poterba (1989) argues that annual expenditures are a better indicator than annual income to appreciate the degree of the regressivity of a tax since fluctuation of income for households at the bottom of the annual income distribution might exaggerate the regressivity[5]. Although, taking

[3]The reader can refer to Ohlendorf et al. (2021), for a recent literature review on distributional effects.

[4]The permanent income hypothesis states that consumers tend to smooth their consumption over time and anticipate expected future income in their decision (Friedman et al., 1957).

[5]Sterner (2012) find several cases of progressive impact from taxing transport, for instance in Serbia when using annual income criteria and also in Sweden when taking an expenditures criteria.

wealth as a comparison criteria accentuates the regressivity of taxes on energy products[6] (Teixidó and Verde, 2017). Discriminating households in the function of their location of residence show a significant difference between them in terms of price-reaction, rural households being more responsive than urban households[7] as shown for the US (Saussay, 2018; Cronin et al., 2019) or France (Douenne, 2020b). One generally speaks about *vertical heterogeneity* when distributional effects are evaluated respectively to households income. However, other factors can also be at play in terms of distributional effects, such as the location of residence, quality of housing, or the presence of public transportation systems, inducing broad redistributive impact within the same class of income, in which case, one would label *horizontal heterogeneity*. More recent studies further the analysis of redistributive issues by exploring the horizontal distributional effects of carbon taxing.

Nevertheless, the main bulk of this growing literature is adopting a partial equilibrium setting, neglecting the contribution of income effects which are, as argued by Rausch et al. (2011), of foremost importance to consider the regressivity of the tax scheme. The mobilization of the CGE in this context helps trace the income formation and address the efficiency/equity trade-off. Economists decompose the incidence of the tax between two types of effects; *Use-side* effects and *source-side* effects. *Use-side* effects are those induced by the change in the prices of goods and services on purchasing power or well-being. Therefore, their influence on the distribution depends on expenditures and how they are structured by household. *Source-side* effects are the change in purchasing power that can be attributed to a policy-induced change in the income structure, wages, returns to capital, and transfers, impacting households differently in the function of their income structure. To address this question, several studies combined CGE or input-output models with micro-simulations models

[6]In an inter-generational perspective, this regressivity is even greater since households assets distribution is more concentrated on older generations than income.

[7]The elasticity is in absolute value increasing with the size of the city.

through the methodology conceived by Rutherford and Tarr (2008), which consists of an iterative converging process towards an overall consistent solution between the two models (Labandeira and Labeaga, 1999; Grainger and Kolstad, 2010; Fullerton et al., 2011; Fremstad and Paul, 2017; Landis, 2019; Mayer et al., 2021; García-Muros et al., 2022; Ravigné et al., 2022). It is generally assumed in these studies that consumers have no price reaction since the goal is to estimate *ex-ante* effects. The recourse to this strategy of *soft-linking* a macroeconomic CGE model with a micro-simulations model leads to benefit from the heterogeneity of observations in the micro-model. Other general equilibrium approaches aiming at catching the dynamic aspect of carbon taxing have been proposed, such as Williams III et al. (2015) who combine a CGE model with a dynamic OverLapping Generation Model (OLG) and offer a distributional analysis between generations.

In the case of an incentive tax, since the government's objective is to alter the consumption behaviors of the population through changing commodities' relative prices, the estimation of distinct reactions within the population is paramount to address the distributive effects fully. Zhang (2015) shows in a study on electricity consumption using Turkish data that the lower the household income, the more limited its substitution possibilities, which runs counter to the conclusions of an earlier study (West and Williams III, 2004), which concluded that low-income households tend to be more responsive to price changes than high-income households. However, there is a consensus that short-run price elasticities tend to be between -0.2 and -0.3, while long-run elasticities are between -0.6 and -0.8, as shown in the meta-analysis on distributional effects by Labandeira et al. (2017).

For obvious reasons, in the context of climate change, the response to changes in energy prices has been more widely studied than for other types of products. However, it restricts the analysis to direct household emissions (i.e., emissions occurring during the combustion of an energy product), representing only a portion of total household

emissions. We find different reasons that could explain this gap for the absence of comprehensive analysis

First, indirect emissions (i.e., emissions occurring along the production process of goods and services and serving a final consumption) are usually scrutinized through the lens of the supply-side of the economy, where firms are the agents of interest, from which substitution toward less-emitting production processes can arise. It adopts a full supply view of the transition, although final demand can incentivize producers to rely less on energy products and lower their emissions. Second, no official carbon intensity factors are provided by the national statistics office for consumption goods, whereas for energy products, conversion factors are published that help estimates the carbon emitted from final consumption.

Finally, from the final consumer viewpoint, the incidence of pricing carbon on firms, assuming neither technological change nor technical progress, shall be equivalent to indirect taxation since maximizing their profit implies raising their output price to their marginal cost[8].

Finally, the influence on the income formation of the economy's evolution and the role the government could have in correcting distortions created by the carbon tax is essential to fully capture economic effects induced by the taxing of carbon (Dissou and Siddiqui, 2014; Mathur and Morris, 2014; Aubert and Chiroleu-Assouline, 2019; Mayer et al., 2021).

Carbon taxation, whether it takes the form of indirect taxation on final consumption or emissions pricing for businesses, aims to raise the price of emitting products, which leads to a general increase in the price level of goods, depending on their respective carbon intensity. Integrating these goods into the study of redistributive effects sheds additional light on this branch of the literature by extending the scope of analysis to all consumer goods. This paper seeks to study the distributional im-

[8]Even if the input price repercussion on output price is not fully complete, this argument holds since it alters the amplitude of the variation just being lowered.

pact of carbon taxes with different tax bases and consider different frameworks. We attempt to extend the scope of emissions generally scrutinized in the literature to the whole set of emissions included in the consumption-based accounting approach. These GHG emissions from production processes are called indirect emissions and account for the main bulk of total emissions (for France, it represents more than 80% of the national carbon footprint and 70% of the national emissions inventory). Indeed the rationale of carbon pricing is that the marginal price for carbon should be equal to the marginal damage induced by the release of GHG emissions. Following this argument, there is no rational reason to focus on direct emissions and exclude from the analysis the indirect emissions induced by households' final consumption, except in the case where these indirect emissions where are

The objective of this paper is twofold. It is first to assess and compare the distributive effects of a carbon tax, either on energy fuels or on the carbon associated with final goods consumption. Second, to evaluate carbon tax in a general equilibrium setting, to estimate the contribution of the *supply-side* effect. We select a In the first section, we present the CGE model and how we couple it with households micro-data and present the database on individual carbon footprint. In the second section, we estimate the income and price-elasticities with an econometric model AIDS. In the third section, we conduct micro-simulations on carbon taxes and compare their distributive effects. The fourth section performs the same type of exercise but in a general equilibrium setting. The fifth section concludes.

## 2.2 Model and Data

In this section, we explain how we enhance the ThreeME model of the French economy to analyze the effects of a carbon tax policy with a representation of several classes of households and which data sources we mobilize to calibrate the macroeconomic model and the representative household's behavior. We integrate a national multi-sector energy-economic CGE model with a multi-households block calibrated on micro-data. The resulting multi-household model accommodates an economy-wide perspective, accounting for changes in commodity and factor prices throughout the economy and differentiating households' responses to these changes.

The model accounts for a detailed representation of households' heterogeneity with respect to income and expenditure patterns. Below we describe the model and the calibration of micro-data to be used in the multi-household CGE model.

### The ThreeME model

ThreeME is an open-source country-level Computable General Equilibrium model (CGE) originally developed to support policymakers in designing and evaluating decarbonization pathways in France. ThreeME is specifically designed to evaluate the short-, medium- and long-term impact of environmental and energy policies at the macroeconomic and sectoral levels. To this end, the model combines several important features:

- Its sectoral disaggregation allows for analyzing the transfer of activities from one sector to another, particularly regarding employment, investment, energy consumption, or balance of trade.

- The highly detailed representation of energy flows through the economy allows for analyzing the consumption behavior of economic agents with respect to energy. Sectors can arbitrate between capital and energy when the relative

price of energy increases and substitute between energy vectors. Consumers can substitute between consumption goods.

As a CGE model, ThreeME fully considers feedbacks between supply and demand. Demand (consumption and investment) drives supply (production). Symmetrically supply drives demand through the incomes generated by the production factors (labor, capital, energy products, and materials). ThreeME is a neo-Keynesian model. Compared to standard Walrasian-type CGEs that are largely supply-driven, prices do not adjust instantaneously to clear markets. Instead, the model is dynamic, and prices and quantities adjust slowly. Producers adjust their supply to the demand, allowing for situations of market disequilibria (in particular, the presence of involuntary unemployment). This framework is particularly well suited for policy analysis. In addition to providing information about the long term, it allows for analyzing transition phases over the short and medium terms, which is especially relevant when assessing the implementation of climate policies. We consider in our setting that consumers adjust their consumption instantaneously to price variation, contrarily to the supply side, which slowly adjusts. The detailed equations are provided in Appendix C.

### Coupling the CGE model with household microdata

In this section, we explain how we proceed to integrate micro-data for households into the CGE model. The majority of studies performing such a coupling applies the methodology developed by (Rutherford and Tarr, 2008)[9].

The so-called *soft-linking*[10] approach has the advantage of keeping the data richness but restricts the possibility of using estimated parameters. For this reason, we

[9]This methodology relies on successive iterations between a macro CGE model with one representative agent and the micro-model, decomposing one numerical problem into two sub-problems. Taking factor and commodity prices as input in the micro-model and the subsequent quantities of labor and consumption, aggregated as an input into the macro model, converges towards equilibrium prices and quantities solution.

[10]*Soft-linking* enables the complexities of even relatively large sub-models to be kept more or less intact, whereas *Hard-linking* often implies a simplified description of one or both of the sub-models to integrate it into the primary model. For more details, refer to Krook-Riekkola et al. (2017).

do not proceed to a *soft-linking* between two models and rather perform a complete integration of the multi-households demand system into the macroeconomic model.

In the main version of the ThreeME model, the consumer demand system is built upon a Linear Expenditures System (Brown and Heien, 1972) utility function extended to non-unitary elasticity of substitution between the commodities. Consumers allocate a share of their income to their overall expenditures (denoted $\tilde{w}_{c,h}$).

$$(X_c - \overline{X}_c)\ P_c^X = \tilde{w}_{c,h} \left( (1 - MPS)\ I^{VAL} - \sum_c P_c^X X_c \right) \tag{2.1}$$

Where $X_c$ corresponds to the volume of consumption (expenditures) in commodity $c$ and $P_c^X$ to its price. $\overline{X}_c$ is the incompressible volume of expenditures in commodity $c$, $I^{VAL}$ is the households' disposable income, and $MPS$ is their marginal propensity to save. In the case of no incompressible expenditures ($\overline{X}_c = 0$), households aim at allocating a share $\tilde{w}_{c,h}$ of their total expenditure (in value), $(1 - MPS).I^{VAL}$, to commodity $c$. This share is constant if the elasticity of substitution between the commodities is equal to one. In this case (Cobb-Douglas utility function without incompressible expenditures), commodity $c$ expenditures remain proportional to income. In the case of a CES function where the elasticity of substitution is $\eta^{LES_CES}$, the marginal propensity to spend varies depending on the relative prices according to the following specification:

$$\Delta \log \tilde{w}_{c,h} = (1 - \eta^{LES_CES})\ \Delta \log \frac{P_c}{P^{LES_CES}} \tag{2.2}$$

$$P^{LES_CES} = (\sum_c \tilde{w}_{c,h,t_0}\ P_c^{1-\eta^{LES_CES}})^{\frac{1}{1-\eta^{LES_CES}}} \tag{2.3}$$

In order to account for heterogeneous behavior, we update the consumer behavior on its expenditures allocation, based on the *Almost Ideal Demand System* (AIDS) model developed by (Deaton and Muellbauer, 1980). The AIDS model is derived from the first-order linear approximation of the cost-expenditure function and imposes restrictions such as additivity, homogeneity in prices and total expenditures, Slutsky

symmetry, and two-stage budgeting to be consistent with the demand theory. In this way, the parameters are estimated using a similar specification of the demand function. Since the econometric estimation adopts the same restrictions, the demand system is balanced[11].

Let $\sum_c P_c^X \; X_{h,c}$ being the total expenditures in value of household $h$. $P_h$ is the translog price index for household $h$, $w_{c,h}$ the weight of product $c$ in the household $h$ total expenditures in volume, $P_{c'}$ the price of product $c'$, and $\alpha_{c,h}$, $\gamma_{c,c',h}$ and $\beta_{c,h}$ are coefficients. Usually, the AIDS model is specified as follows:

$$w_{c,h} = \alpha_c + \sum_{c'} \gamma_{h,c,ca} \log(P_{c'}) + \beta_{h,c} \log\left(\frac{\sum_c P_c^X \; X_{c,h}}{P_h^*}\right) \tag{2.4}$$

the AIDS demand equation 2.4 expressed in variation yields:

$$\Delta \log w_{c,h} = \sum_c \gamma_{c,c',h} \; \Delta \log P_{c'} + \beta_{c,h} \; \Delta \log \frac{\sum_c P_c \; X_{c,h}}{P_h^*} \tag{2.5}$$

We adopt a Stone Index to create an income group-specific deflator $P_h^*$, which is defined as the weighted sum of past period expenditures from household $h$:

$$\Delta \log P_h^* = \sum_c \; w_{c,h,t-1} \; \Delta \log P_c \tag{2.6}$$

Finally, By aggregation, the total consumption of commodity $c$ is:

$$\Delta \log X_c = \sum_c \; X_{c,h} \tag{2.7}$$

## Dataset

Our dataset is built upon three main components: (i) National accounts from Eurostat for France, (ii) a sample of French households from the 2011 Household Budget Survey (HBS) *Budget des Familles* and (iii) emissions accounting derived from the multi-regional input-output dataset EXIOBASE. We merge them through a shared and common nomenclature of products and activities through a bridging matrix. We

[11]The econometric estimation is exposed in the next section.

obtain an integrated dataset of national accounting, incorporating heterogeneity in expenditure patterns and income sources captured through ten representative agents for the households. The CGE model is calibrated on country-level data from Eurostat, on a nomenclature NACE[12] and for the year 2015.

The sample of households is derived from the Budget des Familles survey, a widely used source for data on consumption, income structure, and socioeconomic and demographic household characteristics, collected by the french national institute since 1979 every five years. Each household is interviewed two times[13] and proceed to self-report their expenses weekly. Results then are paired with national accounting data and subject to a sample correction to reduce biases from incomplete or missing reporting by applying a marginal calibration.

GHG emissions are calculated from EXIOBASE. For the national accounting framework, we account for indirect emissions in a satellite matrix linked to firms' intermediate consumption of energy products and direct emissions resulting from the final consumption of energy products for households. Regarding the micro-simulations, we adopt another accounting concept since we only consider the demand side and therefore rely on consumer-based emissions accounting of carbon footprint. We rely on the same emissions factors determined in Chapter I, using the database EXIOBASE for 2011.

To obtain expenditure data consistent with the definition of consumption goods in our macroeconomic data, we have to map HBS product categories to NACE accounts. It is accomplished first by aggregating HBS 255 different products into COICOP nomenclature of 86 products (level 3 of the COICOP) and then using a bridging matrix[14]. We end up with a twelve products and twelve sectors decomposition of the

[12]We rely on an initial segmentation of the economic activities and products into 163 subcomponents.

[13]Seven waves of interviews are conducted during the civil year and within the time frame of a week for each household.

[14]We use the same methodology as we did in chapter one to calculate the individual carbon footprints) to map expenditures from NACE to COICOP nomenclature.

economy segmented according to the COICOP nomenclature level 1.

To match these datasets, we decompose the representative household into ten income groups of equal population, each representing a decile of income. We then calculate the share of each commodity consumed by a decile of income based on their expenditures into the HBS as the shares for the different components of their primary income (labor income, financial income, social income, and other sources of income). We proceed likewise regarding the additional taxes.

To ensure consistency with national accounting data used for the CGE model calibration, we then apply these shares to aggregate variables calculated within the national accounting framework. This setting allows us to keep the national accounting framework of the CGE model consistent and proceed to ventilate the aggregate variables related to consumption into different income deciles[15]. The general sectoral decomposition is based on the same commodities nomenclature used in the previous section and on which the estimation has been performed.

Table 2.1: Decile shares of expenditures and income composition (in %)

| item | D 1 | D 2 | D 3 | D 4 | D 5 | D 6 | D 7 | D 8 | D 9 | D 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Food | 7.02 | 7.80 | 8.46 | 8.93 | 9.77 | 10.12 | 10.49 | 11.41 | 12.05 | 13.96 |
| Clothing and Footwear | 7.86 | 7.15 | 7.37 | 8.54 | 8.36 | 8.98 | 10.34 | 11.66 | 13.38 | 16.37 |
| Energy (Housing) | 5.43 | 7.80 | 8.60 | 9.46 | 9.89 | 10.40 | 10.87 | 10.73 | 12.25 | 14.58 |
| Housing | 6.03 | 8.42 | 9.95 | 10.18 | 10.48 | 10.49 | 10.35 | 10.10 | 10.78 | 13.23 |
| Energy (Transport) | 4.67 | 6.92 | 8.25 | 9.01 | 10.14 | 11.24 | 11.25 | 12.37 | 12.92 | 13.23 |
| Transport | 3.60 | 5.18 | 6.57 | 7.73 | 8.60 | 10.02 | 12.04 | 12.20 | 14.21 | 19.85 |
| Recreational goods & services | 3.69 | 5.12 | 5.95 | 7.15 | 7.58 | 9.18 | 10.65 | 12.69 | 15.44 | 22.54 |
| Other goods and services | 4.38 | 6.57 | 7.57 | 8.25 | 9.05 | 9.86 | 10.78 | 12.24 | 13.51 | 17.79 |
| Income | 2.62 | 5.21 | 6.16 | 7.25 | 8.17 | 9.32 | 10.63 | 12.26 | 14.33 | 24.05 |
| Labor income | 1.44 | 3.60 | 4.83 | 6.39 | 7.78 | 9.50 | 11.05 | 13.02 | 15.12 | 27.27 |
| Financial Income | 0.90 | 1.76 | 2.64 | 3.62 | 5.27 | 5.83 | 7.87 | 12.19 | 16.14 | 43.77 |
| Social Income | 5.06 | 8.79 | 9.27 | 9.36 | 9.31 | 9.38 | 10.12 | 10.75 | 12.57 | 15.39 |
| Others | 2.93 | 6.16 | 5.90 | 6.34 | 5.83 | 8.68 | 11.39 | 12.15 | 14.10 | 26.52 |
| Taxes | 1.13 | 2.21 | 2.39 | 3.79 | 4.50 | 6.49 | 7.91 | 12.65 | 15.76 | 43.17 |

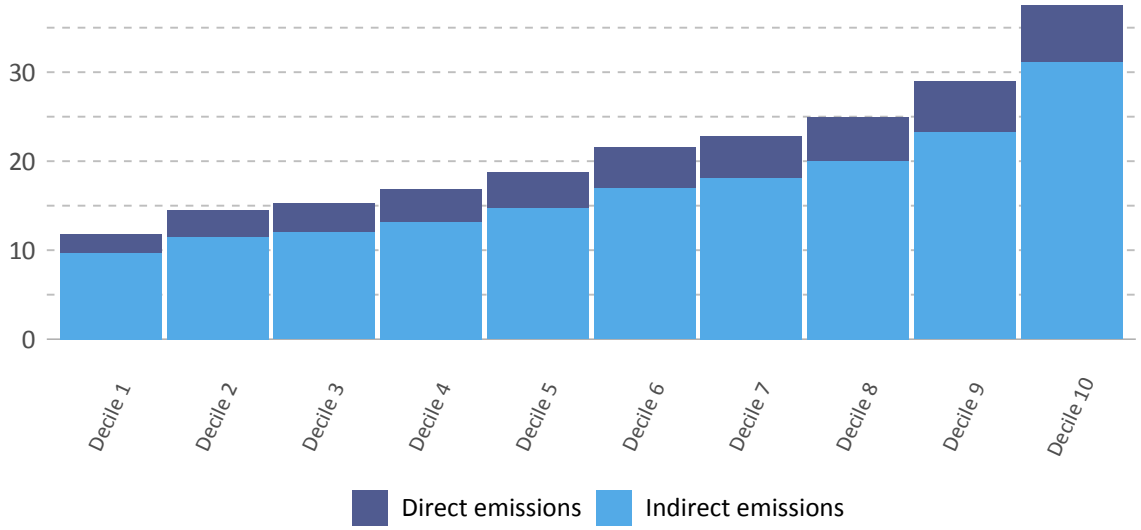
The sample population is categorized into decile of income of standard of living[16] (see Figure 2.1) and the distribution of the carbon footprint is established at the individual level[17].

[15] to be noted that the choice of the classification of the households does not need to be based on income criteria and can also discriminate households on other characteristics.

[16] We will alternatively use the term *decile* without loss of generality.

[17] the associated carbon intensity to expenditures are calculated at the COICOP 3 level (86 products) and then aggregated up to the COICOP 1 level at which the estimations are performed.

Figure 2.1: Distribution of carbon footprint emissions by decile of standard of living




## 2.3 Econometrics

### Estimation strategy

In this section, we estimate the price elasticity for 12 consumption goods defined at the first level of COICOP products classification and for different groups of households. In the first part, we estimate the price elasticities at the aggregate level and for the different income groups.

On a sample representative of the whole population, then on sub-sample representative of income of standard of living classes, separated in decile.

This AIDS model is derived from the first-linear approximation of the cost-expenditure function and satisfies (under some constraints on the value of its parameters[18]) the properties of the demand function which in this case are:

- Homogeneity of degree 0 in prices and expenditures
- Expenditures shares sum to one

[18]For adding-up homogeneity and symmetry, the following restrictions must be satisfied: $\sum \alpha_c = 1; \sum \beta_c = 0; \sum \gamma_{c,c'} = \sum \gamma_{c',c}$

- The symmetry of the Slutsky matrix.

Usually, the model is specified as in equation 2.4. In the original article of Deaton & Mullbauer, the price index $P$ is defined as:

$$\log(P) = \alpha_0 + \sum_{c'} \alpha_{c'}\ w_{c'} \log P_{c'} + \frac{1}{2} \sum_{c'} \sum_{c} \gamma_{c,c'} \log(P_c) \log(P_{c'}) \tag{2.8}$$

As formulated in equation 2.5, we use a Stone's price index ($P^*$) instead of $P_h$, in which case, we switch to a Linear Approximate AIDS (LA/AIDS) model (Blanciforti and Green, 1983)[19]. It allows us to perform a regression without a temporal dimension in the price variables.

The Stone price index, approximating the general level of prices, is defined as :

$$\log(P^*) = \sum_{c=1}^{C} w_c \log p_c \tag{2.9}$$

Moreover, to integrate the price variables, we use the annual Consumer Price Index (CPI) published by the french national statistical institution INSEE where prices are expressed by products according to the COICOP nomenclature. Following Ruiz and Trannoy (2008) and using the CPI at the COICOP 3 level of product classification, in order to overcome the stringency in price variability (for which we only have one point of observation), we construct individual price indexes $P_{h,c}$ and distinguished product for every observation of products consumption by one household $h$. This individual price index is constructed as the average price index for each subgroup of products, weighted by the expenditure shares of a subgroup of products for each household. As an example, considering product A is composed of subgroup products B and C, the personal price index $P_h^A$ is expressed such as:

$$\log\left(P_h^A\right) = \frac{p^B w_h^B + p^C w_h^C}{w_h^B + w_h^C} \tag{2.10}$$

[19]The LA/AIDS approach assumes that prices are highly collinear, in which case $P$ may be proportional to $P^*$.

This method allows for introducing more price variability between households, depending on the underlying structure of their expenditures. Formally the model that we are going to estimate is written as follows:

$$w_{h,c} = \alpha_c + \sum_{c'} \gamma_{c,c'} \log(P_{h,c'}) + \beta_c \log\left(\frac{Q_h}{P*}\right) + \epsilon_{h,c} \tag{2.11}$$

Where $Q_h$ is the total expenditures of household $h$, $P*$ is the Stone price index, $w_{h,c}$ the weight of product $c$ in the household $h$ total expenditures, $P_{c'}$ is the price of product $c'$ and $\epsilon_{h,c}$ is an error term. $\alpha_c$, $\gamma_{c,c'}$ and $\beta_c$ are coefficients. We perform the LA/AIDS regressions using the R package *micEconAids* on the full sample and subgroups of deciles of the standard of living income, excluding Education expenditures[20]. In the following, we will only present the results for the direct elasticities. The results of the regression are reported in Appendix A.

The (Marshallian) uncompensated price-elasticity measures the relative change in expenditures as:

$$\eta_{c,c'}^{Marshall} = \frac{d\log Q_c}{d\log P_{c'}} = -\delta_{c,c'} + \frac{d\log w_c}{d\log P_{c'}} = -\delta_{c,c'} + \frac{\gamma_{c,c'}}{w_c} - \frac{\beta_{c,c'}}{w_c}\frac{d\log P*}{d\log P_{c'}} \tag{2.12}$$

where $\eta_{c,c'}^{Marshall}$ refers to allocations within the sample and keeping constant total expenditures $X$ and all other prices $(P_k, k \neq c')$ constant, $\delta_{c,c'}$ is the Kronecker delta ($\delta_{c,c'} = 1$ for $c = c'$ and 0 otherwise).

Using the Slutsky equation, we can derive the compensated (Hicksian) price-elasticity formula:

$$\eta_{c,c'}^{Hicks} = \eta_{c,c'}^{Marshall} + w_c(1 + \frac{\beta}{w_c}) \tag{2.13}$$

[20]The households misreport expenditures of education since the bulk of the cost is publicly supported. For this reason, we exclude it from the estimation

## Econometric results

The results are econometrically significant[21] We find hicksian elasticities with a range between 0.28 and -2.58[22] (see Table 2). The expenditure elasticities values indicate the effect of a marginal increase in income on expenditures.

Table 2.2: direct expenditures and price elasticities on the full sample

| | products | expenditures | hicksian | marshallian |
|---|---|---|---|---|
| 1 | Food and non-alcoholic beverages | 0.85 | 0.28 | 0.12 |
| 2 | Alcoholic beverages and Tobacco | 1.11 | -1.36 | -1.41 |
| 3 | Clothing and footwear | 0.99 | -0.72 | -0.77 |
| 4 | Housing, water, gas, electricity and other fuels | 0.61 | -0.67 | -0.76 |
| 5 | Furnishing and household equipment | 1.14 | -0.57 | -0.64 |
| 6 | Health | 0.71 | -0.62 | -0.63 |
| 7 | Transport | 1.52 | -1.23 | -1.43 |
| 8 | Communications | 0.52 | -2.58 | -2.61 |
| 9 | Recreation and culture | 1.25 | -1.06 | -1.17 |
| 10 | Education | 2.11 | -16.09 | -16.11 |
| 11 | Restaurants and hotels | 1.50 | -0.89 | -0.98 |
| 12 | Miscellaneous, goods and services | 0.87 | -0.22 | -0.34 |

We shall bear in mind that these elasticities results are associated with a basket of goods and services since we base the price variability on a COICOP 3 level of nomenclature[23]. Whether they are consistent with the literature, they, in some cases, differ from other estimations made on french data. (Ruiz and Trannoy, 2008) find lower elasticity (absolute) value on the same set of products, but with data from different vintage and with a QUAIDS specification (Banks et al., 1997). For instance, they find a direct price elasticity for Transport of -0.55 against -1.23 in our estimation. Using monthly price data rather than annual, as we did, could explain the difference in the results. (Clerc and Marcus, 2009) in similar work, focused on energy products price-elasticities estimations find for different populations a price-elasticity for fuel

[21] Regressions results are reported in Appendix A.

[22] Exception made for the expenditures for education, which is specific because the bulk of spending in education is publicly funded and therefore has been a drop from our sample.

[23] For this reason, we were not able to distinguish energy products explicitly.

between -.068 and -1.51 depending on their use of a private car (households using their car for commuting or not, living in a rural area or not, being poor or wealthy).

For the expenditure items Transport and sheltering, which include the consumption of energy products for travel and heating, respectively, other studies find results in the same order of magnitude[24]. Labandeira et al. (2017), in a recent meta-analysis, finds an average estimate of long-term price elasticity of 0.6 for energy products and slightly lower for studies that adopt a demand system (-0.789). In another study, using transport-related consumption items, Brännlund and Nordström (2004). even find price elasticities below -1 [25]

Table 2.3: price (hicksian) elasticities for the different deciles of income

| | Products | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 | D10 | Full sample |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Food and non-alcoholic beverages | 0.49 | 0.15 | 0.16 | 0.22 | 0.30 | 0.27 | -0.04 | -0.09 | -0.07 | 0.31 | 0.28 |
| 2 | Alcoholic beverages and Tobacco | -1.41 | -1.51 | -1.55 | -1.38 | -1.25 | -1.38 | -1.36 | -1.18 | -1.37 | -1.33 | -1.36 |
| 3 | Clothing and footwear | -0.94 | -0.62 | -0.67 | -0.70 | -0.61 | -0.77 | -0.66 | -0.71 | -0.76 | -0.64 | -0.72 |
| 4 | Housing, water, gas, electricity and other fuels | -0.73 | -0.76 | -0.76 | -0.97 | -0.55 | -0.81 | -0.57 | -0.54 | -0.69 | -0.55 | -0.67 |
| 5 | Furnishing and household equipment | -0.37 | -0.57 | -0.46 | -0.48 | -0.57 | -0.66 | -0.64 | -0.63 | -0.70 | -0.60 | -0.57 |
| 6 | Health | -0.42 | -0.54 | -0.56 | -0.64 | -0.71 | -0.71 | -0.69 | -0.64 | -0.68 | -0.71 | -0.62 |
| 7 | Transport | -0.93 | -0.93 | -1.09 | -1.25 | -1.25 | -1.34 | -1.56 | -1.45 | -1.65 | -1.79 | -1.23 |
| 8 | Communications | -4.58 | -2.73 | -2.84 | -1.29 | -1.83 | -1.02 | -1.90 | -2.31 | -1.44 | -2.12 | -2.58 |
| 9 | Recreation and culture | -1.38 | -1.19 | -1.21 | -1.14 | -1.04 | -0.98 | -1.02 | -0.97 | -0.90 | -0.61 | -1.06 |
| 10 | Restaurants and hotels | -1.98 | -2.13 | -1.38 | -1.34 | -1.03 | -0.88 | -0.76 | -0.60 | -0.50 | -0.77 | -0.89 |
| 11 | Miscellaneous, goods and services | -0.43 | -0.19 | -0.27 | -0.23 | -0.20 | -0.14 | -0.12 | -0.08 | -0.09 | -0.27 | -0.22 |

Regarding the estimations by decile of income of standard of living, the results are consistent with the aggregate one, the estimated elasticities being distributed around the average value. However, the ordinal ranking by decile is not necessarily the same, depending on the good type. It seems that there is a distinction that operates in the price-elasticities estimation. Concerning Housing, water, gas, electricity, and other fuels, we observe a first increasing and then decreasing elasticity by income level. Concerning food products and transportation, households' demand becomes more and more elastic with their income (this is much more straightforward for transportation than for food products). Since this product classification aggregates different goods,

[24]The majority of studies that estimate price elasticity econometrically use a product nomenclature that distinguishes specific energy products associated with a composite good that aggregates all other items.

[25]With a QUAIDS model, the authors find uncompensated own price elasticities estimates: Petrol: -1.18, Public transport -0.65; Other transports: -1.30 Heating -1.81 Other goods -1.06.

it is uneasy to ascertain what component drives this effect. We can advance as a proposition to explain that the share of transportation expenditures dedicated to basic and, therefore, less elastic economic activities such as work-home commuting is more prominent for the poorest households and decreases with the level of expenditures. Finally, for superior goods such as communication, recreation and culture, restaurant and hotels, health, furnishing, and household equipment, we observe a more apparent trend where the demand becomes more and more elastic with the income level.

Therefore, the effect of a carbon tax fiscal shock would depend on the expenditures and shares of the households but also on the price reaction they would adopt. These two appear to be income-dependent. In the next section, we will simulate a carbon tax fiscal shock to estimate the distribution of impact we could expect from it.

## 2.4 Scenarios

The primary objective of this paper is to empirically assess the trade-off between the efficiency of climate policies and equity concerns, embodied by the degree of the regressivity of the carbon tax on classes of households. Before using a general equilibrium setting, we will, in the first part, explore several distributional impacts on households of different climate policies through micro-simulations.

### Analytical framework

Our analytical framework consists of a static analysis of the carbon tax shock on a demand model with micro-simulations and CGE simulations performed with the improved ThreeME model described in 2.2. The micro-simulations are based on a static demand model with elasticities calibrated according to the estimation results in the previous section. We start by considering the set of expenditures of each household in our sample, which is composed of several products $i \in \{1, ..., i, ..., I\}$. The shock on product price depends on the carbon tax rate and its base in the scenarios presented below. Its impact on the level of expenditure is the product of the quantities $Q_i^0$ consumed and their price $P_i^0$, which we consider to be equal to 1 in the reference scenario without loss of generalitySince $P_i^0 = 1; X_i^0 = Q_i^0$..

In order to disentangle the effects on the expenditures $X_i$ and the quantities $Q_i$ consumed, we proceed to the decomposition of the price effect $dP_i$, such as:

$$\frac{dX_i}{X^0} = \frac{dP_i}{P_i^0} + \frac{dQ_i}{Q_i^0} = \frac{dP_i}{P_i^0} + \frac{dP_i}{P_i^0}\frac{P_i^0}{dP_i}\frac{dQ_i}{Q_i^0} \tag{2.14}$$

Rearranging the terms leads to the following:

$$\frac{dX_i}{X_i^0} = \frac{dP_i}{P_i^0}\,(1 + \frac{P_i^0}{Q_i^0}\frac{dQ_i}{dP_i}) = \frac{dP_i}{P_i^0}(1 + \eta_i) \tag{2.15}$$

Subsequently, the quantity variation is:

$$\frac{dQ_i}{Q_i^0} = \frac{dX_i}{X_i^0} - \frac{dP_i}{P_i^0} = \frac{dP_i}{P_i^0}(1 + \eta_i) - \frac{dP_i}{P_i^0} = \frac{dP_i}{P_i^0}\eta_i \tag{2.16}$$

The variation of expenditures and quantities depends on the relative price variation $\frac{dP}{P^0}$ and the value of the price elasticity $\eta$.

The new expenditures after the introduction of the carbon tax (CT) $X^{CT}$ and quantities $Q^{CT}$ are expressed:

$$X_i^{CT} = X_i^0 + dX_i = X_i^0(1 + \frac{dX_i}{X_i^0}) = X_i^0(1 + \frac{dP_i}{P_i^0}(1 + \eta_i)) \tag{2.17}$$

$$Q_i^{CT} = Q_i^0 + dQ_i = Q_i^0(1 + \frac{dQ_i}{Q_i^0}) = Q_i^0(1 + \frac{dP_i}{P_i^0}\eta_i) \tag{2.18}$$

Similarly, since the GHG emissions are linearly related to the consumed quantities of goods and services, the carbon footprint variation can be expressed such as:

$$f_i^{s,CT} = f_i^{s,0} + df_i^s = e_i^s\ Q_i^0 + e_i^s\ dQ_i = Q_i^0(e_i^s + \frac{dP_i}{P_i^0}\ \eta_i\ e_i^s) \tag{2.19}$$

## Parameters

We describe in this section the different scenarios we simulate using the model that differ along four dimensions: (i) the tax base, which is the source of emissions subject to carbon pricing, (ii) the mode of redistribution, (iii) behavior of households and (iv) the presence of supply-side effects. Carbon tax rates are calibrated so that carbon tax receipts account for 1% of aggregate household income for every simulation and in all analytical frameworks. Our scenarios, therefore, differ from the elements they include in their setting.

### (i) Tax base

Concerning the tax base, we rely on different metrics of carbon accounting. We first consider direct household emissions that result from energy use by the final consumers. We then accounted for indirect emissions from production processes and embodied in the goods or services serving a final use. We finally aggregate these two to account for a carbon footprint metric. Since we rely on a national model, we do not account for

imported emissions in the CGE case. Without loss of generality, considering domestic emissions as part of indirect emissions has no impact on the micro-simulations of the redistributive effects since we assume that the share of imported emissions is constant per product and the same for all households. Therefore, there is no distortionary effect induced by the introduction of a domestic tax.[26]. Relying on a general equilibrium approach and accounting for a comprehensive representation of a national economy, we adopt the concept of territorial emissions[27] to consider the tax base of the carbon tax. Firms are imposed on their $CO_2$ emissions associated with production (energy use from the supply side), and households on their direct emissions. Compared with the previous section, we changed our perspective of emissions accounting, considering indirect emissions from a consumption-based approach where emissions are imputed to the final consumer.

**(ii) Redistribution**

Regarding the mode of redistribution, We study three measures of income allocation that differ in their capacity to discriminate against households on their income level. The degree of discrimination allows for modulating the amount of the transfers accordingly to the individual or group-based households' income. Since we are scrutinizing regressive tax schemes, the redistribution measures seek to counterbalance the initial tax effect by lowering the transfer amount with the levels of households' income. The first redistribution measure assumes an equal, direct rebate to all households. This measure assumes no discrimination among households and therefore serves as a benchmark case. In the second one, the amount of the rebate depends on the average decile income to which the household belongs. In this setting, only vertical hetero-

[26]Moreover, the substitution effects between the domestic economy and the rest of the world have been neutralized.

[27]In comparison with the previous section, we operate a complete shift on the concepts of emissions. Since we represent domestic productive activity, we directly linked domestic indirect emissions to them. Regarding the scope, we do not account for imported emissions.

geneity is addressed. In the third and final one, the amount of the rebate depends on the individual household's income of standard of living[28]. We also consider that the collected carbon tax integrally funds the recycled income in all configurations. In the CGE setting, we introduce another redistribution option toward firms since we integrate a supply side. The amount collected on emissions from the production activities is then redistributed to firms directly as a payroll tax.

### (iii) Behavior of households

As to the households' response to the price change, we review four different cases. Two reference cases with ad-hoc values and two others taking econometrically estimated values from 2.3. In our first reference case, households are not responsive to price changes and therefore do not adapt their consumption pattern to the price shock. We refer to this setting as *ex-ante* evaluation[29]. Formally it corresponds to a null elasticity for all products. In the second reference case, we consider that households can react to price variation in such a way that they maintain their level of expenditures constant. The interest of this case, which we call *unit price elasticities*, is to consider that expenditures per product remain constant. Formally, all elasticities are set to -1.

In the first set of price-reaction, we consider that households react to price changes assuming they all adopt the same behavior, which is calibrated using the results of the estimations on the hicksian price elasticities for the whole sample from the household budget survey. We refer in this case to *homogeneous ex-post* behavior. In a second case, we still consider price-reaction, but this time using the estimation results for

[28]In terms of policy design, if the first case would correspond to an egalitarian form of redistribution, the two others can use income tax reporting as an information source to discriminate households. In the second case, the reversed amount is associated with the level of income and defined accordingly to income brackets, in this case, defined as deciles of income per standard of living—the third case where the amount is directly calculated from the individual income.

[29]To be noted that in public policies evaluation of impact studies, it is generally the case to consider no reaction from households in the funding of a policy as its budgetary impact.

each income decile, referring to *heterogeneous ex-post*. Comparing these two cases highlights the differences brought by specific behavior related to the class of income with respect to common behavior.

**(vi) Supply side effects**

The macroeconomic impact of a carbon pricing policy induces —at the global scale — a substitution of fossil fuels with other inputs. It leads to heterogeneous supply shocks in the different sectors' output prices, channeling through the other sectors of the economy. In turn, the substitution effect shifts inputs demand toward those becoming relatively cheaper. Among these other inputs, Capital and Labor constitute the primary sources of household income and are heterogeneously distributed among the classes of households, with the share of capital returns increasing with the income level. Therefore an initial shock in energy price can have a different effect on a household income, depending on its composition. In order to evaluate the contribution of *source-side* effect to the overall effect on households' real income, we compare two scenarios, one serving as a reference scenario. This reference scenario corresponds to the case where the supply side is not responsive to price and, therefore, only channels price effects through the production function without shifting its production technology (It is equivalent to considering a General Leontief production function of the economy). Formally, we constrain all the elasticities of substitution between inputs to be null.

In the second set, we calibrate the elasticities of substitution, taking a conservative value, namely 0.5, between all inputs in the production function. In addition, note that since there is an adjustment in the substitution effect reaction of a change in relative price, the diffusion of the effect is progressive in the downstream channel on production prices and, therefore, consumption prices[30]. Finally, we consider that there

[30]We do not take advantage of the elasticity of substitutions estimations conducted in chapter III since they are performed on a different sectors nomenclature. Moreover, we consider a general

is no substitution effect between domestically produced and imported commodities, the Armington elasticities being null in the two cases[31].

It leads us to 27 possible combinations of parameters between (i), (ii), and (iii) for the micro-simulations and even 108 with the macroeconomic model (iv). In order to specify our analysis, we will concentrate on 13 scenarios, each defined by a specific combination of parameters.

## Scenarios construction

We select representative scenarios to isolate some effects and successfully add new components to the scenario. Disentangling the different effects allows us to pin down key elements that drive redistributive effects. The scenarios are interlinked between them by the successive addition of one element from each dimension taken in our framework. For instance, regarding the step on the choice of the redistribution scheme on the distributional effects, we take as a common feature the whole set of emissions (direct and indirect) in the different scenarios. Similarly, the integration of households' behavior is based on a tax base on whole emissions associated with a lump-sum redistribution transfer scheme.

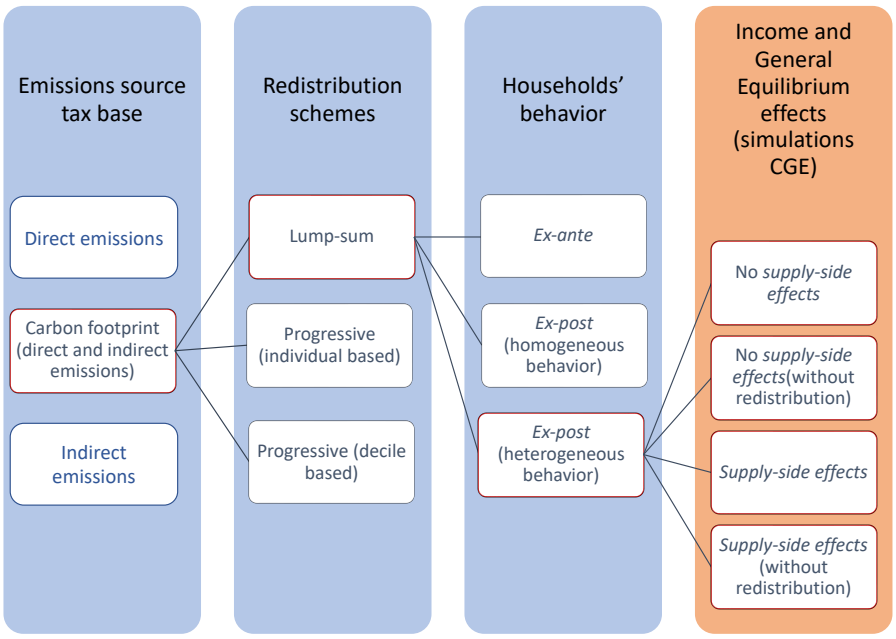
By default, we do not consider either redistribution schemes associated with the emissions source tax base or specific price-reaction from households (households keep constant their consumption, the variation of their expenditures reflecting the initial price variation induced by the shock). Figure 2.2 summarizes this process in constructing our scenarios and how they are interlinked.

We then consider three cases regarding the integration of price-reaction on the households' expenditures patterns and the fiscal impact they bear. The first three scenarios highlight the relative redistributive effects associated with the tax base.

setting to appreciate how households and income would react when considering the supply side.

[31] Alternatively, this is equivalent to considering that the rest of the world is also implementing a carbon tax at the same level, leaving relative prices between domestic and imported commodities balanced.

Figure 2.2: Summary of simulations conducted




Note: Reading is from left to right. The arrows indicate which case each dimension is retained for the following scenarios. The blue color highlights that scenarios are going to be analyzed in a micro-simulations setting, and the orange color that they are going to be analyzed in a general equilibrium framework

The three next ones consider the whole carbon footprint as the tax base but differ in the choice of their redistribution scheme. These nine scenarios are simulated with our micro-simulation model. We distinguish four scenarios in the CGE setting that focus on the combination of supply-side effects with redistribution measures toward firms proportionally to their production in real terms and to households through a proportional lump-sum transfer.

## 2.5 Results and discussion

Before presenting the results from the CGE simulations, we analyze some redistributive aspects of carbon taxing with static micro-simulations.

### The micro-simulations

The individual impact of the carbon tax is driven at first by the household's tax base, which depends on its consumption pattern, and the commodities taxed.

In all settings, the carbon tax remains regressive but shows some disparities according to the scope of emissions concerned by the taxing scheme or heterogeneous household behavior. The combination of more or less targeted redistribution measures also influences the tax's redistributive effects. Each subsection of this section is devoted to a specific aspect of redistributive impact, following the proposed articulation of the first three effects in Figure 2.2. All other simulations are reported in 2.B.

#### Tax base

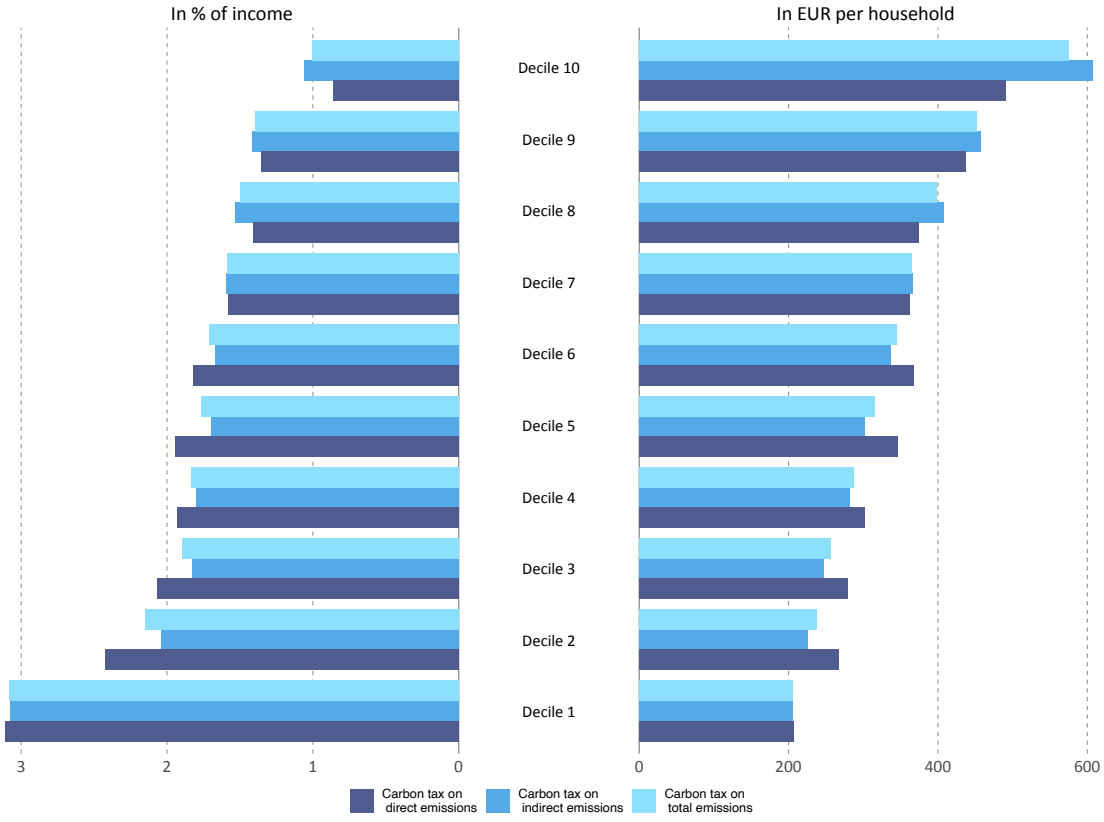
To analyze the difference brought by choice of the tax base, i.e., the type of emissions, we compare the effect of the carbon taxes on the general level of expenditures of households by class of income of standard of living (see Figure 2.3). As is the case for most indirect taxes, our carbon tax scenarios are all regressive and follow a similar pattern, though with specifics for nearly all the income distribution.

Households in the first decile are a special case. They are particularly affected by the carbon tax, which represents more than 3% of their income on average, with no real difference between the scenarios. For the rest of the population, the impact is, on average less, ranging from 2.3% to 0.8% per decile. Taxing direct emissions is relatively more regressive than taxing indirect emissions. The burden incurred

by households between the $2^{nd}$ and $7^{th}$ deciles is thus greater with a tax on direct emissions than indirect emissions.

In absolute value, the tax burden starts at 200 EUR on average for the first decile and rises to 600 EUR for households from the last decile when only indirect emissions are taxed. Taxing direct emissions appears to particularly penalize the households of what is generally called the middle-income class, which in our case comprises between the $2^{nd}$ and $7^{th}$ by choosing only to address direct emissions, which support an extra effort of XX EUR on average with respect to the case where all emissions would be equally taxed. Beyond these vertical redistributive effects, the dispersion of impacts within each income class is also significant.

Figure 2.3: redistributive impact of the carbon taxes



### Redistribution scheme

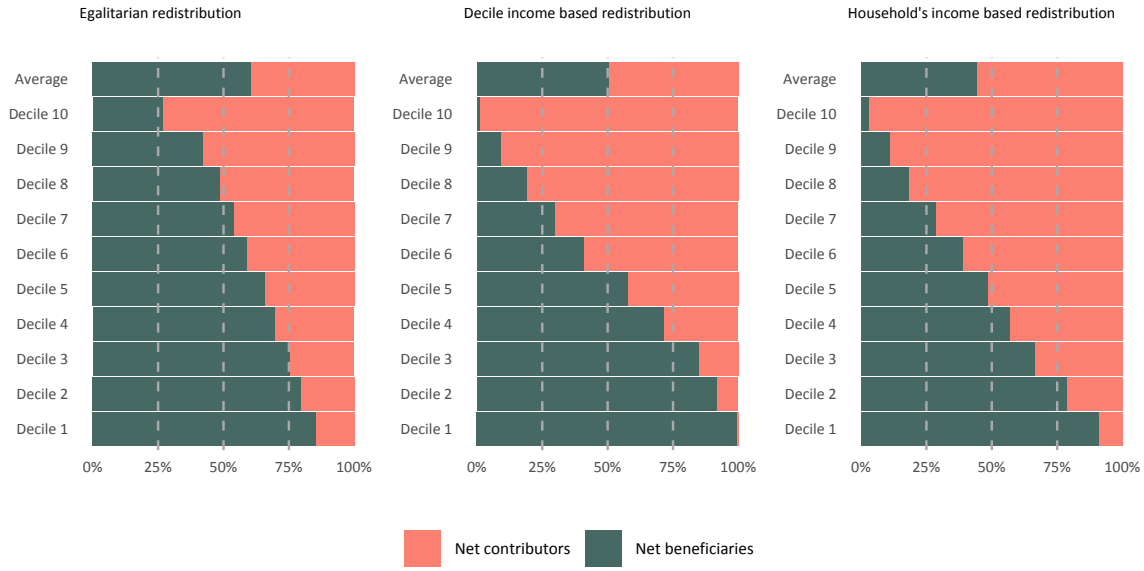
We only consider the carbon tax on total emissions (both direct and indirect emissions) from the previous part and focus on comparing the redistribution scenarios. As a benchmark, we take the case where there is no redistribution associated with the carbon tax. Full recycling of carbon tax revenues toward households can be seen as an income redistribution among households. If the tax depends on the consumption pattern of households, the redistribution in our cases depends solely on the standard of living income. Other redistribution schemes could be possible to assert, taking other socio-economic dimensions into account in the mechanism designs as done in Douenne (2020b); Berry (2019); Cronin et al. (2019).

In the first case, each household received an egalitarian income transfer of 353 EUR, which roughly corresponds to the tax borne by the $5^{th}$ decile of income. Therefore, on average, low-income deciles are net beneficiaries of this recycling scheme, whereas those with a higher income are net contributors. From Figure 2.4, we can see that, on average, 60% of the population benefits from an egalitarian form of redistribution, and the share of net contributors by decile of income increases with income. Among the 30% poorest households of the population, this share is 20%, against nearly 60% among the 30% richest.

Adopting a more progressive redistribution scheme would, as expected, reduce the share of net contributors among the lowest classes of income, but it also reduces it for the total population, to 44% in the case where it is based on the average incomes by decile, and to 50% when it is based on the individuals' incomes. For a decile income-based redistribution scheme where transfers are of different amounts according to the class of income, it increases the share of net beneficiaries within the 30% poorest households from 60% to 92% for the egalitarian case. In the case where the amount reversed to the households is calculated from their income, this increase is smaller and by 18.6% points of percent for these households with respect to the egalitarian

case. On the opposite side of the income ladder, the 30% of the richest households who benefit from the redistribution with these two options decreases by 75% (from a 40% share of net beneficiaries to 10% in both cases) The decile income-based criteria, contrarily to what we could expect, leads to a higher share of the beneficiaries among the 30% poorest households (for the 70% remaining households, this share is lower than for an individual-based-income transfer) than when the transfer depends on household's income.

Figure 2.4: Share of net contributors and beneficiaries by class of income of standard of living



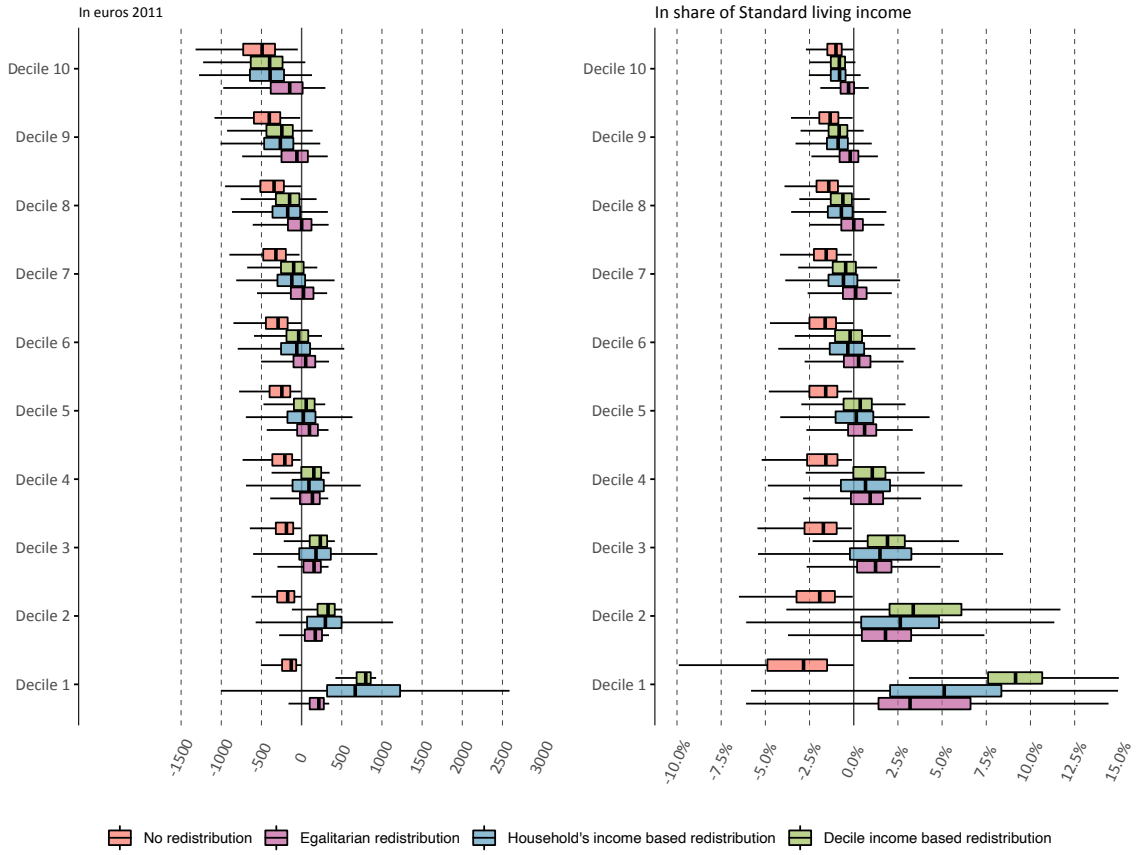

It can be explained when looking at the dispersion of the impacts within each income class (see Figure 2.5) and the fact that emissions are not perfectly correlated with income. Therefore, it creates windfall effects for a significant fringe of the population in the lower deciles, particularly for the first one where 75% of the distribution experienced an increase of their income after tax of more than 7.5% and on average of 9.2%.

It leads to a concentration of resources from carbon revenues on households in the first decile at the expense of a portion of other households whose income is close to

the median and above. When the transfer amount is calculated from the household's income, 75% of the population from the first decile has a net gain higher than 2.4%.

The distribution of emissions is not perfectly correlated to income. The cost to cover a major share of the population within the poorest households (the 30% poorest of the total population) when indexing the transfers is relatively high.

Figure 2.5: Distributive effects of the carbon tax and the redistribution schemes on the classes of income of standard of living




### Households' behavior

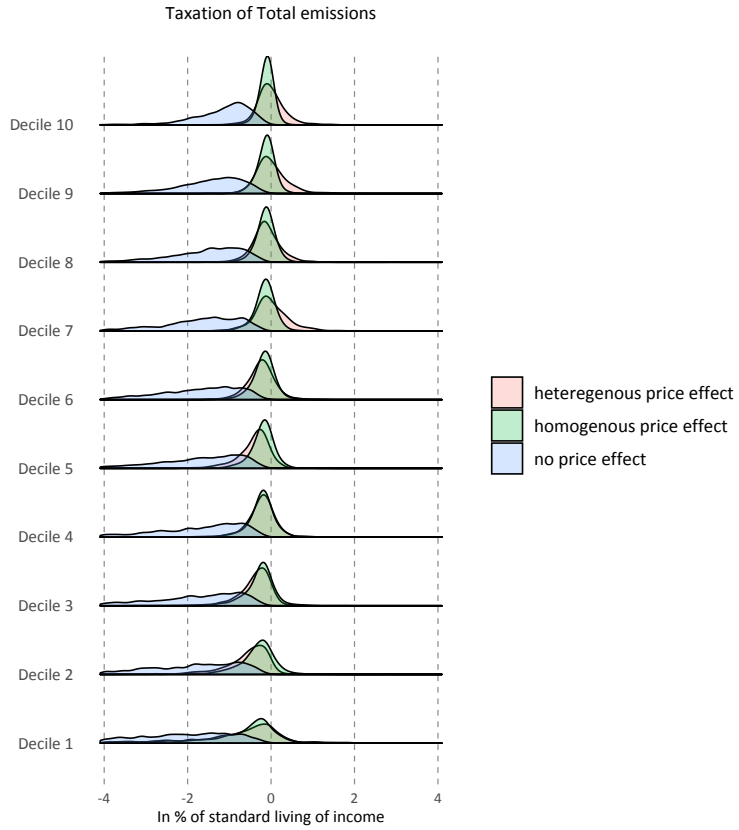
Taking into account the reaction of households to the price shock leads them to modify their spending on each item according to the value of the price elasticity used in the simulations and its price variation. First, from 2.6, we can already notice the heterogeneity of the initial impact of the price shock across income groups, with

the kurtosis of the distributions increasing with income level, meaning the horizontal heterogeneity is less important in upper-income classes than in lower-income classes. By comparing the red zone to the green zone, we can infer how each income group modifies its consumption and, thus, its expenditure pattern relative to the average household response. The richest 40 % of households respond more to the initial price change, thus mitigating the initial fiscal impact when compared with a uniform behaviour[32]. The fact that different income groups respond differently to the price shock amplifies the initial regressive effect of the carbon tax. Indeed, the ability to reduce their expenditures is greater among high-income households than for other categories of households, which experience a stronger budgetary impact when the behavior is dissociated by income class than when their reaction is considered homogeneous with the whole population. It shows that although the effect is reduced in absolute terms, the introduction of differentiated behavior can increase the dispersion of effects and thus contribute to increasing the regressivity.

The desired effect of the carbon tax is to decrease emissions, which will also depend on the response to price changes in different configurations, as shown in 2.7. We assume a unit price elasticity (in absolute value) for all products and all income classes as an alternative reference point. Only the composition effect of the initial consumption structure differentiates households in this configuration and leads to a decrease of 2.26% in household emissions. In other words, the share of expenditure on $w$ products remains constant. The assumption of a homogeneous distribution of price elasticities by product between income classes already leads to a slight heterogeneity between households since the observed emission variation is between 1.94% and 2.03%. The differences in emission variations are explained here by the different contributions of each consumption item to the total variation, which a differentiated household consumption structure can only explain.

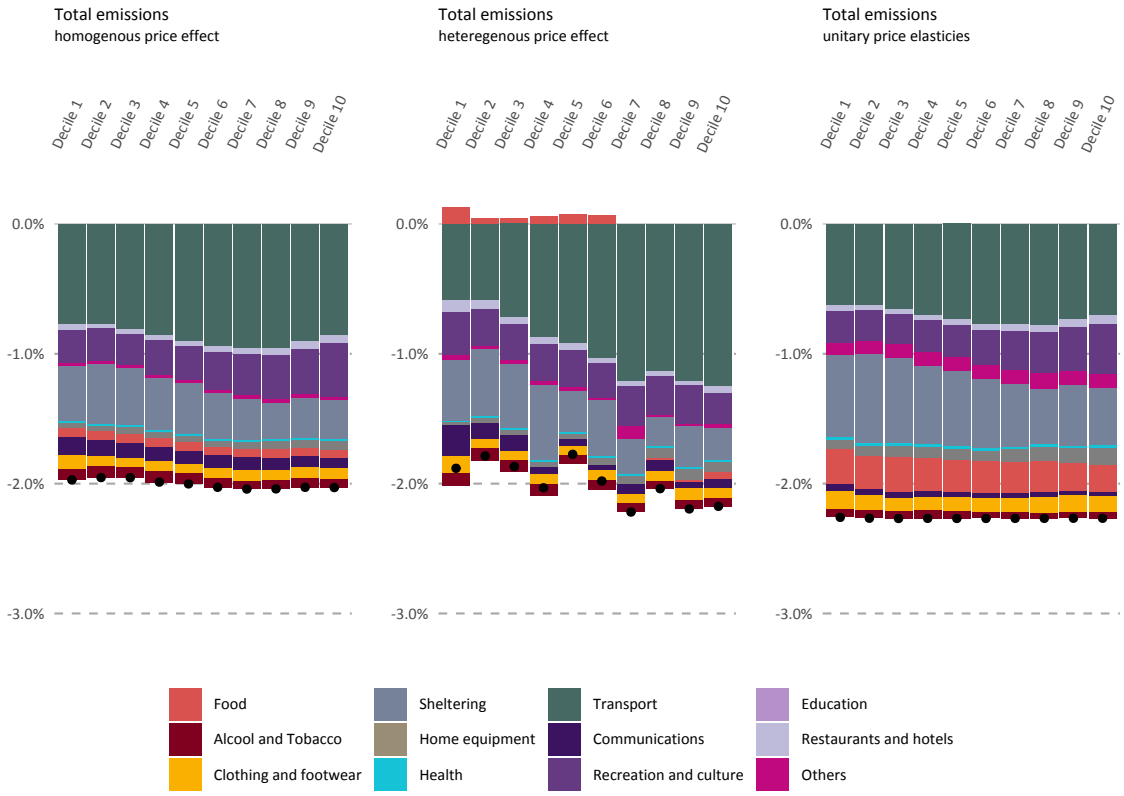
[32]Visually, this reflects with a part of the red distribution shifting to the right of the green one.

Figure 2.6: Impact of a carbon tax on emissions on the deciles of income




The introduction of differentiated behaviors leads to a modification of the distribution of these effects. Some categories of households are thus able to reduce their consumption (and therefore their emissions) relatively more than others. Whereas households from the $7^{th}$, $9^{th}$ and $10^{th}$ deciles reduce their emissions more than on average, those belonging to the $2^{th}$, $3^{th}$ and $5^{th}$ deciles emissions decrease the least. The other households show a total variation that remains relatively close to the average. The differences in reaction to the transportation item mainly explain the total variation observed, especially for high-income households. Conversely, the emissions associated with the sheltering item are the ones that decrease relatively the most for low-income households. In total, these two items contribute to 67.23% of the total reduction in emissions. The contributions of the other consumption items to this total variation are much more homogeneous between households.

Figure 2.7: $CO_2$ Emissions reduction induced by the carbon tax




We do not explore other dimensions to consider beyond the household's income in the calculations of a redistribution mechanism policy. However, other criteria should also be considered to compensate the most severely affected households without creating major windfall effects. It should be noted that in the case of direct emissions taxation, the heterogeneity is even wider than for a broader scope of taxed emissions, and these effects would be amplified[33].

The change in emissions here only comes from a change in household behavior, whereas a carbon tax on indirect emissions should result in a change in companies' production costs. The variation of these costs will lead these companies to modify their production technology by a relative decrease in using the most emitting production factors, principally fossil fuels. In the next section, we will integrate into a simulation framework the consideration of the productive sector in explaining the

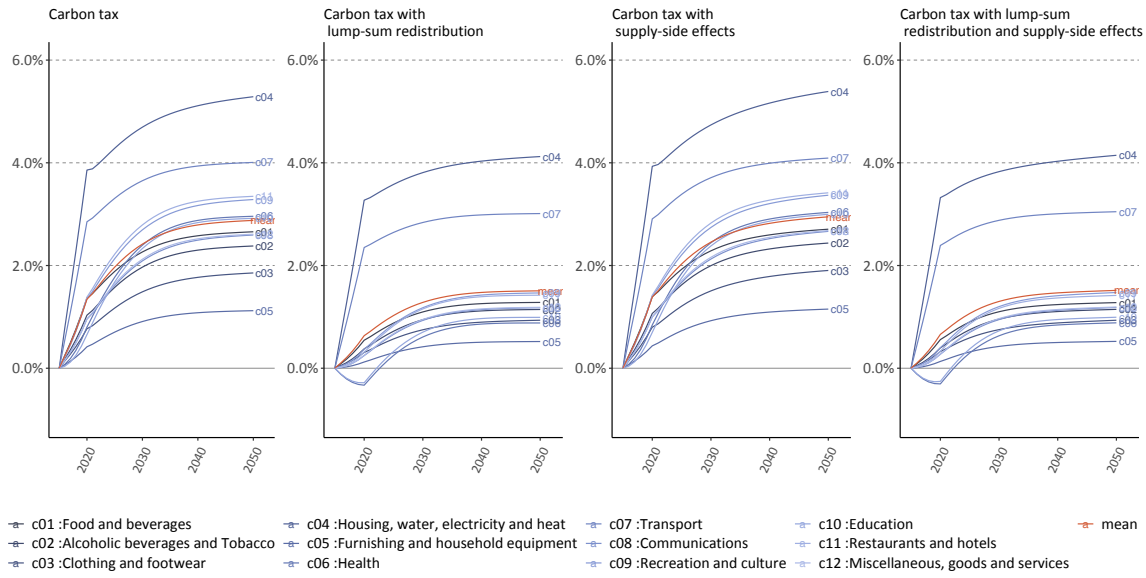
[33]Results are presented in Appendix B.

variations of emissions from consumption and imputed to households for comparison.

## The macroeconomic dimension

The introduction of a carbon tax increases prices proportionally to their carbon intensity. We can see from Figure 2.8 that products associated with direct emissions from households (for Transport and housing purposes) are those for which their prices increase the most, with respectively 5.3% for Housing, water, gas, electricity, and other fuels and 4% for transports. On average, prices increase by 1.3% in the short term and converge to a permanent increase of 2.9% in the long run since indirect emissions recycling is channeled toward firms. Implementing a recycling scheme almost halves the inflationary pressure, with average price shifting from 0.6% in the short term to 1.5% in the long term.

Figure 2.8: Price variation by product




### The macroeconomic effects

The negative contribution of implementing the recycling scheme can be seen as counter-intuitive since it exerts a supplementary demand, expecting to increase the price. However, the dominant effect at play is not associated with the household's demand but rather with the supply side. The redistribution of carbon revenues toward

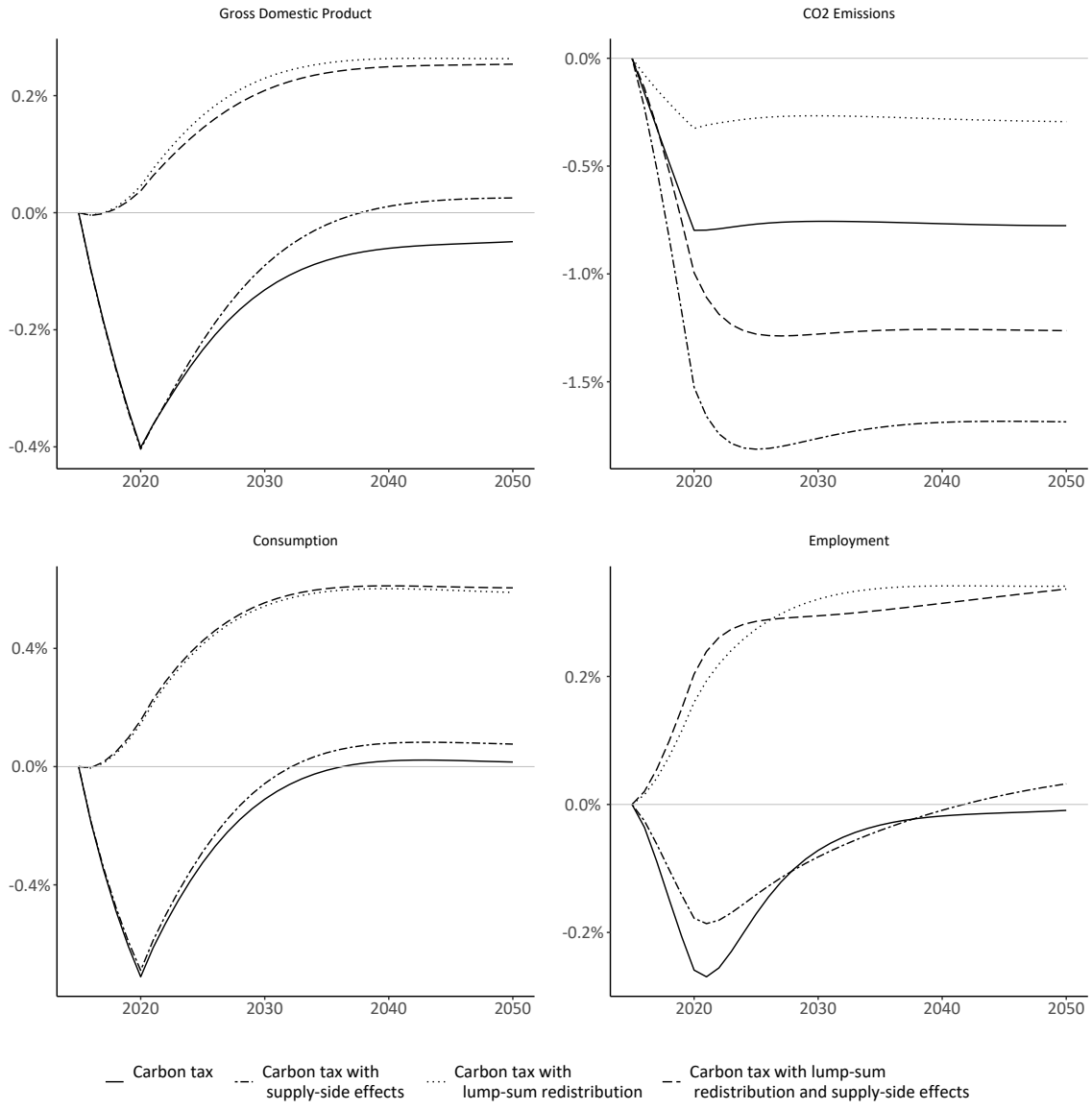
firms tempers the overall production cost inflation. It is to be noted that substitution effects in the production process merely influence the price dynamics, shifting further up the variations.

We find a short-term GDP decrease with the progressive introduction of the carbon tax, from 2015 to 2020, with an estimated reduction of -0.4% compared to the baseline at this date. This reduction in economic output results directly from the price effect, substitutions effects reversing this trend afterward, processing to a reallocation of households' expenditures, which drives the shift in the productive structure. The same analysis applied to aggregate household consumption, with a drop of its level by 0.55% in 2020, with a progressive return to its baseline, which can also be permanently greater in the event of substitutions within the production process. Long-term GDP converges toward a stable level, above the baseline line when considering supply-side effects but without it. The effect on employment, as for the general level of activity, is negative in the short-term with an estimated reduction of between -0.28% and -0.16%, depending on the inclusion of supply-side substitution effects, and converging at least toward their baseline level, and even slightly above when labor can partially replace energy uses. The CO2 emissions are also permanently reduced by -0.25% through expenditure reallocation. The reduction of energy use from the supply side leads to adding 1.4% of emissions reduction, reaching a -1.65% constant long-term emissions reduction when supply-side effects are considered.

The recycling of the carbon tax receipt toward economic agents leads in the short-term to offset recessive effects on the general level of activity, consumption, and employment. Households on an aggregate level do not experience a net loss in their purchasing power and proceed to reallocate their expenditures accordingly to the new relative prices, even leading to an increase in their consumption in the long-term by 0.55%.

The GDP and employment increase to 0.3% in the long term. The contribution

Figure 2.9: Deviation from baseline along four economy-wide indicators




of supply-side effects seems near null to explain these dynamics, with the recycling of carbon tax receipts being the major effect at play. However, regarding emissions, differences in long-term dynamics subsist. The recycling scheme leads to lower emissions reduction induced by the tax, but not completely, with a long-term reduction shifting from -0.8% to 0.4% without supply effects and from -1.7% to -1.2% when considered. The permanency of the emissions reduction results from the structural changes in the production function and consumption patterns, not from the downsiz-

ing of the economic activity. Long-term trends in emissions in our scenarios are driven by changes in relative energy prices, which result from the introduction of a carbon tax. It is, therefore, possible in our framework to observe a double dividend, in terms of consumption, activity, and employment, with a decline of $CO_2$ emissions. The introduction of a recycling scheme in association with carbon taxing can be interpreted as an economic buffer of the recessive impact the carbon tax bears on society, to the extent of a less significant emissions reduction. It highlights the cost-efficiency trade-off in the design of the carbon tax, either having a starker reduction of emissions with an overall economic cost or proceeding to income transfers to cover this cost but with a more limited emissions reduction. The more the supply side can shift its production process in reaction to price variation, the more this cost will be lowered. In the next section, we will explore these policies' redistributive impacts.

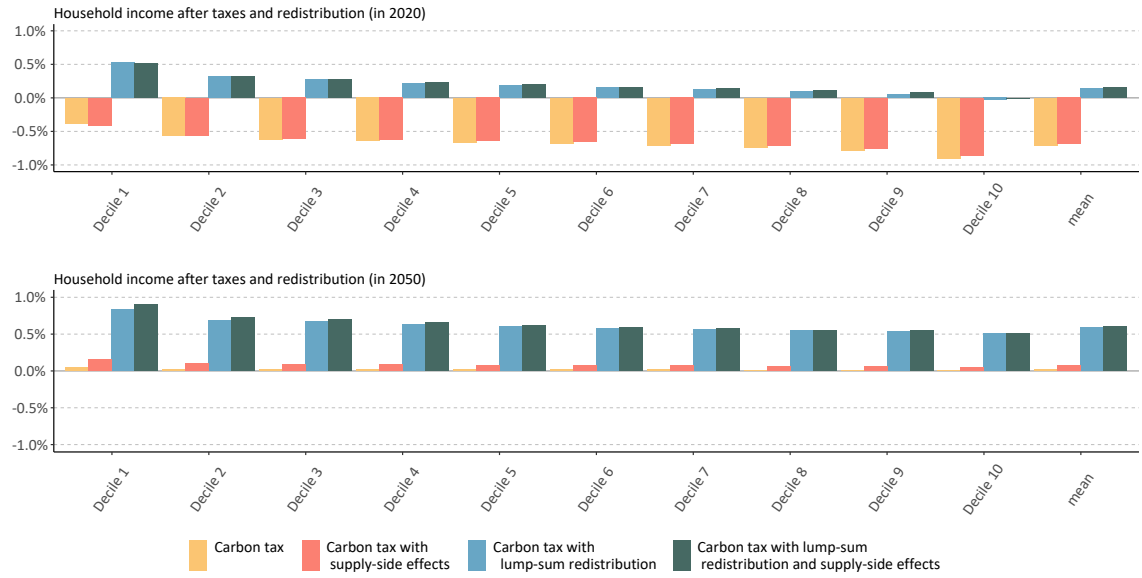
### The redistributive impacts

The redistributive impacts in our CGE modeling approach eventually rely on several factors, which are challenging to independently tract. At first, the structure of households' expenditure bundle and income will lead to different expositions to the initial shock. Second, the specific distribution of parameters for their consumption function conduct the households to react differently to a similar shock in price.

The real income reduction effect comes through two channels: A global activity recession and price inflation. The initial shock in price lowers final consumption, which in turn impacts production and, therefore, the global income structure of the economy. We find that the real income reduction is progressive with the income level (see Figure 2.10). On average, households face a downsize of their real income of 0.6% in the short term, which progressively vanishes in the long term. The richer the households, the greater the effect. When the 10% poorest households experience a decline of the real income slightly under 0.4%, the 10% richest households face

a 0.9% decrease in their real income. The other income groups experience a loss between 0.57% and 0.79%.

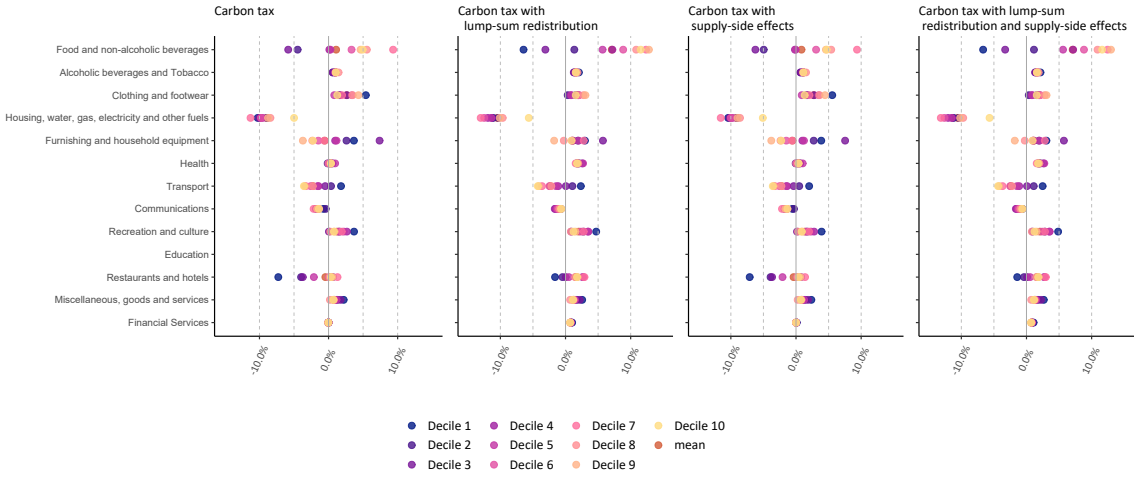
Figure 2.10: Variation of households' incomes in real terms




The lump-sum redistribution proportionally benefits the poorest income groups of households, at least in the short term. The first decile has a higher real income with respect to the baseline, up to 0.5% from the lump-sum transfers. The gain decreases with the income level to become even null for the last decile. In the long run, the gain, despite staying regressive with the income, tends to be less dispersed and, on average close to 0.5%. As for the price variation, the supply-side effects do not significantly change the variation in the real income, lowering the initial fiscal shock. Figure 2.11 shows a variation of consumption (in real terms) in 2050 for each decile and each commodity. These results capture the price effect of the tax (as in the previous section), adding cross-price effects, which proceed to the rebound effect in terms of consumption expenditure allocation. Therefore it is hard to disentangle the contribution of each effect to the observed variation in consumption. However, we can make some remarks on the results presented in this figure. First, the supply-side effect, as a whole, does not affect the household's modification of the consumption

bundle. The choice of a constant value for the elasticities of substitution in the production function certainly explains this result. Choosing another distribution of elasticity parameters would introduce heterogeneity in the production price formation mechanism between sectors, which should reflect household expenditure allocations. Moreover, income transfers do not result in a significant change in the variation, except for Food products, which consume more than income groups. The consumption of the commodity Housing and energy commodities decreases for all households by about 15%.*Food* and *Restaurant and Hotels* consumption decrease for the poorest households (the three first deciles) but remains constant or increases for the others. Consumption of *Transport* also decreases but slightly increases for the two lowest deciles. We observe an opposite effect for *Furnishing and households equipment*

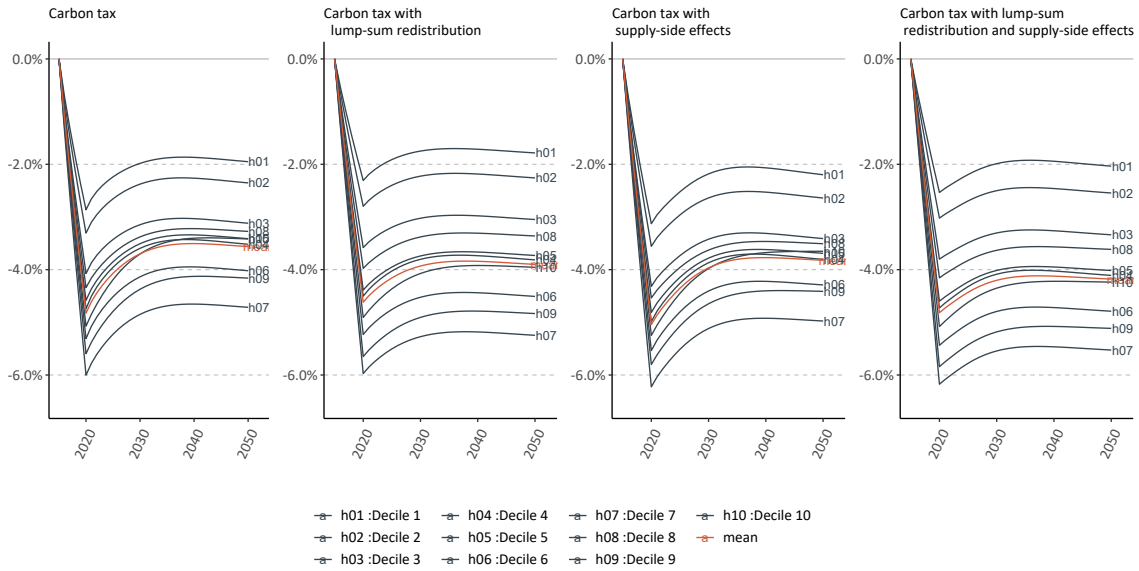
Figure 2.11: Variation of consumption in real terms




The emissions reduction dynamic of the different income deciles follows a similar pattern and distinguishes themselves on the shock amplitude (see Figure 2.12). After having an instant drop in emissions to a minimal level, CO2 emissions bounce back to adjust to a long-term level slowly. On average, households experience an immediate reduction of their emissions of 4.8, which converges afterward to a 3.5% decrease in emissions. Recycling the tax income leads to slightly tempering the short-term shock (-4.6 %) but leads to a greater reduction in emissions (- 3.9%) in the long

term. Supply-side effects contribute marginally to the reduction of households' indirect emissions, with a contribution of -0.25% without a reduction scheme and 0.35% when one is implemented.

Figure 2.12: Variation of $CO_2$ Emissions by decile of income and for each scenario




Regarding how this emissions reduction is distributed among the population, we observe a wide dispersion around the mean. When households from the first decile decrease their emissions by 2.8% following the introduction of the carbon tax, households from the $7^{th}$ decile exhibit the greatest variation with a 6% reduction. We observe that households experiencing an emissions reduction greater than the average belong to the richest households (from the $6^{th}$,$7^{th}$, $9^{th}$ deciles of income), and those having smaller variation belong to the poorest[34]. The rebound effect associated with the recycling scheme and its income effect appears to enhance the variation in $CO_2$ emissions.

[34]It cannot, however, be stated as a general observation since for instance households from the $8^{th}$ decile reduce their emissions less than the whole population on average.

## 2.6 Conclusion

The objective of this chapter was to perform simulations of carbon taxes at the micro and macro levels. We also estimated econometrically the price elasticities for a category of 11 products and each income decile, thus highlighting the contribution of heterogeneous consumer behavior in analyzing the redistributive effects associated with a carbon tax. We find that the wealthier a household is, the greater its reaction to price changes. Depending on the tax base chosen, horizontal heterogeneity differs significantly, being more important when only direct emissions are taxed. Regarding vertical distributional effects, indirect and direct emissions taxation shows a similar regressive profile with household income, with indirect taxation of emissions being relatively less regressive.

Introducing a redistribution system reverses the tax's regressivity, leading to a progressive tax system. Egalitarian redistribution covers up to 80% of the poorest 30% of households but results in a larger fiscal impact for those who still suffer a net loss. Alternative redistribution systems, adjusted based on household income, could cover these households, but this also leads to a decrease in the average transfer to the other households and even for part of those in the third decile.

When considering carbon taxation as an essential tool to reduce GHG emissions, it seems crucial, for several reasons, to take into account the source of emissions. Direct emissions, which account for less than one-fifth of the total French carbon footprint, seem to be low-hanging fruit in a decarbonization strategy and easier for policymakers to impose. The scientific assessment of the carbon content of an energy product or the pre-existing energy taxation system argues in favor of creating this tax base. However, indirect taxation of emissions, domestic (representing 35.3% of the total carbon footprint) or imported (47.2%), accounts for the bulk of GHG emissions. Despite a lesser effect on emissions reduction, it also ensures less distortion on households, which seems easier to compensate with a progressive redistribution

system and would lead to more energy efficiency.

Extending the analysis to alternative redistributive measures, particularly incorporating vertical heterogeneity, would clarify the question of who might be eligible for specific transfers. In the same vein, considering redistribution scenarios of carbon tax revenues with different earmarking between companies and households would allow us to better characterize this issue of balance between equity and efficiency in the construction of climate policies. Indeed, the use of these revenues is what, according to our results, mainly characterizes the determination of the overall effect on the economy, whether in terms of activity, consumption, and emissions, and the redistributive effect on households. The trade-off here is to choose between a redistribution to firms, which in our simulations is accompanied by a gain in investment and job creation (to a lesser degree) and increased efficiency in emissions reduction, and a redistribution to households, which moderates the initial income effect, but also leads to an increase in real income higher than 0.5% for all income classes in the long term. Comparing different rules of splitting carbon tax receipts between firms and households would allow better pinning this trade-off between equity and efficiency and the underlying tension between short-term concerns and long-term goals.

## 2.A Appendix A: Estimation results

The table present the results of the estimations for the $\alpha, \beta$ and $\gamma$ parameters from the equation 1. Standard deviation are into brackets and the stars indicate the level of significance (*, ** and *** at the 10%, 5% and 1% threshold).

Table 2.4: Estimation results

| Products | $\alpha$ | $\beta$ | $\gamma^1$ | $\gamma^2$ | $\gamma^3$ | $\gamma^4$ | $\gamma^5$ | $\gamma^6$ | $\gamma^7$ | $\gamma^8$ | $\gamma^9$ | $\gamma^{10}$ | $\gamma^{11}$ | $\gamma^{12}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 01 | $0.292^{***}$ | $-0.026^{***}$ | $0.854^{***}$ | $-0.115^{***}$ | $-0.105^{***}$ | $0.063^{***}$ | $0.066^{***}$ | $-0.009^{**}$ | $0.011^{**}$ | $-0.215^{***}$ | $-0.02^{***}$ | $-0.161^{***}$ | $-0.204^{***}$ | $-0.165^{***}$ |
| | (0.01) | (0.001) | (0.039) | (0.005) | (0.019) | (0.008) | (0.007) | (0.006) | (0.006) | (0.013) | (0.003) | (0.021) | (0.016) | (0.014) |
| 02 | $0.008^{**}$ | $0.003^{***}$ | $-0.115^{***}$ | $0.046^{***}$ | $0.024^{***}$ | $0.023^{***}$ | $-0.007^{**}$ | $-0.004^{**}$ | $0.038^{***}$ | $0.009^{***}$ | $0^{**}$ | $0.004^{**}$ | $0.014^{***}$ | $-0.034^{***}$ |
| | (0.004) | (0.001) | (0.005) | (0.003) | (0.003) | (0.004) | (0.002) | (0.001) | (0.003) | (0.002) | (0.002) | (0.002) | (0.003) | (0.004) |
| 03 | $0.09^{***}$ | $-0.002^{**}$ | $-0.105^{***}$ | $0.024^{***}$ | $0.207^{***}$ | $0.009^{**}$ | $-0.029^{***}$ | $0.006^{**}$ | $-0.02^{***}$ | $0^{**}$ | $-0.027^{***}$ | $0.018^{**}$ | $0.03^{**}$ | $-0.111^{***}$ |
| | (0.006) | (0.001) | (0.019) | (0.003) | (0.017) | (0.005) | (0.004) | (0.004) | (0.004) | (0.008) | (0.002) | (0.01) | (0.01) | (0.008) |
| 04 | $0.503^{***}$ | $-0.063^{***}$ | $0.063^{***}$ | $0.023^{***}$ | $0.009^{**}$ | $-0.197^{***}$ | $0.011^{**}$ | $0.012^{***}$ | $-0.003^{**}$ | $-0.011^{***}$ | $0.017^{***}$ | $0.003^{**}$ | $0.021^{***}$ | $0.052^{***}$ |
| | (0.007) | (0.001) | (0.008) | (0.004) | (0.005) | (0.008) | (0.004) | (0.002) | (0.005) | (0.003) | (0.003) | (0.003) | (0.005) | (0.006) |
| 05 | $-0.019^{***}$ | $0.014^{***}$ | $0.066^{***}$ | $-0.007^{**}$ | $-0.029^{***}$ | $0.011^{**}$ | $0.018^{***}$ | $-0.003^{**}$ | $-0.004^{**}$ | $-0.006^{**}$ | $-0.013^{***}$ | $-0.002^{**}$ | $-0.009^{**}$ | $-0.022^{***}$ |
| | (0.004) | (0.001) | (0.007) | (0.002) | (0.004) | (0.004) | (0.004) | (0.002) | (0.003) | (0.003) | (0.002) | (0.002) | (0.004) | (0.005) |
| 06 | $0.027^{***}$ | $-0.002^{***}$ | $-0.009^{**}$ | $-0.004^{**}$ | $0.006^{**}$ | $0.012^{***}$ | $-0.003^{**}$ | $-0.017^{***}$ | $0.002^{**}$ | $-0.003^{**}$ | $0.001^{**}$ | $-0.001^{**}$ | $0.003^{***}$ | $0.014^{***}$ |
| | (0.002) | (0) | (0.006) | (0.001) | (0.004) | (0.002) | (0.002) | (0.002) | (0.002) | (0.003) | (0.001) | (0.002) | (0.004) | (0.004) |
| 07 | $-0.202^{***}$ | $0.064^{***}$ | $0.011^{**}$ | $0.038^{***}$ | $-0.02^{***}$ | $-0.003^{**}$ | $-0.004^{**}$ | $0.002^{**}$ | $-0.105^{***}$ | $-0.008^{***}$ | $0.018^{***}$ | $0.002^{**}$ | $0.021^{***}$ | $0.047^{***}$ |
| | (0.007) | (0.001) | (0.006) | (0.003) | (0.004) | (0.005) | (0.003) | (0.002) | (0.006) | (0.002) | (0.003) | (0.002) | (0.004) | (0.005) |
| 08 | $0.312^{***}$ | $-0.032^{***}$ | $-0.215^{***}$ | $0.009^{***}$ | $0^{**}$ | $-0.011^{***}$ | $-0.006^{**}$ | $-0.003^{**}$ | $-0.008^{***}$ | $0.313^{***}$ | $-0.006^{***}$ | $0.001^{**}$ | $-0.025^{***}$ | $-0.051^{***}$ |
| | (0.004) | (0.001) | (0.013) | (0.002) | (0.008) | (0.003) | (0.003) | (0.003) | (0.002) | (0.008) | (0.001) | (0.007) | (0.007) | (0.006) |
| 09 | $-0.054^{***}$ | $0.025^{***}$ | $-0.02^{***}$ | $0^{**}$ | $-0.027^{***}$ | $0.017^{***}$ | $-0.013^{***}$ | $0.001^{**}$ | $0.018^{***}$ | $-0.006^{***}$ | $0.001^{**}$ | $-0.002^{**}$ | $0.012^{***}$ | $0.019^{***}$ |
| | (0.005) | (0.001) | (0.003) | (0.002) | (0.002) | (0.003) | (0.002) | (0.001) | (0.003) | (0.001) | (0.002) | (0.001) | (0.002) | (0.003) |
| 10 | $-0.031^{***}$ | $0.005^{***}$ | $-0.161^{***}$ | $0.004^{**}$ | $0.018^{**}$ | $0.003^{**}$ | $-0.002^{**}$ | $-0.001^{**}$ | $0.002^{**}$ | $0.001^{**}$ | $-0.002^{**}$ | $0.155^{***}$ | $0.008^{**}$ | $-0.027^{***}$ |
| | (0.005) | (0) | (0.021) | (0.002) | (0.01) | (0.003) | (0.002) | (0.002) | (0.002) | (0.007) | (0.001) | (0.026) | (0.006) | (0.005) |
| 11 | $-0.069^{***}$ | $0.022^{***}$ | $-0.204^{***}$ | $0.014^{***}$ | $0.03^{**}$ | $0.021^{***}$ | $-0.009^{**}$ | $0.003^{**}$ | $0.021^{***}$ | $-0.025^{***}$ | $0.012^{***}$ | $0.008^{**}$ | $0.13^{***}$ | $-0.001^{**}$ |
| | (0.006) | (0.001) | (0.016) | (0.003) | (0.01) | (0.005) | (0.004) | (0.004) | (0.004) | (0.007) | (0.002) | (0.006) | (0.012) | (0.008) |
| 12 | $0.144^{***}$ | $-0.008^{***}$ | $-0.165^{***}$ | $-0.034^{***}$ | $-0.111^{***}$ | $0.052^{***}$ | $-0.022^{***}$ | $0.014^{***}$ | $0.047^{***}$ | $-0.051^{***}$ | $0.019^{***}$ | $-0.027^{***}$ | $-0.001^{**}$ | $0.279^{***}$ |
| | (0.007) | (0.001) | (0.014) | (0.004) | (0.008) | (0.006) | (0.005) | (0.004) | (0.005) | (0.006) | (0.003) | (0.005) | (0.008) | (0.012) |

# 2.B Appendix B: Simulation results

## Tax incidence

Figure 2.13: Share of net contributors and beneficiaries by class of income of standard of living Impact of carbon taxing (heterogeneous behavior)

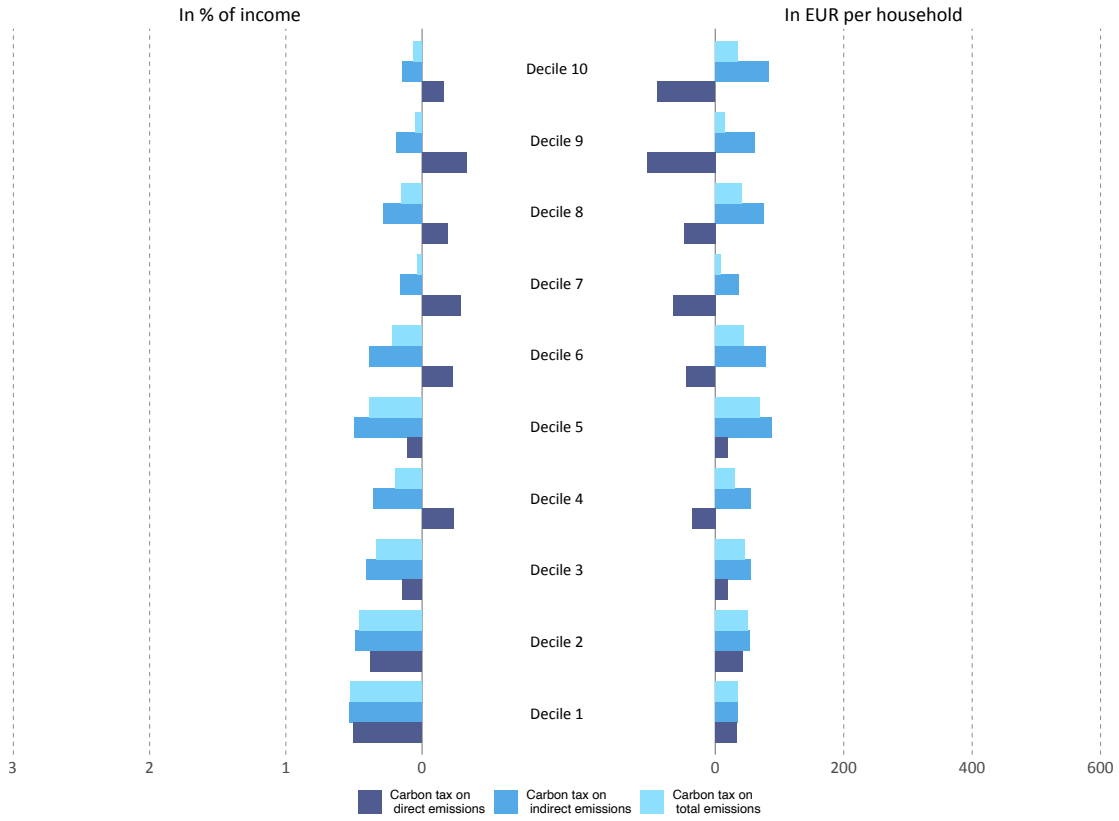


Figure 2.14: Impact of carbon taxing (homogeneous behavior)

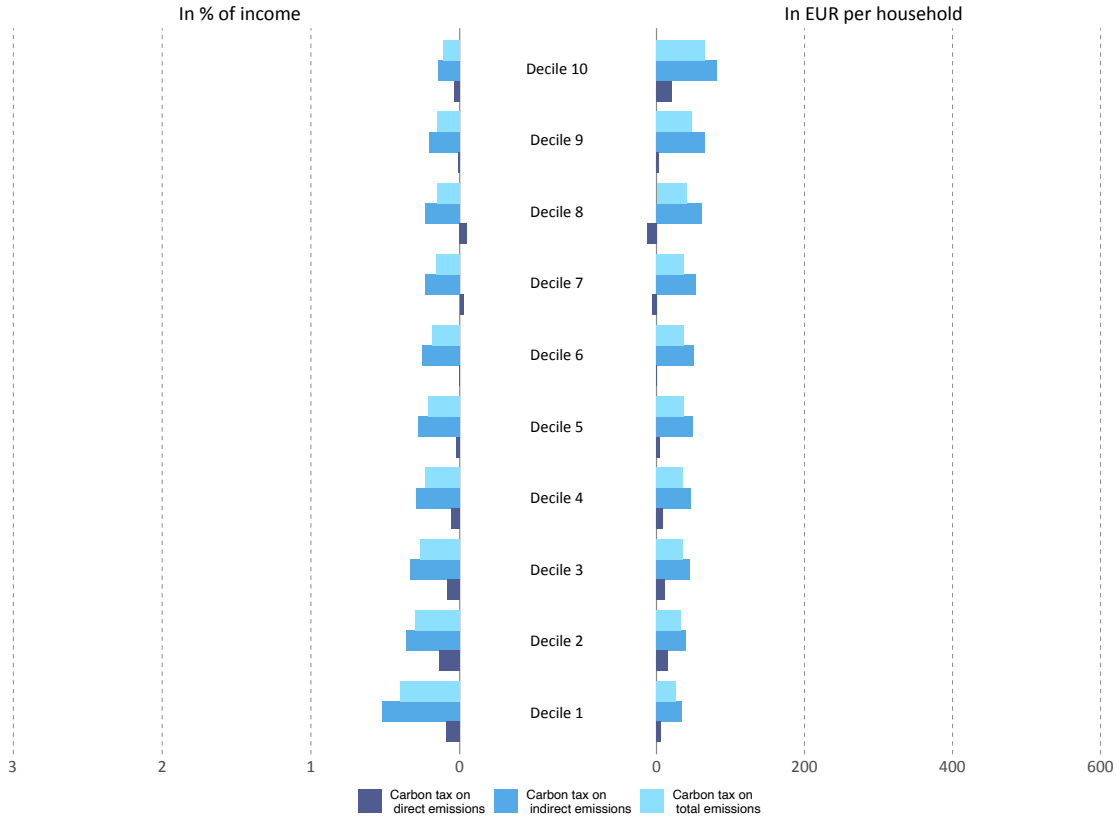
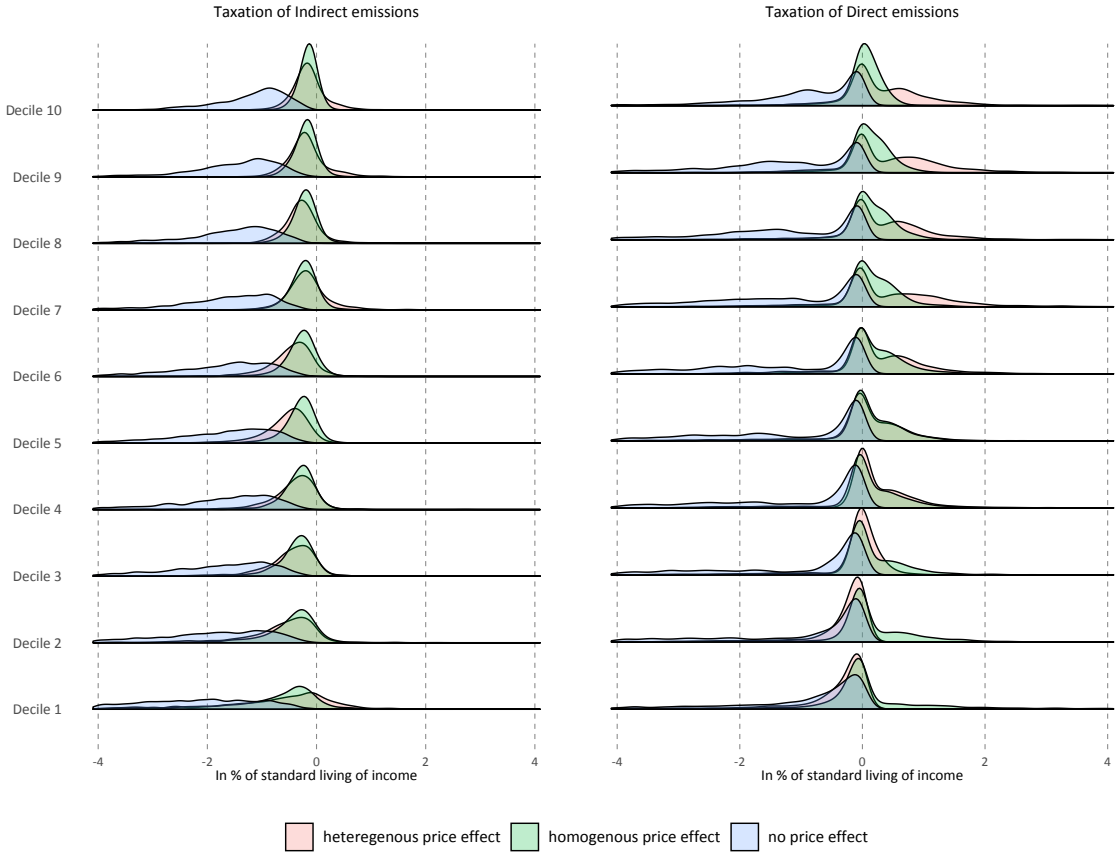


Figure 2.15: Distribution of impacts on households



## Redistribution scheme

Figure 2.16: Share of net contributors and beneficiaries by class of income of standard of living (carbon tax on direct emissions)

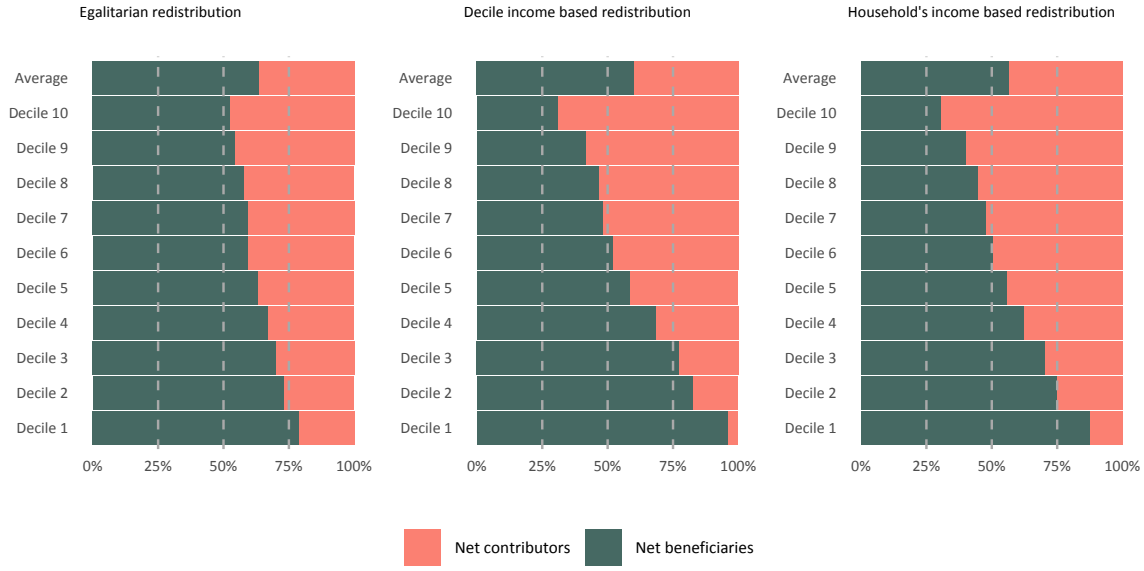



Figure 2.17: Share of net contributors and beneficiaries by class of income of standard of living for (carbon tax on indirect emissions)

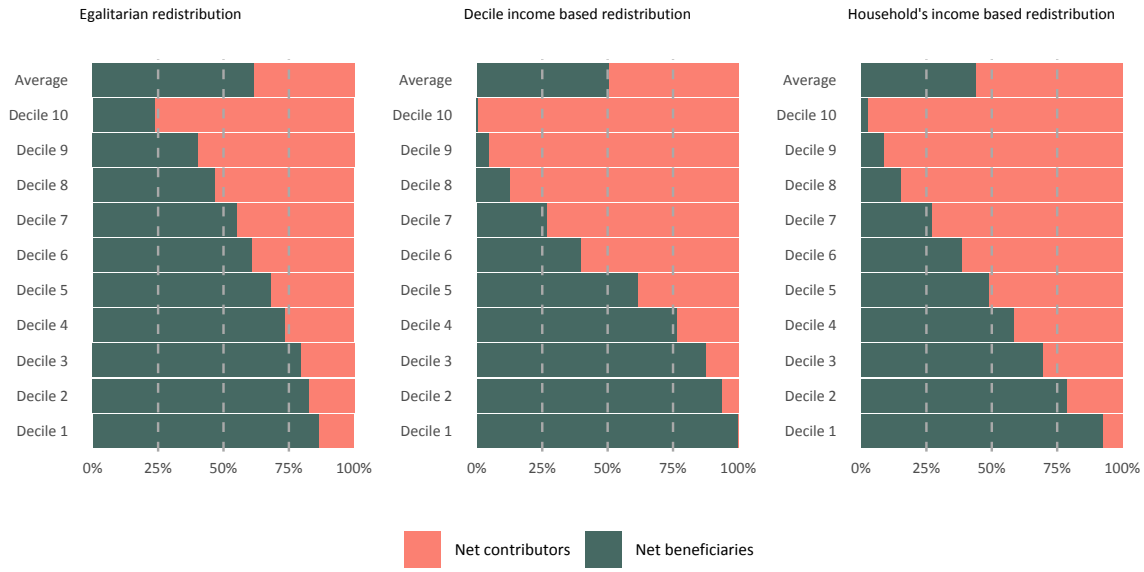


Figure 2.18: Distributive effects of the carbon tax and the redistribution schemes by decile (carbon tax on direct emissions and homogeneous behavior)

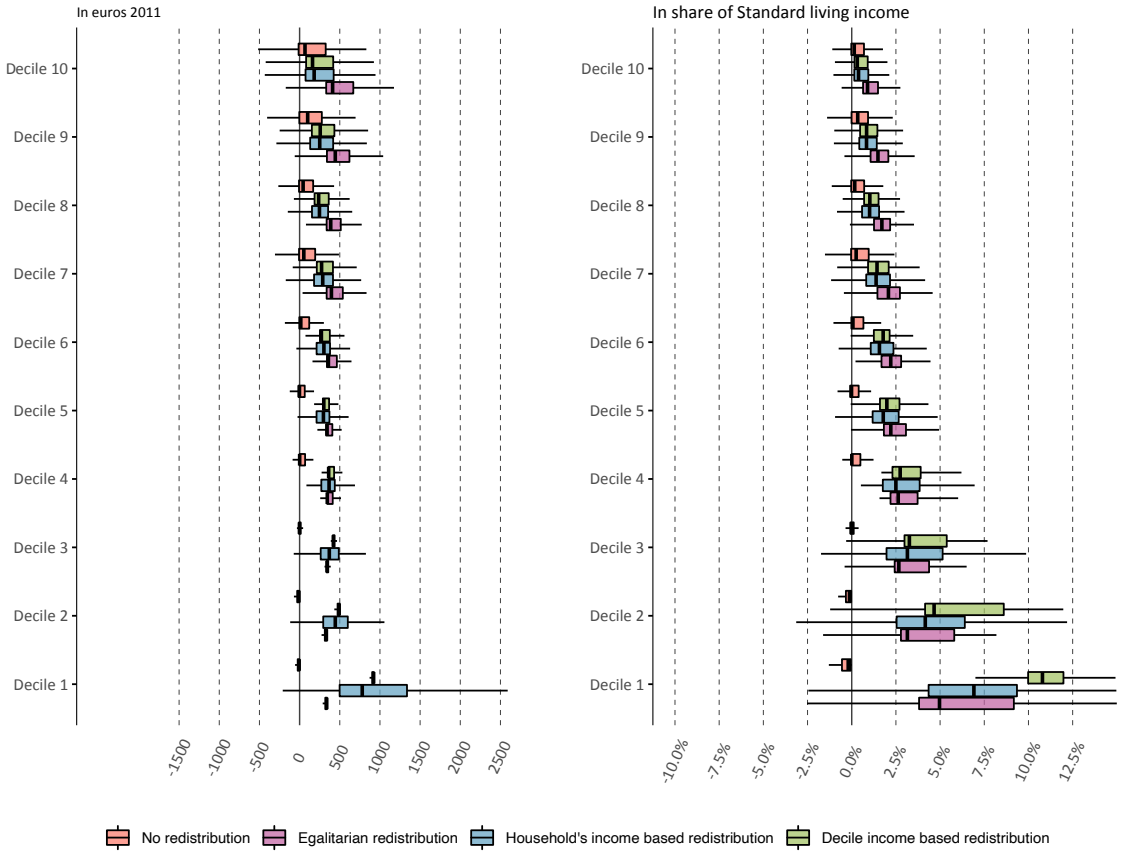


Figure 2.19: Distributive effects of the carbon tax and the redistribution schemes by decile (carbon tax on direct emissions and heterogeneous behavior)

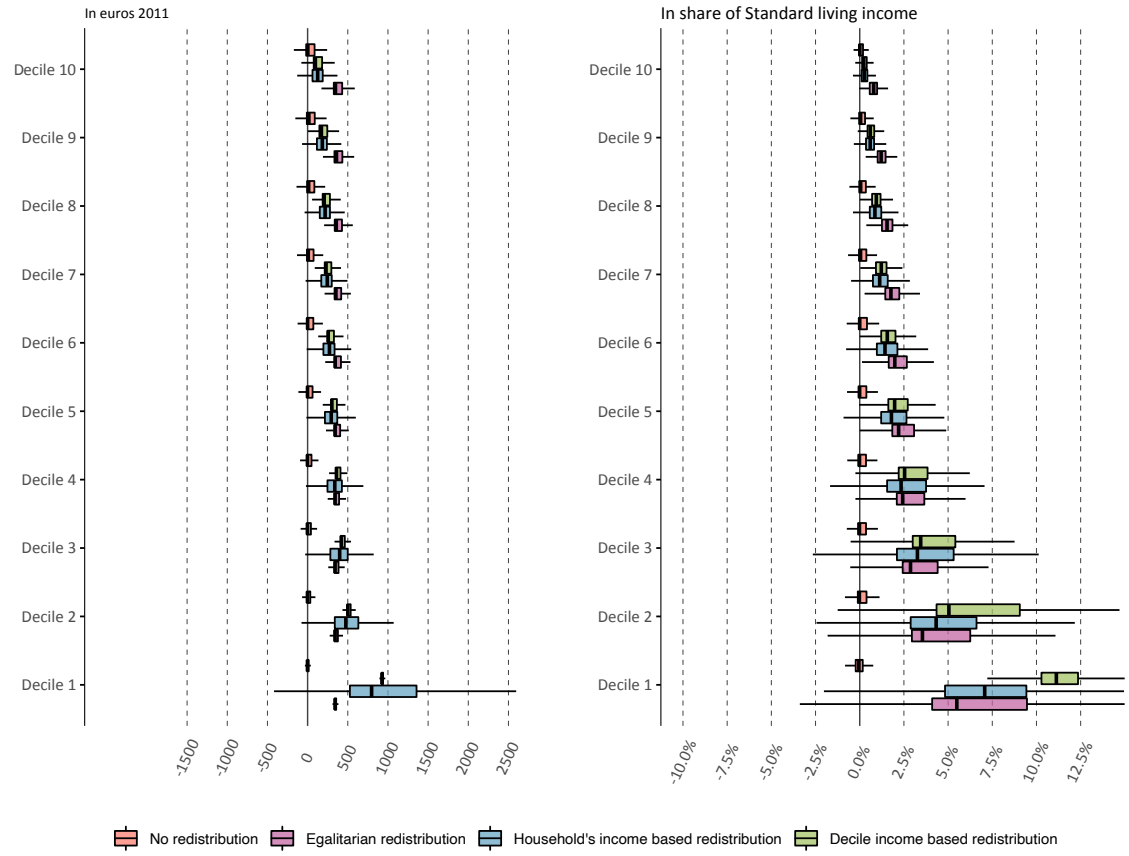


Figure 2.20: Distributive effects of the carbon tax and the redistribution schemes by decile (carbon tax on indirect emissions and homogeneous behavior)

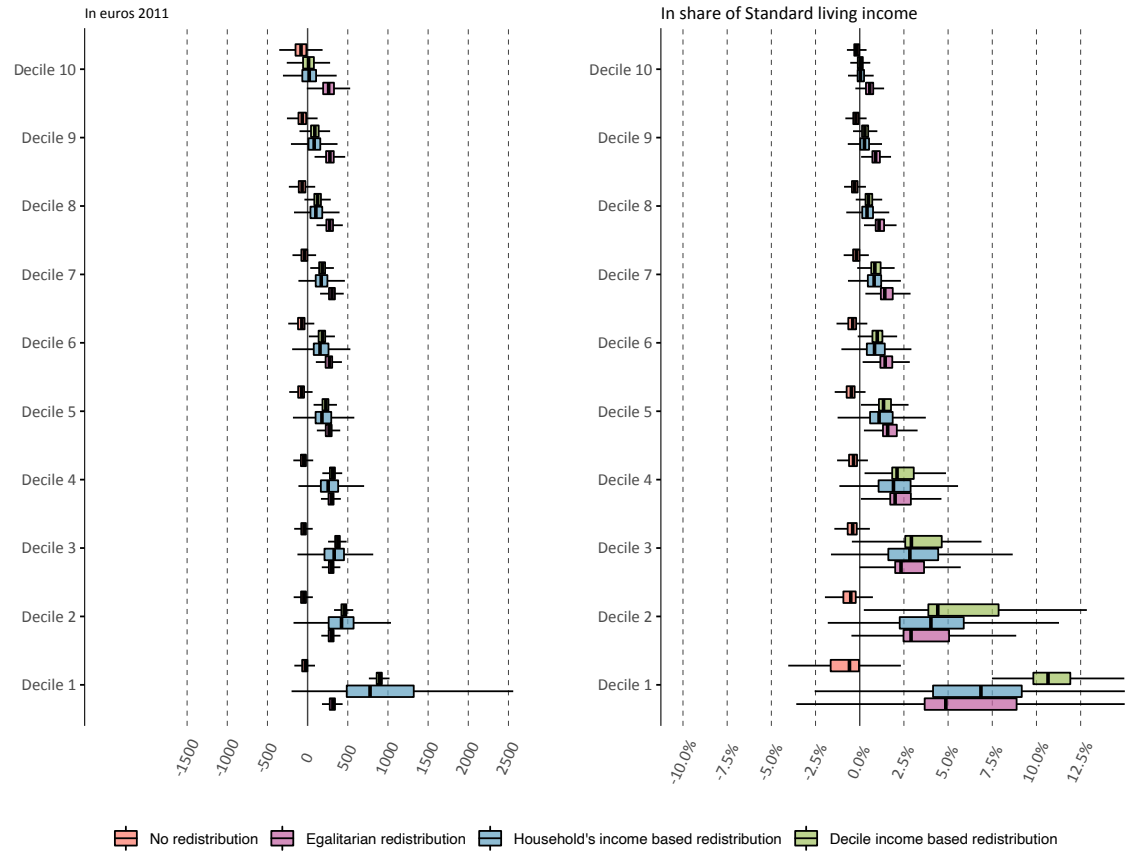
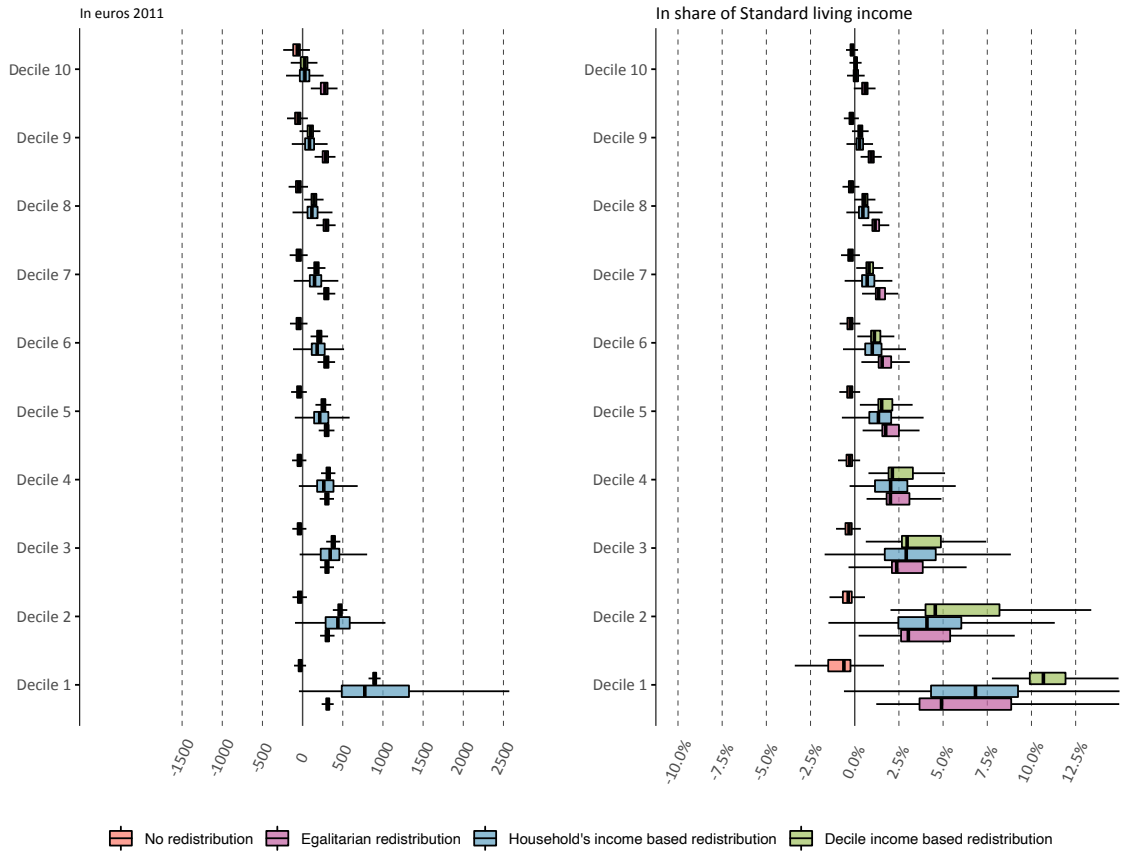


Figure 2.21: Distributive effects of the carbon tax and the redistribution schemes by decile (carbon tax on indirect emissions and heterogeneous behavior)



# Chapter 3

# Empirical estimates of the elasticity of substitution of a KLEM production function without nesting constraints: The case of the Variable Output Elasticity-Cobb Douglas[1]

[1]This chapter has been co-authored with Frederic G. Reynes

## 3.1 Introduction

Computable General Equilibrium (CGE) models are widely used by different institutions (public administrations, academia, think tanks, and international organizations) to support policy evaluations and prospective analyses. They rely on a complex representation of the economic system, which allows for quantitatively determining through a numerical resolution the *ex-ante* effects resulting from an exogenous shock (e.g., a technical shock) or the implementation of a given policy (e.g., a carbon tax). The first empirically estimated macro-econometric model was constructed for the Dutch economy by Tinbergen in 1936 (Dhaene and Barten, 1989) and opened a field of research in applied macroeconomics. A CGE model that combines dynamic effects with a multi-sectoral representation of the economy was first proposed by Johansen (1960b) following the strand of Input-Output analysis on inter-branch relations developed by Leontief. Their application has been revived by the climate change threat and the need to evaluate the economic impacts of sustainable long-term decarbonization strategies (Böhringer and Löschel, 2006).

However, CGE models have often been criticized because their results are highly sensitive to the value of exogenous parameters whose estimation is uncertain. In the energy transition scenarios analysis, their results are highly contingent on the substitutability of energy with other inputs (Németh et al., 2011). Due to the limited data availability, modelers frequently use either macroeconomic estimation of elasticity of substitution or econometric estimations on micro-data for specific sectors. Either way, it induces a bias because these estimations are inconsistent with the set of data employed for the CGE model's calibration or because they are based on a different functional form than the model's equation.

Jacoby et al. (2006) demonstrate this impact in their MIT EPPA model[2]: setting

[2]The Emissions Prediction and Policy Analysis (EPPA) model is a recursive-dynamic multi-regional general equilibrium model of the world economy that is part of the MIT Integrated Global Systems Model (IGSM) simulating the social systems.

different values of the elasticity of substitution between energy and non-energy commodities would dramatically change the costs of a mitigation policy case, the Kyoto protocol. The conclusions were similar regarding the rebound effect: the value of the elasticity directly impacts its magnitude (Jaccard and Bataille, 2000). The values of the elasticities of substitution in the production function play a central role in the dynamic of CGE models, especially regarding price-based instruments such as implementing carbon or energy taxes. Okagawa and Ban (2008), for instance, found that conventional parameter distribution could overestimate the carbon price required for a given targeted level of emissions reduction by 44%. Landa Rivera et al. (2016) using a CGE analysis and simulating an energy transition scenario with a carbon tax policy in Mexico, show that the change of the elasticity between capital and energy (from 1.5 to 0) leads to a 20% difference in GHG emissions reduction by 2050[3].

Modeling communities have attempted to tackle this issue using econometric estimation of these parameters. Albeit, due to the limited data availability, empirical estimations of the parameters of the production function at a sectoral level are rather limited[4]. Another point of debate remains in the choice of the production function specification to conduct the econometric estimations. Relying on a CES has the advantage of being consistent with the macroeconomic theory but imposes important constraints on the possibility of substitutions between inputs. The Translog specification[5] popularity in the 1980s comes from its higher flexibility. However, it relies on an approximation of the production function by a second-order Taylor-expansion, and the well-behaved properties of the production function prove difficult to impose (Diewert and Wales, 1987; Ryan and Wales, 2000). Despite continuous work to pro-

[3]This difference can be interpreted as the contribution of energy efficiency measures to the total variation of GHG emissions.

[4]The first econometric estimation of these parameters from input-output data was done by Burniaux et al. (1992) for the CGE model GREEN, using OECD data on a sample of 12 countries and seven industries.

[5]The translog function is based on a second-order linear approximation of production function and is characterized by input symmetry and Hicks neutrality.

vide selection criteria on the form to adopt, there is still no consensus in the research community on which specification of the production function to favor. The same is true regarding the nested-CES structure that accurately fits data.

In this study, we perform empirical estimations of elasticities of substitution for a KLEM[6] production function using Seemingly Unrelated Model (SUR) estimation procedures. More specifically, we use the VOE-CD specification as the standard case and test two alternative nested structures. The originality of this approach is twofold. First, we rely on an original and consistent panel dataset from the *WIOD 2016 Release* and from which all the variables (prices and quantities) used in the estimation are derived. Secondly, we introduce a new production function specification, which has not yet been tested in an empirical analysis.

The remainder of the paper is organized as follows. We first introduce the VOE-CD specification of the production function and derive the estimated equations. We then describe the dataset construction in a third section and the econometric strategy we apply in Section 4. Section 5 presents our estimation results, discussing which nesting structure fits the dataset best. Section 6 concludes and discusses policy implications.

[6]This acronym stands for the inputs considered separately into the production function where the Value-Added is decomposed between Capital (K) and Labor (L) and the intermediate consumption between Energy (E) Materials (M).

## 3.2 The model specification

A production function describes a process of transforming a certain quantity of inputs into a quantity of output. In CGE models, the Cobb-Douglas, the CES, and the Translog functions are the primary functional forms used. The modeling of the producer's behavior generally relies on three main assumptions:

- The firm produces only one output
- The production function is homogeneous of degree one, meaning that the returns to scale are constant
- The substitutability between production inputs is limited

The CES production function introduced by Solow (1956) and formalized by Arrow et al. (1961) has become widely used in the CGE modeling community. It has the advantage of allowing for representing a continuum of substitution possibilities between the inputs, from the Leontief production function where the Elasticity of Substitution (ES) is 0 (strict complementarity) to the linear production function where the ES is infinite (perfect substitution). The Cobb-Douglas function (unitary ES) is also a particular case of the CES function. However, the CES function limits the possibilities of substitution. As its name says, it imposes a constant ES along the isoquant. As shown by Uzawa (1962) and McFadden (1963), it constrains the elasticity to be equal across every pair of inputs, which may prove very limiting in the case of more than two inputs. To circumvent these limits, Sato (1967) proposed a nested form of the function. For instance, in a case with three inputs $(X_1, X_2, X_3)$, a system of a nested CES function can be written:

$$Y = \left( \alpha X_1^{\frac{\eta_{X_1,Z}-1}{\eta_{X_1,Z}}} + (1-\alpha) Z^{\frac{\eta_{X_1,Z}-1}{\eta_{X_1,Z}}} \right)^{\frac{\eta_{X_1,Z}}{\eta_{X_1,Z}-1}} \tag{3.1}$$

$$Z = \left( \beta X_2^{\frac{\eta_{X_2,X_3}-1}{\eta_{X_2,X_3}}} + (1-\beta) X_3^{\frac{\eta_{X_2,X_3}-1}{\eta_{X_2,X_3}}} \right)^{\frac{\eta_{X_2,X_3}}{\eta_{X_2,X_3}-1}} \tag{3.2}$$

Equation (3.1) states that Input $X_1$ is substitutable to the composite input $Z$ in the production of output $Y$ with an ES of $\eta_{X_1,Z}$ whereas equation (3.2) states that $X_1$ and $X_2$ are two substitutable inputs in the production of the composite input $Z$.

Although this approach has been widely used in the literature, it is subject to criticism. As argued by van der Werf (2008), there is no theoretical reason to favor a nested structure over another. The choice of the nested structure is therefore left to the modelers' discretion. In one of the earliest works on this literature, Prywes (1986) on US manufacturing industries assumed a three-level-CES production function with a [[[KE]L]M][7] nested structure without providing theoretical nor empirical justifications.

Several studies attempt to provide approaches to determine the correct nested structure. In a study on German manufacturing sectors, Kemfert (1998) proposed a data-driven approach to discriminate between different nested structures. The strategy she uses is to estimate the different combinations of nested structures and select the model with the highest $R^2$ statistics. However, this criterion appears to be statistically inadequate to compare non-linear models since it assumes that the underlying model being fit is linear (Spiess and Neumeyer, 2010; Lagomarsino, 2020). Despite becoming popular in the CGE literature, it has also been questioned by some authors of this field who argue that in the case of an indirect method based on conditional factor demand is not recommended because the final comparison is made between models based on different dependent and explanatory variables (Baccianti, 2013; Dissou et al., 2015).

Zha and Zhou (2014) insert a Translog specification into the two-level CES production function to select the most appropriate nested structure. Similarly, Lagomarsino (2020) proposed in a meta-analysis on the nested-CES production function to proceed

[7]For this case and the following of this paper, the brackets represent the organization of the nest. In this case, $K$ and $E$ are combined to produce $KE$, $KE$ is combined with $L$ to produce $KEL$, and $KEL$ is combined with $M$ to produce the output $Y$.

through the use of a Translog specification of each nested structure. A Wald test on the separability and homogeneity assumption for each Translog specification informs if the nested model is rejected or not statistically.

In a recent study on CGE models in China, Feng and Zhang (2018) surveyed the nesting structure of their production function specification and found that the [[KL]E] form has been mostly preferred in 75% of the cases, the [[KE]L] nest being chosen three times and [[EL]K] none. However, the choice is rarely motivated.

Some authors argued against taking the value-added variable as a composite variable from K and L in the upper level combined with E (referred to as a [[KL]E], whereas others claimed to adopt a [[KE]L] structure. It may reflect two visions of the functioning of the economy. The first one favors the income approach by combining Capital & Labor to form an added-value input in the production process. The second one puts emphasis on the physical relation between Capital (equipment) & Energy in the production process [8].

To overcome this limit, we take advantage of the VOE-CD specification of the production function (Reynès, 2019). It is a flexible form of the Cobb-Douglas production function, which provides a generalization of the CES functional form to the case where the Elasticity of Substitution (ES) between each pair of inputs is not equal. In this sense, it exhibits properties that are well-suited to the case of the multi-factors CES production function without assuming a specific nesting structure.

## The VOE Cobb-Douglas function

Considering a general production function where output $Y$ is produced from a combination of input $X_i$ such as:

$$Y = Y(X_1, X_2, \ldots, X_i, \ldots, X_n) \tag{3.3}$$

[8] At the microeconomic level, it is generally considered a Leontief production function between these two production factors.

and for which the standard assumptions apply: the production function is a continuous, twice differentiable function that is homogeneous of degree one; the output is increasing in inputs ($Y'(X_i) = \frac{\partial Y}{\partial X_i} > 0$) and strictly concave ($Y''(X_i) = \frac{\partial^2 Y}{\partial {X_i}^2} < 0$)

Using the Euler theorem, Reynès (2019) shows that equation (3.3) can be written in growth rate[9] (or similarly in logarithm first difference).

$$\dot{Y} = \sum_i \varphi_i \, \dot{X}_i \leftrightarrow d\ln Y = \sum_i \varphi_i \, d\ln X_i \tag{3.4}$$

where $\varphi_i$ is the output elasticity, which measures a relative change in output induced by a relative change in input $i$. It is defined according to the following equation:

$$\varphi_i = \left[ \sum_j \frac{Y'(X_j) \; X_j}{Y'(X_i) \; X_i} \right]^{-1} \tag{3.5}$$

The definition of the ES proposed by Hicks (1932) and Robinson (1933) measures the change in the ratio between two factors of production ($i$ and $j$) due to a change in their relative marginal productivity. Formally this yields:

$$-\eta_{ij} = \frac{d\ln(X_i/X_j)}{d\ln(Y'(X_i)/Y'(X_j))} \leftrightarrow \dot{X}_i - \dot{X}_j = -\eta_{ij} \; (\dot{Y}'(X_i) - \dot{Y}'(X_j) \tag{3.6}$$

Using the profit maximization behavior from the producer, we can derive the demand function by minimizing the production cost (3.7).

$$C = \sum_i P_i^X \; X_i \tag{3.7}$$

From the first-order conditions, the ratio between the marginal productivities of two inputs equals the ratio between prices ($Y'(X_i)/Y'(X_j) = P_i^X/P_j^X$). Combining the first-order conditions with equation (3.5), the OE of input $i$ corresponds to the cost share of input $i$:

$$\varphi_i = \frac{P_i^X \; X_i}{\sum_j P_j^X \; X_j} \tag{3.8}$$

[9]The first and second partial derivatives of the function $Y$ with respect to $X_i$ are respectively $Y'(X_i) = \partial Y/\partial X$ and $Y''(X_i) = \partial^2 Y/\partial X_i^2$ . Variables in growth rate are referred to as $\dot{X} = dX/X = d(\ln X)/dX$. All parameters written in Greek letters are positive.

Finally, combining the first-order conditions, the definition of the ES (3.6) and the production function (3.4) gives the demand function for each factor as a positive function of the output and a negative function of the relative prices between inputs:

$$\dot{X}_i = \dot{Y} - \sum_{j=1} \eta_{i,j}\varphi_j(\dot{P}_i^X - \dot{P}_j^X) \tag{3.9}$$

## 3.3 Data

Our econometric estimation is based on panel data.It allows for considering a more apparent distinction between input substitution and technological change than time-series (Baccianti, 2013).

The ES estimation requires prices and quantities for all the economic variables used in the economic regression. For the construction of the final database, we use the following data sources:

- WIOD Socio-Economic Account (WIOD SEA)
- WIOD National Supply-Use Tables (NIOT)
- WIOD World Input-Output Tables (WIOT)

These data sets belong to the World Input-Output Database Project (WIOD) (Timmer et al., 2015), a consistent regional input-output dataset with a detailed sectoral granularity of the world economy. In its latest version (2016 Release), the dataset covers the period from 2000 to 2014 and distinguishes 42 countries (plus the rest of the world) and 56 sectors (see Table 1 in Appendix A). Since the WIOD tables are both provided in current prices ($CP$) and previous year prices ($PYP$), we can distinguish, for each variable, value (in current price) and volume (nominal price) using the chained-price method[10]. The examples of other panel data sources employed in the literature include Eurostat's National Accounts and COMEXT (Németh et al., 2011), the IEA Energy Balances and the OECD International Sectoral Database (Saito, 2004; van der Werf, 2008) as well as the OECD International Trade by Commodities Statistics and the OECD Input-Output Database (Sato, 2014).

[10]In previous studies on the estimation of the ES of a KLEM production function, authors used the 2013 release of WIOD, which do not provide previous year prices national accounts. They, therefore, adopted an alternative source of data to construct the price series (see Baccianti (2013); Koesler and Schymura (2015); Antoszewski (2019)).

From the WIOT dataset, we extract for each sector their aggregate intermediate consumption of energy goods[11] and non-energy goods.

The price growth rate of the input $X$ used in the sector $i$ is computed according to the following equation:

$$\dot{P}^X_{i,t} = \frac{X^{CP}_{i,t}}{X^{PYP}_{i,t}} - 1 = \frac{X_{i,t}\ P^X_{i,t}}{X_{i,t}\ P^X_{i,t-1}} - 1 = \frac{P^X_{i,t}}{P^X_{i,t-1}} - 1 \tag{3.10}$$

Furthermore, taking a unitary value for the price at the base year ($2000 = 1$) allows us to calculate the price index :

$$P^X_{i,t} = \prod_t (1 + \dot{P}^X_{i,t})\ P^X_{i,0} \tag{3.11}$$

Finally, using it as a deflator on the input series expressed in current price allows for expressing these series in real terms:

$$X_{i,t} = \frac{X^{CP}_{i,t}}{P^X_{i,t}} \tag{3.12}$$

The capital and labor price and volume series are constructed from the WIOD SEA database following series: Total hours worked by employees (in millions) ($H_EMPE$), compensation of employees[12] ($COMP$), capital compensation ($CAP$) and nominal capital stock ($K^{VAL}$). By default, the series are expressed in nominal value and in national currencies[13].

Dividing $COMP$ by $H_EMPE$ gives the hourly wage $W$ for each period, country, and sector. We then compute the labor economic volume variable $L$, as the total work expressed in hours multiplied by the hourly wage base year value $W_{i,0}$

$$L_{i,t} = W_{i,0}\ H_EMPE_{i,t} \tag{3.13}$$

[11] The intermediate energy consumption aggregates the *Manufacture of coke and refined petroleum products* (C19) and *Electricity, gas, steam and air conditioning supply* (D35).

[12] The WIOD SEA database provides an alternative metric for labor compensation ($LAB$) that we did not consider because it includes self-employed workers.

[13] We convert the economic values in $ currency using the same exchange rates table used in WIOD to construct the international Supply-Use Tables.

The price-variation of labor $\dot{P}^L_{i,t}$ is directly derived from the wage growth rate $(W_{i,t}/W_{i,t-1} - 1)$, from which we directly derive the labor price index.

$$P^L_{i,t} = \prod_{t=1}(1 + \dot{P}^L_{i,t}) \tag{3.14}$$

Regarding the distinction between quantities and prices for capital, we can not use the same approach for labor because there is no variable expressed in volume in the dataset that would allow for calculating a price deflator. To estimate the volume of capital stock, we use the standard approach of the Perpetual Inventory Method (PIM), which consists in deriving the capital stock from data on investment flows[14] The capital accumulation equation can be written in value or volume metrics:

$$K^{VAL}_{i,t} = K^{VAL}_{i,t-1}\,(1 - \delta_{i,t}) + P^I_{i,t}\,I_{i,t} \tag{3.15}$$

$$K_{i,t} = K_{i,t-1}\,(1 - \delta_{i,t}) + I_{i,t} \tag{3.16}$$

Inverting equation (3.15) and using the definition of the growth rate of capital, $\dot{K}^{VAL}_{i,t} = \frac{K^{VAL}_{i,t}}{K^{VAL}_{i,t-1}} - 1$, allows for deriving a relation for the depreciation rate:

$$\delta_{i,t} = \frac{P^I_{i,t} I_{i,t}}{K^{VAL}_{i,t-1}} - \dot{K}^{VAL}_{i,t} \tag{3.17}$$

This equation is used to derive the depreciation ratio from the WIOD database, which contains time series for the capital stock and investment in value. The depreciation rate is used to estimate the capital stock in volume thanks to equation (3.16). Finally, the nominal to real capital stock ratio provides a capital price index.

$$P^K_{i,t} = \frac{K^{VAL}_{i,t}}{K_{i,t}} \tag{3.18}$$

As in Antoszewski (2019), this price index will be used as a proxy for the cost of the capital input. This specification has the advantage of simplicity. Its main

[14]Some authors, such as Lee (2005) and (Soytas and Sari, 2007) use directly investment data as a proxy for capital stock. This approach underestimates the capital stock since it does not consider the lifespan of capital.

drawback is that it does not account for the opportunity cost related to investment. For several reasons, the capital cost specification remains controversial (Jorgenson and Griliches, 1967; Hall and Jorgenson, 1969; Hudson and Jorgenson, 1974; Levinsohn and Petrin, 2003; Collard-Wexler and Loecker, 2016) in the literature, among which the difficulties in distinguishing between physical and financial capital or between the user cost, opportunity cost, or desired rate of return. Addressing these issues goes largely beyond the scope of this paper. Hence we keep the impact of alternative specifications on the cost of capital for further research.

The final panel dataset gathers the following variables in volume ($Y$, $K$, $L$, $E$, $M$) and prices ($pY$, $pK$, $pL$, $pE$, $pM$). We also compute their respective growth rates ($\dot{Y}, \dot{K}, \dot{L}, \dot{E}, \dot{M}, \dot{pY}, \dot{pK}, \dot{pL}, \dot{pE}, \dot{pM}$) from which we perform the econometric estimations presented in the next section.

## 3.4 Econometric strategy

Our empirical analysis considers a four inputs production function, often known as KLEM: Capital (K), Labor (L), Energy (E), and non-energy intermediate inputs (M). The function parameters to estimate are determined for each sector $s$ specified in the WIOD database.

In the panel, we distinguish 13 periods $t$ and 44 countries or regions $r$.

### Literature review

The literature has proposed three approaches to estimating a nested CES production function: The direct approach based on its non-linear estimation, the indirect approach based on a cost minimization program, and the approximation based on its Kmenta's linearization.

The direct approach consists in using non-linear least squares estimation based on *ad-hoc* non-linear optimization algorithms[15]. However, their use is intricate because of the need to find a proper starting value to achieve a numerical convergence[16]. Since the CES production function is not-linear in its parameters, it implies that their values cannot be directly estimated with a standard OLS estimator.

The indirect approach has been often used to estimate nested CES production function (Prywes, 1986; Okagawa and Ban, 2008; Antoszewski, 2019). It relies on the assumption of the maximizing behavior of the supply-side (either through a cost-minimization or a profit-maximization problem) and therefore involves collecting data on prices, besides quantities.

An alternative approach to non-linear estimation is the one proposed by Kmenta (1967). The outcome is a restricted form of the general Translog function. It uses a

[15] A version of this algorithm developed by Henningsen and Henningsen (2012) has been made available for empirical applications in the package *micEconCES*.

[16] According to Henningsen and Henningsen (2012), results obtained through this method should be taken with caution since they were not able to replicate the original findings from the (Kemfert, 1998) article adopting this approach.

linear approximation of the CES function to estimate its parameters. This approximation is a linear Taylor series expansion when the ES is around 1. This method has been criticized by Thursby and Lovell (1978), arguing that the Kmenta's approximation only converges to the underlying CES function in the region of convergence determined by the true parameters of the CES function. For these reasons, the linearization method proposed by Kmenta was rarely chosen [17].

The specification we test is derived from the demand function determined by the VOE-CD production function as stated in 3.9.

Since the economic framework assumes a constant return to scale, and to avoid endogeneity in the estimation, we take as explained variable the difference between the growth rates of input $j$ and output $Y$. We also consider time and country fixed effects. We regress our model on a sub-panel independently defined for each sector.

Regarding our strategy, we want to take into account the advantage of the general form of the VOE-CD to perform a regression on the system of equations that defines the production process. Since the economic framework assumes a constant return to scale, and to avoid endogeneity in the estimation, we take as explained variable the difference between the growth rates of input $j$ and output $Y$. We also consider time and country fixed effects. We perform regressions of our model independently for each sector.

## Estimation approaches

We adopt a Seemingly Unrelated Regression (SUR) approach originally developed by Zellner (1962) and extended to panel data analysis by Avery (1977) and Baltagi (1980). It allows for accounting for potential correlations between the errors from equations of the system. Moreover, in order to take into account the assumption of

[17] Koesler and Schymura (2015) compare the estimates obtained from the Kmenta's approximation with a non-linear estimation and conclude that the former performs less well in terms of statistics fit.

symmetry of the ES between inputs ($\eta_{ij} = \eta_{ji}$), we have to impose cross-constraints restriction of the system of equations (3.19). Having derived the inputs demand (3.9) for a system of four inputs, the estimated system is:

$$\begin{cases} \dot{K}_{r,t} - \dot{Y}_{r,t} = \alpha^K + \eta^{K,L}\ \varphi^L_{r,t-1}\ (\dot{P}^K_{r,t} - \dot{P}^L_{r,t}) + \eta^{K,E}\ \varphi^E_{r,t-1}\ (\dot{P}^K_{r,t} - \dot{P}^E_{r,t}) + \\ \qquad \eta^{K,M}\ \varphi^M_{r,t-1}\ (\dot{P}^K_{r,t} - \dot{P}^M_{r,t}) + \mu^K_t + \mu^K_r + \epsilon^K_{r,t} \\ \dot{L}_{r,t} - \dot{Y}_{r,t} = \alpha^L + \eta^{L,K}\ \varphi^K_{r,t-1}\ (\dot{P}^L_{r,t} - \dot{P}^K_{r,t}) + \eta^{L,E}\ \varphi^E_{r,t-1}\ (\dot{P}^L_{r,t} - \dot{P}^E_{r,t}) + \\ \qquad \eta^{L,M}\ \varphi^M_{r,t-1}\ (\dot{P}^L_{r,t} - \dot{P}^M_{r,t}) + \mu^L_t + \mu^L_r + \epsilon^L_{r,t} \\ \dot{E}_{r,t} - \dot{Y}_{r,t} = \alpha^E + \eta^{E,K}\ \varphi^K_{r,t-1}\ (\dot{P}^E_{r,t} - \dot{P}^K_{r,t}) + \eta^{E,L}\ \varphi^L_{r,t-1}\ (\dot{P}^E_{r,t} - \dot{P}^L_{r,t}) + \\ \qquad \eta^{E,M}\ \varphi^M_{r,t-1}\ (\dot{P}^E_{r,t} - \dot{P}^M_{r,t}) + \mu^E_t + \mu^E_r + \epsilon^E_{r,t} \\ \dot{M}_{r,t} - \dot{Y}_{r,t} = \alpha^M + \eta^{M,K}\ \varphi^K_{r,t-1}\ (\dot{P}^M_{r,t} - \dot{P}^K_{r,t}) + \eta^{M,L}\ \varphi^L_{r,t-1}\ (\dot{P}^M_{r,t} - \dot{P}^L_{r,t}) + \\ \qquad \eta^{M,E}\ \varphi^E_{r,t-1}\ (\dot{P}^M_{r,t} - \dot{P}^E_{r,t}) + \mu^M_t + \mu^M_r + \epsilon^M_{r,t} \end{cases} \tag{3.19}$$

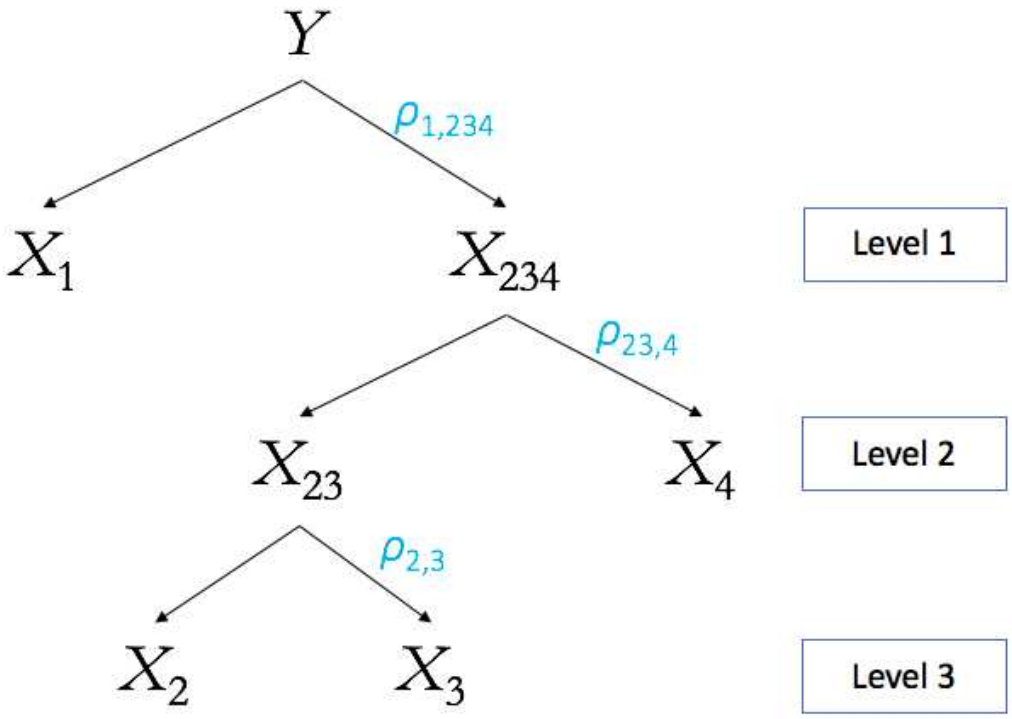
The system of equation (3.19) is solved for each sector $s$ based on 2408 observations. The parameter $\alpha^i$ is the constant, $\eta_{ij}$ are the elasticities of substitution between input $i$ and $j$. $\mu^M_r$ and $\mu^M_t$ are respectively the country and the time fixed-effect terms, and $\epsilon_{i,t}$ is the error term. The input shares that intervene with a time lag in the system (3.19) to avoid endogeneity bias are computed according to equation (3.8):

$$\varphi^X_{r,t} = \frac{P^X_{r,t}\ X_{r,t}}{\sum_j P^X_{r,t}\ X_{r,t}} \tag{3.20}$$

As a generalization of the CES function, the VOE-CD also encompasses nested CES structures. We can therefore use it to test if the ES estimation is consistent with a nested CES structure. To do so, we adopt a standard three-level nested structure of the type $[[[X_2; X_3]X_4]X_1]$ as shown on Figure 3.1)

Writing $\varphi^k_{k'}$ the share of the input $k$ into the output $k'$, ($k'$ being either the final output $Y$ at the first level of the nest or a composite input of production for lower

Figure 3.1: Nesting structure of a four inputs CES production function




levels)[18] , the model can be reformulated as follows :

$$\begin{cases} \dot{X}_1 = \dot{Y} + \rho^{X_1,X_{234}}\ \varphi_Y^{X_{234}}\ (\dot{P}^{X_1} - \dot{P}^{X_{234}}) \\ \dot{X}_{234} = \dot{Y} + \rho^{X_{234},X_1}\ \varphi_Y^{X_1}\ (\dot{P}^{X_{234}} - \dot{P}^{X_1}) \\ \dot{X}_2 = \dot{X}_{23} + \rho^{X_2,X_3}\ \varphi_{X_{23}}^{X_3}\ (\dot{P}^{X_2} - \dot{P}^{X_3}) \\ \dot{X}_3 = \dot{X}_{23} + \rho^{X_3,X_2}\ \varphi_{X_{23}}^{X_2}\ (\dot{P}^{X_3} - \dot{P}^{X_2}) \\ \dot{X}_4 = \dot{X}_{234} + \rho^{X_4,X_{234}}\ \varphi_{X_{234}}^{X_{23}}\ (\dot{P}^{X_4} - \dot{P}^{X_{23}}) \\ \dot{X}_{23} = \dot{X}_{234} + \rho^{X_4,X_{234}}\ \varphi_{X_{234}}^{X_4}\ (\dot{P}^{X_{23}} - \dot{P}^{X_4}) \end{cases} \tag{3.21}$$

We confront the two most used nesting structures of the production function in the literature. The first nesting is of the form $[[[[KL]E]M]$, which considers the

[18]For the second level of the nested production function, the share of the composite good $X_{23}$ into to the output $X_{234}$ is $\varphi_{X_{234}}^{X_{23}} = (1 - \varphi_{X_{234}}^{X_4})$.

value-added as a meaningful economic variable in relation to the intermediate inputs. The alternative case $[[[KE]L]M]$ sees The alternative case [[[KE]L]M] sees the Capital-Energy relation as grounding since it is based on engineering observations of a productive capital functioning (physical capital being run with an energy influx). The $[[[KL]E]M]$ nesting has been adopted in several articles (Okagawa and Ban, 2008; Koesler and Schymura, 2015; Antoszewski, 2019) whereas the $[[[KE]L]M]$ nesting has been preferred by others[19] (Prywes, 1986; Chang, 1994).

The system of equations we estimate is defined as follows:

$$\begin{cases} \dot{X}_1 - \dot{Y} = \alpha^{X_1} + \rho^{X_1,X_{234}}\ \varphi_Y^{X_{234}}\ (\dot{P}^{X_1} - \dot{P}^{X_{234}}) + \mu_t^{X_1} + \mu_r^{X_1} + \epsilon_{r,t}^{X_1} \\ \dot{X}_{234} - \dot{Y} = \alpha^{X_{234}} + \rho^{X_1,X_{234}}\ \varphi_Y^{X_1}\ (\dot{P}^{X_{234}} - \dot{P}^{X_1}) + \mu_t^{X_{234}} + \mu_r^{X_{234}} + \epsilon_{r,t}^{X_{234}} \\ \dot{X}_2 - \dot{X}_{234} = \alpha^{X_2} + \rho^{X_2,X_{34}}\ \varphi_{X_{234}}^{X_{34}}\ (\dot{P}^{X_2} - \dot{P}^{X_{34}}) + \mu_t^{X_2} + \mu_r^{X_2} + \epsilon_{r,t}^{X_2} \\ \dot{X}_{34} - \dot{X}_{234} = \alpha^{X_{34}} + \rho^{X_{34},X_2}\ \varphi_{X_{234}}^{X_2}\ (\dot{P}^{X_{34}} - \dot{P}^{X_2}) + \mu_t^{X_{34}} + \mu_r^{X_{34}} + \epsilon_{r,t}^{X_{34}} \\ \dot{X}_3 - \dot{X}_{34} = \alpha^{X_3} + \rho^{X_3,X_4}\ \varphi_{X_{34}}^{X_4}\ (\dot{P}^{X_3} - \dot{P}^{X_4}) + \mu_t^{X_3} + \mu_r^{X_3} + \epsilon_{r,t}^{X_3} \\ \dot{X}_4 - \dot{X}_{34} = \alpha^{X_4} + \rho^{X_4,X_3}\ \varphi_{X_{34}}^{X_3}\ (\dot{P}^{X_4} - \dot{P}^{X_3}) + \mu_t^{X_4} + \mu_r^{X_4} + \epsilon_{r,t}^{X_4} \end{cases} \tag{3.22}$$

Regarding the system of equations (3.22), this leads to $(X_1 = M; X_2 = E; X_3 = L; X_4 = K)$ in the first case $(((KL)E)M)$ and to $(X_1 = M; X_2 = L; X_3 = E; X_4 = K)$ in the second one $[[[KE]L]M]$.

By developing the system (3.21), we can derive the explicit production factors demand as in the system (3.19). We can also write the ES between each pair of inputs implicitly defined by the system (3.21), $\eta$ being a function of the ES $\rho$ estimated in the nested specification of the production function. Extending the system of equation (3.21) by replacing the composite inputs leads to the explicit formulation of each input as in (3.9). This yields, after simplifying the equations[20], the relation between the ES

[19] In a three inputs-case $(K; L; E)$, we notice that the preferences are more oriented towards the $[[KE]L]$ form (Feng and Zhang, 2018; Kemfert, 1998).

[20] For a full demonstration see Reynès (2019).

of the form:

$$\begin{cases} \eta_{1,2} = \eta_{1,3} = \eta_{1,4} = \rho_{1,234} \\ \qquad\qquad \eta_{2,3} = \dfrac{\rho_{2,3}}{1-\varphi_1-\varphi_4} - \dfrac{\rho_{1,234}\ \varphi_1}{1-\varphi_1} - \dfrac{\rho_{23,4}\ \varphi_4}{(1-\varphi_1)(1-\varphi_1-\varphi_4)} \\ \qquad \eta_{2,4} = \eta_{3,4} = \dfrac{\rho_{23,4} - \rho_{1,234}\ \varphi_1}{1-\varphi_1} \end{cases} \tag{3.23}$$

It is to be noted that in this case, we still have three constrained values ( $\eta_{1,3}$, $\eta_{1,4}$ and $\eta_{3,4}$) to the VOE-CD general case. We also consider for their computation the average shares $\varphi$ on the whole period covered by the data panel.

## 3.5 Results

In this section, we expose the econometric results for three production function structure cases: two constrained cases and the unconstrained cases. Then we use them to calibrate a CGE model and simulate the impact of a carbon tax policy depending on the estimated production structure.

### Estimation results

In order to facilitate the reading of the results due to the large number of sectors, we present them in a graphic form (see Figure 3.2). The detailed estimation tables are provided in 3.6 for the three cases.

The nesting structure has important implications since it leads to two opposite diagnostics regarding the substitution between Capital and Energy. In the $[[[KL]E]M]$ case, where Energy is a direct substitute for the Value-added component in the production function, the econometric estimation finds that the ES between capital and Energy is positive in a majority of sectors (thirty out of fifty-four). It indicates a strong complementary between these two inputs (see Prywes (1986)). In the $[[[KL]E]M]$ case, capital and Energy are, on the contrary, diagnosed as strong substitutes: forty-three sectoral estimations out of fifty-four have a negative ES, and among them, thirty-three with an absolute value greater than 1. Regarding at the average of sectors, the ES between Capital and Energy is 0,20 in the $[[[KL]E]M]$ case against -1,75 in the $[[[KL]E]M]$ case. It highlights a clear contrast with the Labor-Capital ES estimation where the results are consistent across the specifications (the average Labor-Capital ES is -0.31 for the case $[[[KL]E]M]$ and - 0,27 for the case $[[[KL]E]M]$). It indicates a specificity of the capital-energy relationship. When considered direct substitutes, they are strongly substitutable, and when integrated into a composite input, they are strongly complementary.

The more general unconstrained VOE case rather indicates substitutability between capital and Energy. Out of the 31 sectors providing significant results, 29 sectors have a negative elasticity[21]. For results significant at a 99% level [22], we find an average ES between Capital and Energy of -0,76 (resp. -0.5 for the median ES), of -0,83 (resp. -0,85) between Capital and Materials of -0,48 (resp. -0,42) between Labor and Energy, of -1,65 (resp. -1,31) between Labor and Materials of -0,80 (resp. -0,65) and of -2,37 (resp. -1,72) between Energy and Materials. The results confirm recent findings from the Literature. Based on an empirical analysis of the production function using a Translog specification as a benchmark, Lagomarsino and Turner (2017) conclude that a [[[KE]L]M] nested structure is the most appropriate form.

Another point to raise is the differences in estimation that brings the VOE-CD specification concerning the nested specifications. Indeed due to the restrictions imposed by the constraints on the ES estimations (see equation 3.23), non-energy-inputs (M) are considered less substitutable with the other inputs than in the VOE case[23]

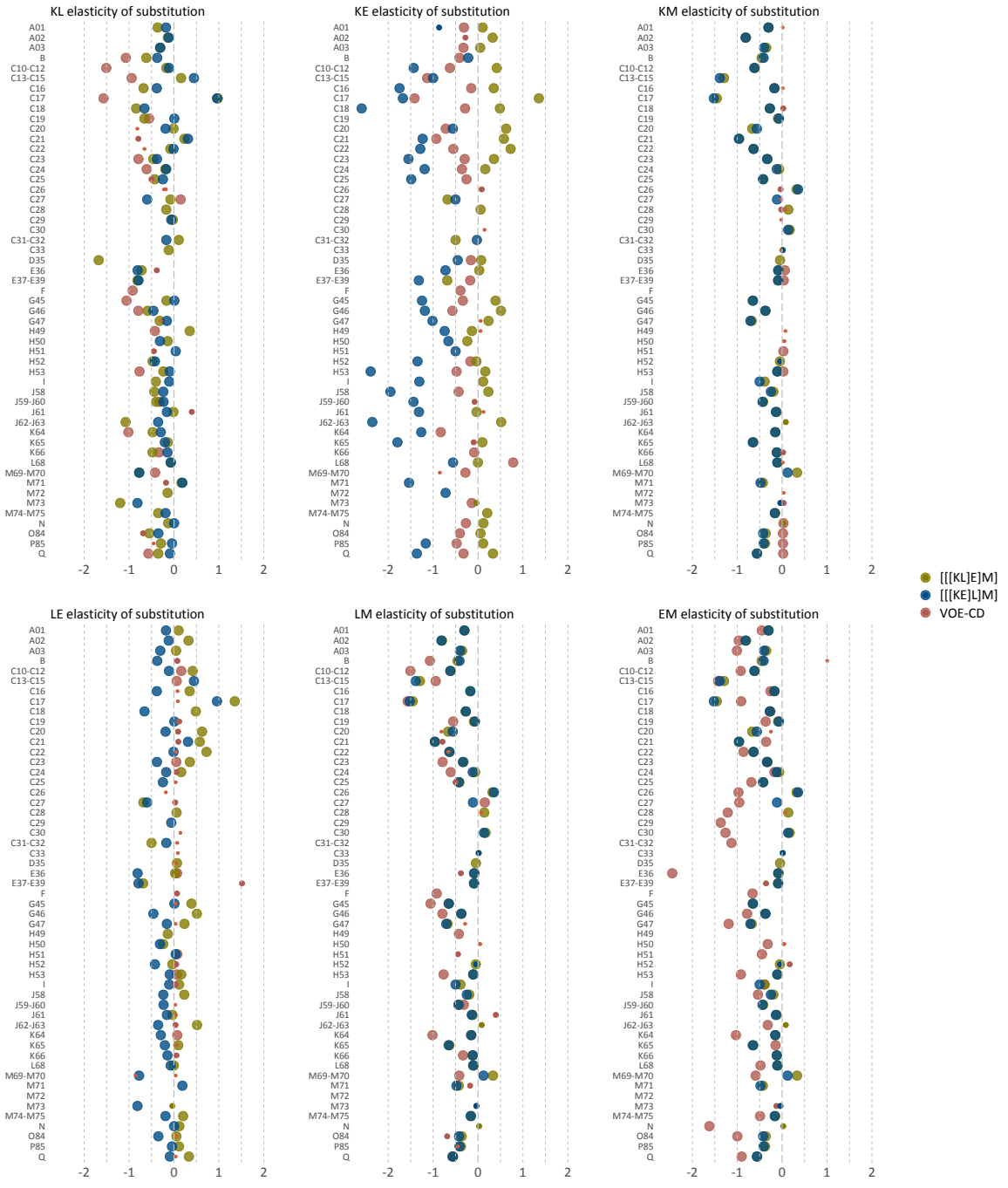
Without further statistical tests, it remains tedious to assess the superiority of a specification to another from an empirical point of view. However, imposing a nesting structure necessarily induces more constraints on the estimation. In the case of the $KM$, $LM$, and $EM$ ES, it seems that these restrictions can even be misleading. If it matches pretty well the estimations from the VOE for the $KM$ substitutability, the findings suggesting a complementarity between capital and Energy for most of the sectors remains questionable.

[21]Out of the three sectors showing complementarity J61 = Telecommunications; C27 = Manufacture of electrical equipment and R_S = Other services activities), two of them are related to electrical equipment, suggesting a sectoral feature in capital and energy use.

[22]After excluding an outlier: the values estimated for the sector E37-E39 (Sewerage; waste collection, treatment; materials recovery, and other waste management services) are in absolute terms higher than 10 for two ES, suggesting misspecification of a data issue.

[23]In the alternative cases, Materials are substitute to the composite input $[[KL]E]$ or $[[KE]L]$.

Figure 3.2: Estimation of the elasticities




Note: The size of the points indicates the level of significance of the estimations (big = 1%; medium = 5%; small = 10%).

## Simulations

As stated in the introduction, results from simulations conducted on CGE are sensitive to the distribution of the exogenous parameters, including the elasticities of substitution. In this part, we will mobilize the CGE model ThreeME to conduct a sensitivity analysis regarding the distribution of these parameters on the aggregate and sectoral results. The model ThreeME is a dynamic CGE model characterized by neo-Keynesian features. It allows for sub-optimal equilibria and transition phases before reaching a long-term steady-state equilibrium (see details in Appendix C). We take as the baseline a 17 sectors version of the model[24], calibrated on the NAF nomenclature, compatible with the NACE Rev2.1 EU nomenclature (and therefore WIOD), which has been used to estimate the impact of the COVID restrictions on the french economy (Malliet et al., 2020).

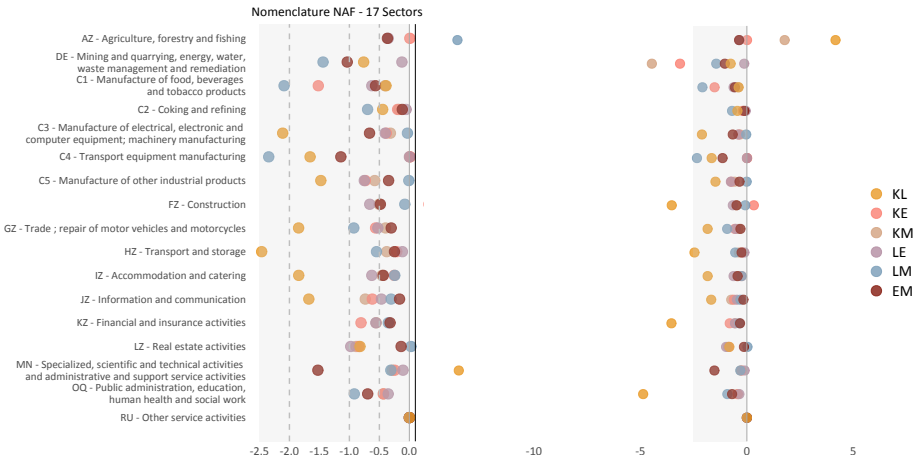
Our ES estimations are based on the WIOD sectoral disaggregation. They must be adjusted to match the NAF nomenclature sector disaggregation used in ThreeME. For each sector of the NAF nomenclature, its ES are calculated as the weighted average of the estimated ES from WIOD data using the production weight from WIOD on the related sectors. The distribution is provided in the Figure 3.3.

We consider a neutral carbon tax scenario with no monetary transfers between households and firms: proceeds of the carbon tax paid by households are redistributed to them, while each sector receives a share of the carbon tax paid by the private sector proportional to its share of total employment. This mode of allocation is favorable to labor-intensive sectors. Following the Quinet commission report (Quinet, 2019), we assume a constant increasing carbon tax trajectory is reaching 250 EUR in 2030, 500 EUR in 2040, and 775 EUR in 2050.

We compare four simulations of this scenario where only the value of the elasticities

[24]The source code can be retrieved from the Github repository: `https://github.com/fosem/ThreeME_V3-open`.

Figure 3.3: Elasticities for the NAF nomenclature

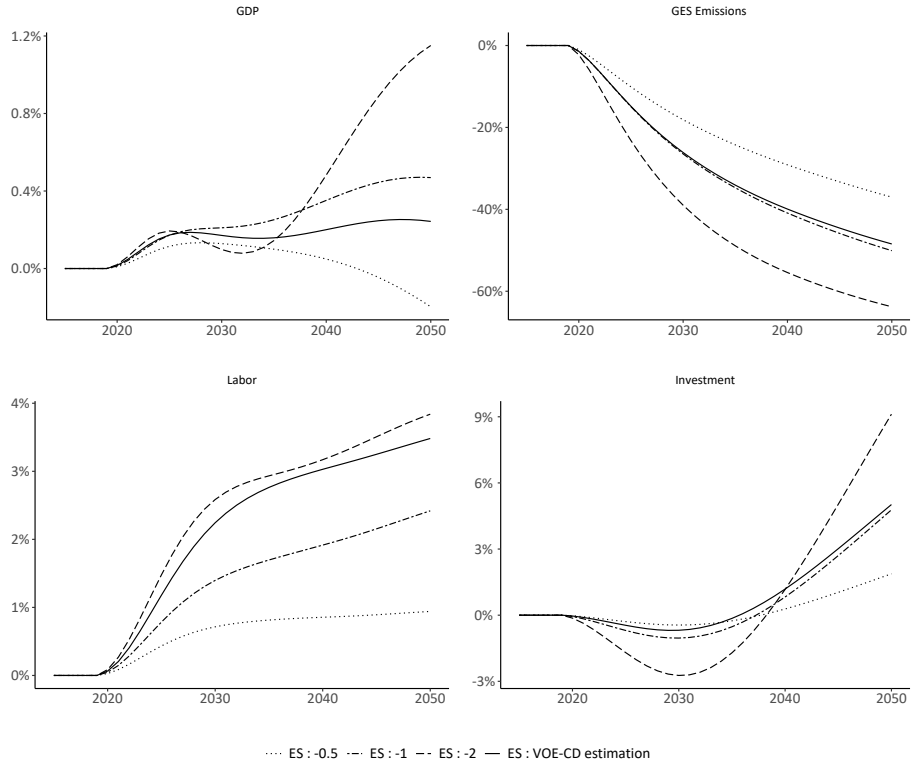



Note: The gray area corresponds to a zoom of the distribution of the elasticities between $-2.5$ and 0 values/ The dashed lines corresponds to the assumptions made for the alternative scenarios for the values of the elasticities of substitution.

of substitution is altered. The first one with an aggregate elasticity of substitution calibrated to $-0.5$ represents a relative inelastic case, and the second one to $-1$ corresponds to a Cobb-Douglas production function specification. The third one with $-2$ states an elastic version of the production function, and in the last one, we report the results obtained from the econometric regression and calibrated on the 17 sectors. The results are reported in Figure 3.4 in relative deviation to the baseline scenario (where no carbon tax policy is implemented).

From a macroeconomic point of view, the scenario with the VOE-CD estimation does not appear as an outlier. It evolves in the same range as the ad-hoc elasticities scenarios with a long-term effect between the $ES : -2$ and $ES : -0.5$ scenarios. Regarding the GDP, we observe a positive increase by 2050 of 0.24% (the amplitude of the deviation is slightly under the Cobb-Douglas scenario for which the impact is 0.47%). From a general point of view, we can see that the results are strongly related to the ES assumption since the results cover a broad amplitude. At the end year of the simulation, 2050, we find a range from $-0.20\%$ for the scenario $ES : -0.5$ to $+1.15\%$ for the scenario $E : -2$).

Figure 3.4: Simulations of a carbon tax policy for each distribution of parameters

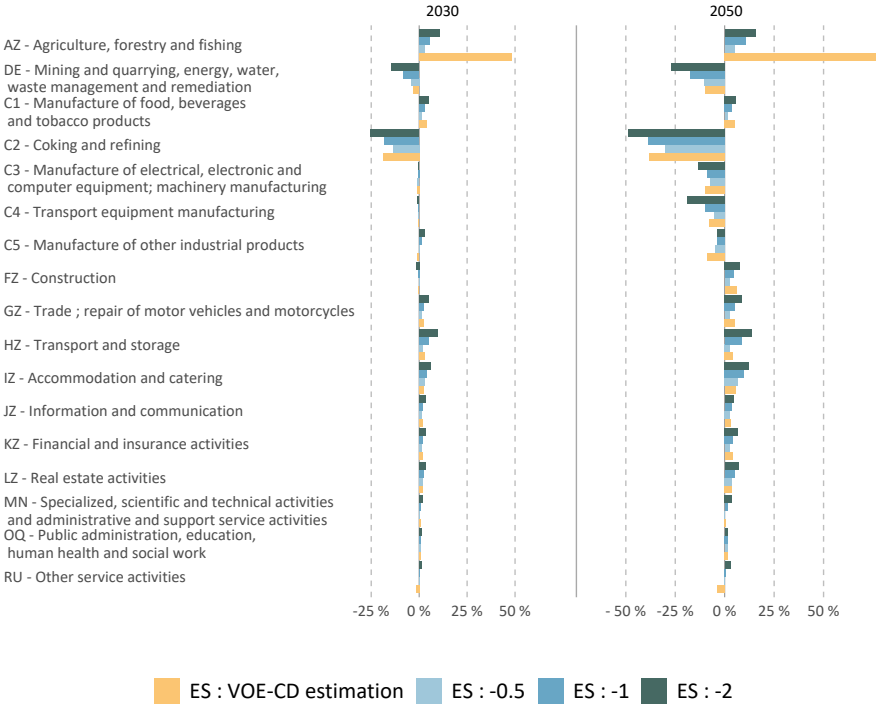



Note: Simulations conducted with the model ThreeME

For the more elastic case, we can see a downturn in the GDP trajectory from 2025 to 2032, which corresponds to a similar shrinking of investments in the same period before catching up and reaching 2050, a 1.15% increase with respect to the baseline. In the most inelastic case (ES:−0.5), the GDP % deviation remains small compared to the others and leads to a long-run negative impact with a 0.2% deviation by 2050.

The dynamics induced in the labor market are pretty straightforwards as well—the more substitutable the inputs, the larger the impact on employment. It reaches by 2050 a positive deviation of 0.9% for the scenario $ES : -0.5$, 2.4% for the intermediate case $ES : -1$, and 3.8% for the scenario $ES : -2$. The estimated elasticities scenario follows the same dynamic as the latest, with a long-term impact of 3.5%. It should be noted that the recycling scheme plays a central role in the direction of the results. Other recycling schemes would not necessarily lead to a positive effect on employment.

Figure 3.5: Value added in % deviation wrt baseline for two selected years




Note: Simulations conducted with the model ThreeME

Finally, the overall impact on emissions ranges from $-63\%$ to $-37\%$ by 2050, the lowest reduction being associated with the scenario $ES : -0.5$ and the highest to the scenario $ES : -2$. The more substitutable the inputs, the lower the fossil fuel energy demand. The scenario with the estimated ES leads to a similar reduction of emissions than in the $ES : -1$ case, with a relative deviation by 2050 equals to $-48.5\%$ (resp. $-50.1\%$). It can be seen as the direct consequence of the values for ES between Capital and Energy, which for some sectors are closer to -2 than to -1[25]

Breaking down at the sectoral level (see Figure 3.5 and looking at the value-added variable, the results from the estimated elasticities deliver the same conclusions as for the aggregate indicators. The effects dwell within the same range as the macroeconomic indicators, except for the agricultural sector, where the variation of labor use

[25]The estimations for the ES between Energy and Labor though are not as much elastic since the results are distributed between 0 and -1.

is much larger. It is the direct consequence of the estimated value of its elasticity between materials and labor, which is equal to -15.2 for this sector. Such an outlying value raises questions about the data quality for this sector since such a value is an outlier. It leads to a long-term variation of value added and employment of more than 60%, much greater than for other scenarios.

## 3.6 Conclusion

We contribute to the empirical literature on substitutions between production factors by proposing the first econometric estimation of the VOE-CD specification. Moreover, we constructed an original panel dataset derived from the WIOD database, one of the most used sources for CGE analysis. We then estimate the ES between KLEM inputs for 54 economic sectors. We evaluate and compare three specifications of the production function, among which two main forms of nested CES production function, namely [[[KL]E]M] and [[[KE]L]M]. We obtain highly significant estimation results for most of the sectors. A comparison of the different specifications allows for deriving three main conclusions:

- By imposing constraints on the estimations, the form of the nest has important implications on the estimated results.
- The Capital-Energy substitution behavior is especially highly dependent on the nest structure since it leads to opposing conclusions: either substitution or complementarity depending on the nest structure's choice.
- The VOE specification supports substitutability between these two factors of production, suggesting that the [[[KE]L]M] nest may be closer to reality.

The VOE-CD specification appears as a relevant, flexible, functional form of the production function. It has the advantage of linear tractability while relaxing the constraint imposed by the CES production function. It is, therefore, a relevant alternative for CGE models. When applied to energy and carbon policy evaluations, the VOE-CD function shows that the nest's choice affects the results critically.

These results shed some light on the Capital-Energy controversy initiated by opposite estimations of the value of the ES between these two inputs: On the one hand, Berndt and Christensen (1973) found complementarity; on the other hand, Griffin and Gregory (1976) found substitutability.

The VOE-CD specification appears as a relevant, flexible, functional form of the production function. It has the advantage of linear tractability while relaxing the constraint imposed by the CES production function. It is, therefore, a relevant alternative for CGE models. When applied to energy and carbon policy evaluations, the VOE-CD function shows that the nest's choice affects the results critically.

The estimated values we obtained from the econometric regressions compared with a Cobb-Douglas production function specification (i.e., with an ES equal to -1) indicate relatively lower substitutability between energy and capital, leading to fewer emissions reduction.

To investigate these estimations' implications on a CGE model's simulation results, we perform a sensitivity analysis regarding the level of ES. Including the values estimated econometrically, we compare them to 3 standard cases of ES. Our results confirm the crucial role of the distribution of the ES parameters on the results of CGE conducted simulations. The implications of the simulation results are paramount. It sketches a more labor-intensive substitution effect from the carbon tax policy than what could be expected in the Cobb-Douglas case but associated with an equivalent reduction in emissions. More specifically, the elasticities between labor and energy in most sectors are lower than -1. These results could be further investigated in several directions. A first lead would be to compare them with those estimated from another flexible production function, such as the Translog, which would disentangle the data's respective role and the estimated results specification. Another possible investigation is the indicators' impact on the estimated elasticity level. For instance, the definition of the capital stock used may impact the results. Investigation of the original dataset should also be carried on since they result from a necessary transformation process of raw data from statistical institutes that can be a source of estimation bias, especially at the sector level. Nonetheless, the implications of the calibration of the elasticities are critical in terms of effect and cannot be ignored or neglected. The data stringency

argument raised in the past to justify ad-hoc values appears no longer valid, and the development of econometric studies for CGE modeling should be more systematized.

# Appendix A: Econometric results

Table 3.1: Estimation results for the VOE-CD production function

| Sectors | $\eta^{KL}$ | $\eta^{KE}$ | $\eta^{KM}$ | $\eta^{LE}$ | $\eta^{LM}$ | $\eta^{EM}$ |
|---|---|---|---|---|---|---|
| A01 | $-0.389^{***}$ | $-0.283^{***}$ | $-0.294^{***}$ | 0.908 | $-0.165^{***}$ | $-2.875^{**}$ |
| | (0.053) | (0.464) | (0.035) | (4.47) | (0.133) | (2.063) |
| A02 | $-0.563^{**}$ | $-3.32^{***}$ | $-1.053^{***}$ | 7.606 | $-0.71^{***}$ | 12.087 |
| | (0.081) | (1.961) | (0.158) | (9.618) | (0.129) | (6.17) |
| A03 | $-0.635^{***}$ | $-1.407$ | $-0.475^{***}$ | 3.548 | $-0.6^{***}$ | $2.904^{**}$ |
| | (0.092) | (0.748) | (0.092) | (4.065) | (0.196) | (2.569) |
| B | $-0.428^{***}$ | $-0.465$ | $-0.668^{***}$ | $-0.492^{***}$ | $-0.216^{***}$ | $-0.911^{***}$ |
| | (0.067) | (0.067) | (0.083) | (0.16) | (0.274) | (0.172) |
| C10-C12 | $-0.459^{***}$ | $-0.287^{***}$ | $-0.572^{***}$ | $-5.753$ | $-0.808^{***}$ | $-0.456^{**}$ |
| | (0.053) | (0.423) | (0.064) | (2.076) | (0.101) | (1.201) |
| C13-C15 | $-0.433^{***}$ | $-0.769^{***}$ | $-0.61^{***}$ | $-0.724^{***}$ | $-0.793^{***}$ | $-1.074$ |
| | (0.064) | (0.162) | (0.091) | (0.714) | (0.126) | (0.352) |
| C16 | $-0.712^{***}$ | $-0.497^{***}$ | $-0.331^{***}$ | 1.08 | $-0.772^{***}$ | $-0.844^{**}$ |
| | (0.098) | (0.535) | (0.048) | (2.516) | (0.129) | (0.681) |
| C17 | $-0.474^{***}$ | $0.165^{***}$ | $-0.572^{***}$ | $-1.466$ | $-1.084^{***}$ | $-2.654$ |
| | (0.075) | (0.189) | (0.053) | (1.468) | (0.113) | (0.361) |
| C18 | $-0.733^{***}$ | $-0.125^{***}$ | $-0.52^{***}$ | $-0.046$ | $-1.078^{***}$ | $-1.047^{*}$ |
| | (0.088) | (0.366) | (0.067) | (1.717) | (0.121) | (1.041) |
| C19 | $-1.022^{***}$ | $0.224^{*}$ | $-0.234^{***}$ | 0.103 | $-0.108^{**}$ | $0.163^{***}$ |
| | (0.135) | (0.207) | (0.076) | (0.457) | (0.159) | (0.074) |
| C20 | $-1.488^{**}$ | $-0.478^{**}$ | $-0.348^{***}$ | 0.554 | $-0.119^{***}$ | $-1.146$ |
| | (0.209) | (0.255) | (0.07) | (1.662) | (0.299) | (0.432) |
| C21 | $-0.393^{***}$ | $-0.21^{*}$ | $-0.142^{***}$ | $-1.4$ | $-1.161$ | $-2.47$ |
| | (0.092) | (0.406) | (0.129) | (1.45) | (0.136) | (0.548) |
| C22 | $-0.392^{***}$ | $-0.875^{***}$ | $-0.588^{***}$ | $-0.903^{***}$ | $-1.027^{***}$ | $-1.621$ |
| | (0.098) | (0.254) | (0.056) | (1.043) | (0.106) | (0.415) |
| C23 | $-0.457^{***}$ | $-1.062^{***}$ | $-0.453^{***}$ | $1.514^{***}$ | $-0.796^{***}$ | $-1.524$ |
| | (0.087) | (0.309) | (0.048) | (1.602) | (0.127) | (0.552) |
| C24 | $-0.483^{***}$ | $-0.313^{***}$ | $-0.465^{***}$ | $-6.222$ | $-0.579^{***}$ | $-1.085$ |
| | (0.102) | (0.243) | (0.05) | (1.914) | (0.092) | (0.387) |
| C25 | $-0.692^{***}$ | $-0.321$ | $-0.569^{***}$ | 1.159 | $-0.831^{***}$ | $-1.576^{*}$ |
| | (0.077) | (0.354) | (0.054) | (1.237) | (0.099) | (0.336) |
| C26 | $0.129^{**}$ | 0.008 | 0.356 | $-0.535$ | $-1.102$ | $-0.876$ |
| | (0.073) | (0.034) | (0.21) | (0.607) | (0.148) | (0.486) |
| C27 | $1.023^{*}$ | 0.203 | $4.612^{***}$ | $-0.043$ | $-1.447^{***}$ | $-0.09$ |
| | (0.134) | (0.123) | (0.45) | (0.743) | (0.178) | (0.488) |
| C28 | $0^{*}$ | $-0.008$ | $-0.001$ | $-0.751$ | $-1.033$ | $-2.257$ |
| | (0.072) | (0.03) | (0.067) | (0.638) | (0.144) | (0.672) |
| C29 | $1.798^{*}$ | 0.455 | $5.127^{***}$ | $-1.88^{**}$ | $-2.732^{***}$ | $-0.657$ |

| | | | | | | |
|---|---|---|---|---|---|---|
| | (0.203) | (0.155) | (0.499) | (0.916) | (0.286) | (0.953) |
| C30 | 4.666*** | −0.062 | 5.551*** | −5.147 | −3.528*** | 2.161 |
| | (0.469) | (0.393) | (0.55) | (3.096) | (0.755) | (4.053) |
| C31-C32 | 0.019 | −0.108 | 0.032 | −5.21* | −1.39 | −0.081 |
| | (0.049) | (0.05) | (0.072) | (0.464) | (0.164) | (0.398) |
| C33 | −0.569* | −0.718* | −0.636** | 1.67 | −0.565*** | −1.563 |
| | (0.197) | (1.067) | (0.144) | (2.663) | (0.319) | (0.959) |
| D35 | −0.457*** | 0.162*** | −0.166*** | −1.253*** | −0.551*** | 0.128*** |
| | (0.058) | (0.027) | (0.037) | (0.165) | (0.349) | (0.066) |
| E36 | −1.714*** | −0.238 | −0.09*** | 3.514 | −1.913 | −5.929*** |
| | (0.254) | (0.423) | (0.102) | (5.291) | (1.083) | (2.982) |
| E37-E39 | −0.608*** | 0.204 | −0.161*** | −0.721 | −0.909 | −4.024*** |
| | (0.094) | (0.35) | (0.108) | (1.009) | (0.146) | (1.314) |
| F | −0.238*** | −1.139*** | −0.618*** | −0.825** | −0.537*** | −0.892** |
| | (0.066) | (0.366) | (0.087) | (0.408) | (0.082) | (0.381) |
| G45 | −0.627*** | −0.395*** | −0.733*** | −0.788 | −0.661*** | −1.431 |
| | (0.067) | (0.295) | (0.059) | (0.39) | (0.081) | (0.388) |
| G46 | −0.748*** | −0.361*** | −0.766*** | −0.175 | −0.514*** | −1.971* |
| | (0.057) | (0.311) | (0.062) | (0.441) | (0.086) | (0.44) |
| G47 | 0.317*** | 0.047 | 1.139*** | −1.717 | −1.678*** | −3.518 |
| | (0.026) | (0.062) | (0.061) | (0.906) | (0.156) | (0.588) |
| H49 | −0.165*** | −0.559 | 0.006 | −2.591*** | −1.472 | −2.551*** |
| | (0.104) | (0.158) | (0.048) | (1.288) | (0.235) | (0.53) |
| H50 | −0.236*** | −1.102*** | −1.086*** | −0.017* | −1.011*** | −0.052* |
| | (0.065) | (0.451) | (0.198) | (1.231) | (0.172) | (1.206) |
| H51 | −0.497*** | −0.745*** | −0.266*** | 2.122*** | −0.964*** | −1.431** |
| | (0.056) | (0.211) | (0.053) | (1.267) | (0.143) | (0.524) |
| H52 | −0.416*** | −1.014*** | −0.343*** | −1.263* | −0.843*** | −0.076 |
| | (0.101) | (0.477) | (0.101) | (0.837) | (0.112) | (0.531) |
| H53 | −0.702*** | −0.385*** | −0.721*** | −1.156* | −1.263*** | −1.737*** |
| | (0.062) | (0.184) | (0.082) | (0.495) | (0.193) | (0.882) |
| I | −0.478*** | −0.315*** | −0.623*** | 2.623 | −1.036*** | −2.109* |
| | (0.072) | (0.479) | (0.09) | (1.066) | (0.122) | (0.691) |
| J58 | −0.316 | −42.303 | −2.269 | 67.411 | −1.287** | 226.966 |
| | (0.449) | (76.828) | (0.689) | (116.917) | (0.929) | (369.362) |
| J59-J60 | −0.161*** | −0.613*** | −0.432*** | −0.209* | −0.323*** | −2.956 |
| | (0.038) | (0.258) | (0.055) | (0.665) | (0.112) | (0.819) |
| J61 | 5.31*** | 0.108** | 13.352*** | −0.509 | −3.814*** | −1.532 |
| | (0.371) | (0.186) | (0.802) | (0.61) | (0.334) | (0.372) |
| J62-J63 | −0.617*** | −0.505** | −0.366*** | −1.968* | −0.594*** | −1.022 |
| | (0.107) | (0.204) | (0.071) | (0.569) | (0.086) | (0.202) |
| K64 | −0.733*** | 0.31* | −0.441*** | −1.197 | −0.619*** | −1.602** |
| | (0.136) | (0.27) | (0.113) | (0.628) | (0.172) | (0.325) |

| | | | | | | |
|---|---|---|---|---|---|---|
| K65 | $-1.534^{***}$ | $-2.938$ | $-0.444^{*}$ | 1.697 | $-0.633^{*}$ | $-1.665$ |
| | (0.669) | (1.494) | (0.188) | (1.051) | (0.14) | (0.426) |
| K66 | $-0.311^{***}$ | $-3.623^{**}$ | $-0.212^{***}$ | 2.293 | $-2.847^{**}$ | 6.318 |
| | (0.07) | (2.207) | (0.067) | (53.546) | (1.399) | (11.484) |
| L68 | $-0.027$ | 0.221 | 0.371 | $-0.987$ | $-0.736^{***}$ | $-2.249^{***}$ |
| | (0.025) | (0.203) | (0.111) | (0.816) | (0.066) | (1.123) |
| M69-M70 | $-0.457$ | $-0.592^{***}$ | $-1.259^{***}$ | 0.088 | $-0.26^{***}$ | $-2.175^{**}$ |
| | (0.084) | (0.518) | (0.168) | (0.2) | (0.078) | (0.612) |
| M71 | $-0.51$ | $-0.833^{***}$ | $-0.438^{***}$ | $-1.034^{***}$ | $-0.826^{**}$ | $-0.512^{**}$ |
| | (0.041) | (0.189) | (0.145) | (0.295) | (0.116) | (0.134) |
| M72 | $-0.897^{***}$ | $0.717^{*}$ | $-1.095^{***}$ | 1.414 | $-1.075^{***}$ | $-1.177^{**}$ |
| | (0.265) | (1.044) | (0.141) | (1.143) | (0.16) | (0.263) |
| M73 | $-1.138^{***}$ | $0.25^{***}$ | $-0.786^{***}$ | 0.444 | $-0.646^{***}$ | $-1.809^{***}$ |
| | (0.168) | (0.824) | (0.109) | (0.65) | (0.08) | (0.252) |
| M74-M75 | $-0.002$ | $-0.027$ | $-0.002$ | $-2.183$ | $-0.604$ | $-2.37^{**}$ |
| | (0.009) | (0.398) | (0.031) | (3.69) | (0.084) | (1.331) |
| N | $-0.639^{***}$ | 0.097 | $-0.334^{***}$ | $-2.232$ | $-1.619^{*}$ | $-4.493^{***}$ |
| | (0.041) | (0.619) | (0.151) | (0.998) | (0.448) | (17.978) |
| O84 | $-0.432^{***}$ | $-0.8$ | $-0.384^{***}$ | $-1.178^{***}$ | $-1.478^{**}$ | $7.859^{***}$ |
| | (0.044) | (0.201) | (0.142) | (0.724) | (0.461) | (5.661) |
| P85 | $-0.635^{***}$ | $-0.461$ | $-0.514^{***}$ | $-0.625$ | $-0.902^{**}$ | $-4.957^{***}$ |
| | (0.046) | (0.336) | (0.163) | (1.076) | (0.375) | (6.271) |
| Q | $-0.888^{***}$ | $-0.353^{***}$ | $-0.405^{***}$ | $0.633^{*}$ | $-0.414^{***}$ | $-2.779^{***}$ |
| | (0.061) | (0.164) | (0.082) | (0.602) | (0.205) | (0.683) |

Table 3.2: Estimation results for the [[[KL]E]M] nested production function

| Sectors | $\rho^{K.L}$ | $\rho^{E.KL}$ | $\rho^{M.KLE}$ |
|---|---|---|---|
| A01 | $-0.348$ | $0.007^{***}$ | $-0.303^{***}$ |
| | (0.016) | (0.001) | (0.03) |
| A02 | $-0.318$ | $0.013^{***}$ | $-0.803^{***}$ |
| | (0.016) | (0.003) | (0.082) |
| A03 | $-0.32$ | $-0.051^{***}$ | $-0.355^{***}$ |
| | (0.021) | (0.003) | (0.074) |
| B | $-0.306$ | $-0.003^{***}$ | $-0.457^{***}$ |
| | (0.033) | (0.005) | (0.033) |
| C10-C12 | $-0.341$ | $0.014^{***}$ | $-0.611^{***}$ |
| | (0.016) | (0.002) | (0.04) |
| C13-C15 | $-0.395^{**}$ | $0.017^{***}$ | $-1.294^{***}$ |
| | (0.015) | (0.015) | (0.081) |
| C16 | $-0.397$ | $0.066^{***}$ | $-0.173^{***}$ |
| | (0.018) | (0.007) | (0.022) |
| C17 | $-0.171$ | $0.022^{***}$ | $-1.453^{***}$ |
| | (0.011) | (0.005) | (0.064) |
| C18 | $-0.559$ | $0.122^{***}$ | $-0.276^{***}$ |
| | (0.024) | (0.02) | (0.031) |
| C19 | $-0.133$ | $0.013^{***}$ | $-0.091^{***}$ |
| | (0.024) | (0.02) | (0.029) |
| C20 | $-0.269^{*}$ | $0.053^{***}$ | $-0.665^{***}$ |
| | (0.022) | (0.008) | (0.048) |
| C21 | $-0.201$ | $0.01^{***}$ | $-0.957^{***}$ |
| | (0.013) | (0.002) | (0.071) |
| C22 | $-0.362^{*}$ | $0.014^{***}$ | $-0.637^{***}$ |
| | (0.016) | (0.005) | (0.038) |
| C23 | $-0.374^{*}$ | $0.03^{***}$ | $-0.324^{***}$ |
| | (0.015) | (0.005) | (0.034) |
| C24 | $-0.123$ | $0.051^{***}$ | $-0.067^{***}$ |
| | (0.022) | (0.007) | (0.025) |
| C25 | $-0.413$ | $0.005^{***}$ | $-0.418^{***}$ |
| | (0.017) | (0.005) | (0.037) |
| C26 | $-0.014$ | $-0.022^{***}$ | 0.321 |
| | (0.007) | (0.033) | (0.05) |
| C27 | $-0.047$ | $-0.432^{***}$ | $-0.057^{***}$ |
| | (0.01) | (0.05) | (0.038) |
| C28 | $-0.053$ | $0.085^{***}$ | $0.138^{***}$ |
| | (0.011) | (0.018) | (0.042) |
| C29 | $-0.003$ | $-0.024^{***}$ | $0.023^{**}$ |

| | | | |
|---|---|---|---|
| | (0.001) | (0.038) | (0.039) |
| C30 | 0.007 | 0.152*** | 0.168 |
| | (0.007) | (0.078) | (0.055) |
| C31-C32 | 0.085 | −0.32*** | 0.029*** |
| | (0.01) | (0.052) | (0.048) |
| C33 | −0.044* | 0.005*** | 0.015** |
| | (0.015) | (0.005) | (0.006) |
| D35 | −1.319*** | 0.049*** | −0.047*** |
| | (0.164) | (0.007) | (0.016) |
| E36 | −0.64*** | 0.015*** | −0.077*** |
| | (0.029) | (0.003) | (0.023) |
| E37-E39 | −0.645 | −0.555*** | −0.092*** |
| | (0.023) | (0.03) | (0.006) |
| F | −0.003 | −0.016*** | −0.004 |
| | (0.003) | (0.038) | (0.009) |
| G45 | −0.309 | 0.023*** | −0.656*** |
| | (0.017) | (0.008) | (0.039) |
| G46 | −0.461 | 0.153*** | −0.375*** |
| | (0.019) | (0.008) | (0.03) |
| G47 | −0.377 | 0.056*** | −0.677*** |
| | (0.017) | (0.009) | (0.065) |
| H49 | 0.288 | −0.109*** | −0.005*** |
| | (0.04) | (0.036) | (0.013) |
| H50 | −0.054 | −0.169*** | 0.044* |
| | (0.023) | (0.023) | (0.024) |
| H51 | −0.005 | 0.001*** | 0.007 |
| | (0.008) | (0.002) | (0.032) |
| H52 | −0.351 | −0.04*** | −0.05*** |
| | (0.02) | (0.009) | (0.018) |
| H53 | −0.171*** | 0.06*** | −0.106*** |
| | (0.021) | (0.022) | (0.015) |
| I | −0.391 | 0.025*** | −0.39*** |
| | (0.022) | (0.004) | (0.059) |
| J58 | −0.333 | 0.068*** | −0.196*** |
| | (0.016) | (0.008) | (0.045) |
| J59-J60 | −0.398* | 0.01*** | −0.423*** |
| | (0.021) | (0.007) | (0.055) |
| J61 | −0.035 | −0.055*** | −0.121*** |
| | (0.007) | (0.016) | (0.025) |
| J62-J63 | −0.606 | 0.348*** | 0.081*** |
| | (0.025) | (0.02) | (0.039) |
| K64 | −0.296 | 0.01*** | −0.151*** |
| | (0.018) | (0.017) | (0.024) |

| | | | |
|---|---|---|---|
| K65 | −0.303 | −0.159*** | −0.641*** |
| | (0.027) | (0.013) | (0.053) |
| K66 | −0.288 | 0.047*** | −0.121*** |
| | (0.028) | (0.065) | (0.02) |
| L68 | −0.07*** | −0.006*** | −0.096*** |
| | (0.008) | (0) | (0.023) |
| M69-M70 | −0.217 | −0.291*** | 0.333*** |
| | (0.025) | (0.16) | (0.033) |
| M71 | −0.089** | −0.058*** | −0.429*** |
| | (0.009) | (0.048) | (0.06) |
| M72 | −0.079 | 0.002*** | −0.004*** |
| | (0.019) | (0.003) | (0.004) |
| M73 | −0.444 | −0.037*** | −0.038*** |
| | (0.03) | (0.018) | (0.015) |
| M74-M75 | −0.23 | 0.022*** | −0.156*** |
| | (0.019) | (0.008) | (0.018) |
| N | −0.056 | 0.083*** | 0.024** |
| | (0.018) | (0.026) | (0.012) |
| O84 | −0.541 | 0.044*** | −0.365*** |
| | (0.014) | (0.003) | (0.072) |
| P85 | −0.293 | 0.09*** | −0.381*** |
| | (0.022) | (0.011) | (0.047) |
| Q | −0.357 | 0.299*** | −0.557*** |
| | (0.02) | (0.009) | (0.061) |
| R-S | −0.632 | 0.053*** | −0.419*** |
| | (0.018) | (0.004) | (0.053) |

Table 3.3: Estimation results for the [[[KE]L]M] production function

| Sectors | $\rho^{K.E}$ | $\rho^{L.KE}$ | $\rho^{M.KLE}$ |
|---|---|---|---|
| A01 | $-0.677$ | $-0.208^{***}$ | $-0.305^{*}$ |
| | (0.269) | (0.012) | (0.03) |
| A02 | $-0.632$ | $-0.31^{***}$ | $-0.815$ |
| | (0.474) | (0.015) | (0.083) |
| A03 | $-13.241$ | $-0.328^{***}$ | $-0.401^{***}$ |
| | (0.528) | (0.023) | (0.074) |
| B | $-0.158^{***}$ | $-0.376^{***}$ | $-0.413^{***}$ |
| | (0.022) | (0.119) | (0.03) |
| C10-C12 | $-0.844$ | $-0.31^{***}$ | $-0.619^{***}$ |
| | (0.152) | (0.018) | (0.039) |
| C13-C15 | $-0.847$ | $-0.258^{***}$ | $-1.388^{***}$ |
| | (0.094) | (0.014) | (0.082) |
| C16 | $-0.541$ | $-0.268^{***}$ | $-0.171^{***}$ |
| | (0.105) | (0.017) | (0.022) |
| C17 | $-1.38$ | $-0.218^{***}$ | $-1.521^{***}$ |
| | (0.157) | (0.01) | (0.067) |
| C18 | $-1.109^{*}$ | $-0.473^{***}$ | $-0.272^{***}$ |
| | (0.176) | (0.024) | (0.031) |
| C19 | 0.004 | $-0.031^{***}$ | $-0.07$ |
| | (0.02) | (0.01) | (0.023) |
| C20 | $-0.408$ | $-0.354^{***}$ | $-0.563^{***}$ |
| | (0.038) | (0.029) | (0.047) |
| C21 | $-0.956$ | $-0.158^{***}$ | $-0.963^{***}$ |
| | (0.122) | (0.012) | (0.071) |
| C22 | $-0.609$ | $-0.337^{***}$ | $-0.636^{***}$ |
| | (0.088) | (0.018) | (0.038) |
| C23 | $-0.682$ | $-0.359^{***}$ | $-0.336^{***}$ |
| | (0.058) | (0.018) | (0.034) |
| C24 | $-0.508$ | $-0.147^{***}$ | $-0.118^{***}$ |
| | (0.064) | (0.023) | (0.026) |
| C25 | $-0.58^{*}$ | $-0.333^{***}$ | $-0.427^{***}$ |
| | (0.058) | (0.017) | (0.037) |
| C26 | 0.016 | $0.019^{***}$ | 0.354 |
| | (0.011) | (0.009) | (0.047) |
| C27 | 0.037 | $-0.404^{***}$ | $-0.114^{***}$ |
| | (0.009) | (0.038) | (0.037) |
| C28 | $-0.007$ | $-0.007^{***}$ | 0.073 |
| | (0.016) | (0.011) | (0.043) |
| C29 | 0 | $-0.022^{***}$ | 0.037 |
| | (0.002) | (0.009) | (0.035) |
| C30 | 0.006 | $-0.032^{***}$ | 0.134 |

| | | | |
|---|---|---|---|
| | (0.007) | (0.036) | (0.051) |
| C31-C32 | 0.528 | $-0.093^{***}$ | $0.056^{***}$ |
| | (0.059) | (0.01) | (0.048) |
| C33 | $-0.051$ | $-0.001^{***}$ | 0.013 |
| | (0.067) | (0.003) | (0.006) |
| D35 | $-0.36^{***}$ | $-3.347^{***}$ | $-0.027^{***}$ |
| | (0.036) | (0.276) | (0.017) |
| E36 | $-0.625$ | $-0.73^{***}$ | $-0.09^{***}$ |
| | (0.082) | (0.033) | (0.024) |
| E37-E39 | $-1.005^{***}$ | $-0.634^{***}$ | $-0.088^{***}$ |
| | (0.181) | (0.027) | (0.005) |
| F | $-0.006$ | $-0.008^{***}$ | $-0.003$ |
| | (0.01) | (0.01) | (0.009) |
| G45 | $-0.32$ | $-0.221^{***}$ | $-0.649^{***}$ |
| | (0.072) | (0.015) | (0.039) |
| G46 | $-0.283$ | $-0.423^{***}$ | $-0.371^{***}$ |
| | (0.042) | (0.024) | (0.028) |
| G47 | $-0.493$ | $-0.266^{***}$ | $-0.707^{***}$ |
| | (0.062) | (0.017) | (0.064) |
| H49 | $-0.411$ | $-0.003^{***}$ | $-0.01^{***}$ |
| | (0.054) | (0.009) | (0.013) |
| H50 | $-0.386^{*}$ | $-0.223^{***}$ | $0.047^{***}$ |
| | (0.038) | (0.047) | (0.026) |
| H51 | $-0.223$ | $0.02^{***}$ | $-0.044^{***}$ |
| | (0.041) | (0.009) | (0.028) |
| H52 | $-0.847$ | $-0.322^{***}$ | $-0.046^{***}$ |
| | (0.076) | (0.022) | (0.018) |
| H53 | $-1.138$ | $-0.1^{***}$ | $-0.108^{***}$ |
| | (0.195) | (0.022) | (0.017) |
| I | $-0.805$ | $-0.176^{***}$ | $-0.501^{***}$ |
| | (0.096) | (0.016) | (0.061) |
| J58 | $-0.793$ | $-0.242^{***}$ | $-0.25^{***}$ |
| | (0.081) | (0.016) | (0.046) |
| J59-J60 | $-1.267$ | $-0.256^{***}$ | $-0.437^{***}$ |
| | (0.349) | (0.017) | (0.055) |
| J61 | $-0.904^{*}$ | $-0.153^{***}$ | $-0.14^{***}$ |
| | (0.057) | (0.011) | (0.025) |
| J62-J63 | $-0.436^{***}$ | $-0.222^{***}$ | $-0.013^{***}$ |
| | (0.054) | (0.019) | (0.041) |
| K64 | $-0.427$ | $-0.234^{***}$ | $-0.153^{***}$ |
| | (0.046) | (0.019) | (0.023) |
| K65 | $-0.985$ | $-0.359^{***}$ | $-0.654^{***}$ |
| | (0.08) | (0.033) | (0.053) |

| | | | |
|---|---|---|---|
| K66 | $-0.571$ | $-0.132^{***}$ | $-0.118^{***}$ |
| | (0.101) | (0.023) | (0.02) |
| L68 | $-0.541$ | $-0.074^{***}$ | $-0.11^{***}$ |
| | (0.065) | (0.007) | (0.023) |
| M69-M70 | 0.053 | $-0.351^{***}$ | 0.121 |
| | (0.038) | (0.028) | (0.024) |
| M71 | $-0.086^{**}$ | $-0.137^{***}$ | $-0.482^{***}$ |
| | (0.02) | (0.018) | (0.06) |
| M72 | $-0.072$ | $0^{***}$ | $-0.005^{***}$ |
| | (0.021) | (0) | (0.004) |
| M73 | $-0.673^{**}$ | $-0.343^{***}$ | $-0.039^{***}$ |
| | (0.068) | (0.029) | (0.015) |
| M74-M75 | $-0.631$ | $-0.176^{***}$ | $-0.165^{***}$ |
| | (0.071) | (0.017) | (0.018) |
| N | $-0.006$ | $0.002^{***}$ | 0.001 |
| | (0.03) | (0.001) | (0.009) |
| O84 | $-0.157$ | $-0.349^{***}$ | $-0.422$ |
| | (0.227) | (0.015) | (0.071) |
| P85 | $-0.663$ | $-0.062^{***}$ | $-0.412^{***}$ |
| | (0.152) | (0.011) | (0.048) |
| Q | $-0.737^{*}$ | $-0.109^{***}$ | $-0.563^{***}$ |
| | (0.117) | (0.012) | (0.061) |
| R-S | $-0.811$ | $-0.44^{***}$ | $-0.467^{***}$ |
| | (0.065) | (0.017) | (0.053) |

## Appendix B: Nomenclature description

Table 3.4: Sectors labels and correspondance

| iso3 code | countries names |
|---|---|
| AUS | Australia |
| AUT | Austria |
| BEL | Belgium |
| BGR | Bulgaria |
| BRA | Brazil |
| CAN | Canada |
| CHE | Switzerland |
| CHN | China |
| CYP | Cyprus |
| CZE | Czechia |
| DEU | Germany |
| DNK | Denmark |
| ESP | Spain |
| EST | Estonia |
| FIN | Finland |
| FRA | France |
| GBR | United Kingdom |
| GRC | Greece |
| HRV | Croatia |
| HUN | Hungary |
| IDN | Indonesia |
| IND | India |
| IRL | Ireland |
| ITA | Italy |
| JPN | Japan |
| KOR | South Korea |
| LTU | Lithuania |
| LUX | Luxembourg |
| LVA | Latvia |
| MEX | Mexico |
| MLT | Malta |
| NLD | Netherlands |
| NOR | Norway |
| POL | Poland |
| PRT | Portugal |
| ROU | Romania |
| RUS | Russia |
| SVK | Slovakia |
| SVN | Slovenia |
| SWE | Sweden |
| TUR | Turkey |
| TWN | Taiwan |
| USA | United States |

Table 3.5: Sectors labels and nomenclatures correspondence

| code sectors WIOD | WIOD sectors names | code NAF17 | NAF17 sectors names |
|---|---|---|---|
| A01 | Crop and animal production, hunting and related service activities | AZ | Agriculture |
| A02 | Forestry and logging | AZ | Agriculture |
| A03 | Fishing and aquaculture | AZ | Agriculture |
| B | Mining and quarrying | DE | Energy, water, waste |
| C10-C12 | Manufacture of food products, beverages and tobacco products | C1 | Agro-food industries |
| C13-C15 | Manufacture of textiles, wearing apparel and leather products | C5 | Other industrial branches |
| C16 | Manufacture of wood and of products of wood and cork | C5 | Other industrial branches |
| C17 | Manufacture of paper and paper products | C5 | Other industrial branches |
| C18 | Printing and reproduction of recorded media | C3 | Capital goods |
| C19 | Manufacture of coke and refined petroleum products | C2 | Coking and refining |
| C20 | Manufacture of chemicals and chemical products | C5 | Other industrial branches |
| C21 | Manufacture of basic pharmaceutical products and pharmaceutical preparations | C5 | Other industrial branches |
| C22 | Manufacture of rubber and plastic products | C5 | Other industrial branches |
| C23 | Manufacture of other non-metallic mineral products | C5 | Other industrial branches |
| C24 | Manufacture of basic metals | C5 | Other industrial branches |
| C25 | Manufacture of fabricated metal products, except machinery and equipment | C5 | Other industrial branches |
| C26 | Manufacture of computer, electronic and optical products | C3 | Capital goods |
| C27 | Manufacture of electrical equipment | C3 | Capital goods |
| C28 | Manufacture of machinery and equipment n.e.c. | C3 | Capital goods |
| C29 | Manufacture of motor vehicles, trailers and semi-trailers | C4 | Transport equipment |
| C30 | Manufacture of other transport equipment | C4 | Transport equipment |
| C31_C32 | Manufacture of furniture; other manufacturing | C5 | Other industrial branches |
| C33 | Repair and installation of machinery and equipment | C5 | Other industrial branches |
| D35 | Electricity, gas, steam and air conditioning supply | DE | Energy, water, waste |
| E36 | Water collection, treatment and supply | DE | Energy, water, waste |
| E37-E39 | Sewerage; waste collection, treatment and disposal activities | DE | Energy, water, waste |
| F | Construction | FZ | Construction |
| G45 | Wholesale and retail trade and repair of motor vehicles and motorcycles | GZ | Trade |
| G46 | Wholesale trade, except of motor vehicles and motorcycles | GZ | Trade |
| G47 | Retail trade, except of motor vehicles and motorcycles | GZ | Trade |
| H49 | Land transport and transport via pipelines | HZ | Transport |
| H50 | Water transport | HZ | Transport |
| H51 | Air transport | HZ | Transport |
| H52 | Warehousing and support activities for transportation | HZ | Transport |
| H53 | Postal and courier activities | HZ | Transport |
| I | Accommodation and food service activities | IZ | Accommodation and food service |
| J58 | Publishing activities | JZ | Information and communication |
| J59_J60 | Motion picture, video, audio and television programme production | JZ | Information and communication |
| J61 | Telecommunications | JZ | Information and communication |
| J62_J63 | Computer programming, consultancy and related activities; information service activities | JZ | Information and communication |
| K64 | Financial service activities, except insurance and pension funding | KZ | Financial services |
| K65 | Insurance, reinsurance and pension funding, except compulsory social security | KZ | Financial services |
| K66 | Activities auxiliary to financial services and insurance activities | KZ | Financial services |
| L68 | Real estate activities | LZ | Real estate services |
| M69_M70 | Legal and accounting activities; activities of head offices; management consultancy activities | MN | Business services |
| M71 | Architectural and engineering activities; technical testing and analysis | MN | Business services |
| M72 | Scientific research and development | MN | Business services |
| M73 | Advertising and market research | MN | Business services |
| M74_M75 | Other professional, scientific and technical activities; veterinary activities | MN | Business services |
| N | Administrative and support service activities | MN | Business services |
| O84 | Public administration and defence; compulsory social security | OQ | Non-market services |
| P85 | Education | OQ | Non-market services |
| Q | Human health and social work activities | OQ | Non-market services |
| R_S | Other service activities | RU | Household services |
| T | Activities of households as employers | RU | Household services |
| U | Activities of extraterritorial organizations and bodies | RU | Household services |

# Conclusion

In this thesis, I sought to combine micro and macroeconomic approaches with the central objective of performing carbon tax scenario simulations using a CGE model. To do so, I used large databases, two MRIOs, and a household budget survey, which I mobilized to develop environmental and economic indicators and perform econometric regressions. I addressed the supply-side dimensions by studying the shape of output and its calibration from estimated data and the demand-side dimensions of behavioral heterogeneity in response to carbon tax shocks.

## Main results

In the first section, I address the issue of international emissions flows associated with French household final consumption. Thanks to the fine granularity of the EXIOBASE database, I have calculated footprint indicators for a range of 200 products, according to their geographical origins, distinguished in 45 countries and four regions of the world. From the survey data, which gathers 15007 observations and the carbon footprint indicators calculated by product, I determine households' carbon footprints, allowing me to build its distribution for the total population. From this sample, I perform several econometric regressions. I show that the income elasticity of the carbon footprint is, on average, close to 0.5 (0.53 for direct emissions and 0.45 for indirect emissions) and that the consumption elasticity of the carbon footprint is close to 0.7 (0.69 for direct emissions and 0.76 for indirect emissions). However, we note that the

value of the latter is strictly decreasing with the level of consumption, being 0.82 for the households of the first decile against 0.67 for those of the last decile concerning indirect emissions. The same observation applies to direct emissions but with a lower value of this elasticity, between 0.7 and 0.5. These results tell us about the regressive character of an indirect tax on emissions because of a marginal propensity to consume that decreases with income and a carbon intensity of consumption expenditures that decreases with income.

In Chapter II, I build on these initial results by conducting micro and macro simulations of carbon tax policies to determine their redistributive effects. To do so, I combine several dimensions related to the construction of the carbon tax scenario by considering (i) different sources of emissions (direct and indirect), (ii) several modalities of redistribution of the tax revenue (lump-sum redistribution, decile income-based, and household income-based), (iii) the contribution of behavioral considerations in response to price shocks (no behavior, average behavior, and decile behavior), and finally (iv) the consideration of supply-side effects. We find that horizontal heterogeneity is lower in the case of indirect than direct emissions taxation and that a more targeted redistribution according to income reduces the proportion of losing households in the first two deciles but contributes to increasing the proportion of other income classes. Heterogeneity in price response behavior increases the dispersion of results, with high-income households reacting more strongly to the price than low-income households, which contributes to increasing the regressivity of the carbon tax compared to an assumption of homogeneous behavior. Finally, the integration of supply-side effects through a general equilibrium framework shows how they influence the redistributive dimension. In the short term, without an associated redistribution mechanism, all households experience a net tax burden that decreases relative to their income. In the long run, the effects are almost zero, as the reallocation of household consumption items and substitution effects in the production

functions of the different sectors contribute to this. However, this substitution effect is, in this case, calibrated on an average value and therefore does not incorporate the heterogeneity that one might expect.

In Chapter III, we address this issue by using a strategy to identify input substitution elasticities for the flexible form of the VOE-CD production function on panels covering the period 2000-2014 for 42 countries and for 54 sectors that explicitly distinguish between quantities for production and the four main inputs $K, L, E, M$ at their respective prices. We replicate this exercise for two forms of nested CES production functions, namely [[[KE]L]M] & [[[KL]E]M], which are widely used in the literature to compare results. We obtain significant results for most sectors and find that the nesting structure directly affects them, especially for the Capital-Energy pair. They are considered complementary in the [[[KL]E]M] case and substitutable in the [[[KE]L]M] case. In the generic case that relaxes the nesting structure constraint, Capital and Energy are generally substitutable. We then use the estimated parameters of the VOE-CD production function to calibrate the elasticities of the ThreeME CGE model and perform a sensitivity analysis to assess their effect on the overall results, considering three alternative cases where the substitution elasticities are set to -0.5, -1, and -2. The results of the simulations conclude that there is a larger substitution effect between energy and labor, leading to a larger effect on employment than can be anticipated in the Cobb-Douglas case while leading to an equivalent reduction in emissions.

## Implications for policy

The implications for economic policy are manifold. First, identifying carbon flows at a finer scale than those currently used allows for a more accurate assessment of the effects of climate policies, including those related to border carbon taxation. The proper representation of international trade and value chains allows for better

identification of the structure of imported emissions and, consequently, the sectors of activity that have the greatest impact on the environment. Moreover, while carbon flows are at the heart of our interest, the more detailed knowledge provided by the MRIOs on the integration of French companies in the global value chain also allows us to better understand their exposure to external climate policies. First, those conducted by the European Commission, where a significant part of French climate policy is determined, also to asymmetric price shocks with other countries, whether driven by trade policy or exposure to a particular country. Knowing the distribution of the carbon footprint within a population also allows for the integration of climate justice considerations and can help ensure a fair distribution of effort in constructing these climate policies, and thus help ensure public support for the program.

From a general point of view, the work presented in this thesis aims to enrich the analytical framework mobilized, notably via a CGE, for the construction and analysis of public policies related to energy and climate. While the European Union is currently going through one of its most serious energy crises, the consequences of a halt in gas deliveries from Russia, the EU's main supplier, are still too uncertain. For some economists, the risk of a shortage is very high, with potentially disastrous consequences for the productive sector, even fearing a halt in the production of energy-intensive industries. For others, substitution capacities, whether at the level of the energy supplier or through the dissemination of more energy-efficient technologies, are sufficient to overcome the supply shortage and thus reduce the total economic impact. While rationing for individuals still seems out of the question, the sharp increase in energy costs is putting a strain on household budgets, especially for those who rely directly on gas for heating. Public interventions aimed at freezing the price or reducing this burden have been put in place in various European countries, such as the tariff shield in France. However, their high public expenditure cost makes it unlikely to be sustained over time. A more targeted intervention framework will

probably be necessary, at least until investments in energy renovation or decarbonized heating systems are in place. These short-term constraints will necessarily modify the anticipated emission reduction trajectories and the levers identified in the SNBC to achieve them. Adaptation to an uncertain macroeconomic framework, with abrupt changes and additional constraints, and where international coordination could become less effective than in previous decades, cannot be excluded. Equipping ourselves with tools to ensure the articulation between very short-term policies and the central objective of carbon neutrality in the longer term is becoming a major strategic challenge for which we must be well prepared.

## Extensions

Future research can be conducted in different areas thanks to the analyses performed for this thesis. As early as Chapter I, identifying the dispersion of carbon intensity for a similar product would allow us to more accurately assess the possibility of substitution in consumption without structural changes in spending. It would be possible by linking the top-down approach we have developed with bottom-up life cycle assessment inventories. Concerning the aggregate carbon footprint, incorporating them into a modeling framework, as we have done with the ThreeME model, would allow us to determine the effects of low-carbon transition policies on imported emissions indicators and to explore the effects of border carbon adjustment mechanisms on the competitiveness of domestic firms under different third-country retaliation scenarios.

Our analysis of the distributional effects of carbon pricing can be extended in different directions. First, it would be interesting to update the analysis on more recent data and compare it with other demand models, such as the QUAIDS model that considers the non-linearity of expenditure shares, to obtain alternative estimates of price elasticities. In addition, adopting a different classification of products that better distinguishes carbon-intensive consumption items would be a good direction.

Adopting an alternative classification of groups that combines income class with a rural-urban distinction would highlight large differences in their expenditure patterns and, hence, their exposure to the price shock.

The micro-simulation results highlight the need for compensatory policies to reduce the regressivity of carbon taxes. The results of the general equilibrium analysis highlight their transitional role as productive sectors gradually decarbonize their production process. It would also be interesting to examine the economic implications of a biased redistribution of carbon tax revenues between agents, from firms to households, or from households to firms. Identifying input substitution elasticities is paramount in a cost-effectiveness analysis, as it significantly influences the results. An extension would be to consider the increase in marginal abatement costs, which would depend on the investment in abatement measures, the mitigation potential, and the state of the technology.

At a time when Europe is experiencing a major energy crisis, faced with the risk of shortages and exploding prices, and when the consequences of global warming are already being severely felt, the energy and climate policy that will be implemented in the coming years will be of the utmost importance in the implementation of the national low-carbon strategy. It will have to combine the protection of the most vulnerable households exposed to inflationary shocks while organizing the gradual exit from fossil products by maintaining the productive fabric operational. Moreover, this policy is part of a more global framework, where abrupt changes in value chains can have significant repercussions. The diversification of gas supplies to which European countries have committed themselves is not without difficulties, and concerns remain for some, particularly those most dependent on Russian gas. I hope that this thesis can contribute to the empirical analysis of the interaction between the macroeconomic and microeconomic dimensions of an ambitious and equitable transition policy.

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# Chapter 4

# Appendix: Description of the main equations of ThreeME

## 4.1 Specification of adjustment mechanisms

Unlike Walrasian models that assume that equality between supply and demand is achieved through a perfect flexibility of prices and quantities, ThreeME represents more realistically the functioning of the economy by taking into account explicitly the slow adjustment of prices and quantities (factors of production, consumption). In this Keynesian framework, permanent or transitory underemployment equilibria are possible and supply is determined by demand. ThreeME assumes that the actual levels of prices and quantities gradually adjust to their notional level. The notional level corresponds to the optimal (desired or target) level that the economic agent in question (the company for prices and the demand for production factors, the household for consumption, the Central bank for the interest rate, etc.) would choose in the absence of adjustment constraints. These constraints mainly come from adjustment costs, physical or temporal boundaries and uncertainties. Formally, we assume that the adjustment process and expectations for prices and quantities are represented by

the following equations:

$$\log F_t = \lambda_0^F \ \log F_t^n + \left(1 - \lambda_t^{0,F}\right) \ (\log F_{t-1} + \Delta\left(\log F_t^e\right)) \tag{4.1}$$

$$\Delta\left(\log F_t^e\right) = \lambda_t^{1,F} \ \Delta\left(\log F_{f,s,t-1}^e\right) + \lambda_t^{2,F} \ \Delta\left(\log F_{f,s,t-1}\right) + \lambda_t^{3,F} \ \Delta\left(\log F_t^n\right) \tag{4.2}$$

Where $F_t$ is the actual value of a given variable (e.g. the production price, labor, capital, etc.), $F_t^n$ is its notional level, $F_t^e$ its anticipated value at period $t$ and $\alpha_i^F$ are the adjustments parameters (with $\alpha^{1,F} + \alpha^{2,F} + \alpha^{3,F} = 1$).

Equation (4.1) assumes a geometric adjustment process. Taking into account the anticipations guaranties that the actual variables converge to their notional levels in the long run. Equation (4.2) assumes that the anticipations are adaptive (*"backward-looking"*). One can see that Equation (4.1) and Equation (4.2) can be reformulated into an Error Correction Model used in the econometric estimations to take into account the non-stationary propriety of some variables:

$$\Delta \log(X_{t-1}) = \alpha_1 \ \Delta \log(X_{t-1} + \alpha_2 \ \Delta \log(X_{t-1}^n) - \alpha_3 \ \log(X_{t-1})/(X_{t-1}^n))$$

For this, the following constraints must hold: $\lambda_0^X = \alpha_3, \lambda_1^X = 0, \lambda_2^X = \alpha_1/(1 - \alpha_3), \lambda_3^X = (\alpha_2 - \alpha_3)/(1 - \alpha_3)$

We also assume that the substitution effects ($SUBST_X$) adjust slowly to the notional substitution effects ($SUBST_X^n$):

$$SUBST_X_t = \lambda_4^X * SUBST_X_t^n + (1 - \lambda_4^X) * SUBST_X_{t-1} \tag{4.3}$$

The three equations above allow a rich set of adjustment as they integrate different types of rigidity (on prices and quantities, on expectations and on substitution mechanisms). For illustrative purposes, we present the full specification of the demand for labor (L). For simplicity, the sector index is omitted. The notional labor demand ($L^n$ is derived by minimizing production costs. It depends positively on the

level of the output ($Y$), negatively on the labor productivity ($PROG_L$) and on an element gathering all the substitution phenomena with the other production factors ($SUBST_L$):

$$\Delta \log(L_t^n) = \Delta \log(Y_{t-1}) \Delta \log(PROG_L_t) + \Delta SUBST_L_t \tag{4.4}$$

We introduce a distinction between the actual and notional substitution effects to account for the fact that labor demand generally responds more quickly to changes in the level of production than to substitution phenomena: while it is *physically* necessary to increase employment to meet rising production, substitutions involve changes to the structure of production whose implementation takes longer. The actual substitution therefore adjusts gradually to the notional substitution ($SUBST_L^n$) which depends on the relative prices between the production factors:

$$\Delta SUBST_L_t^n = -\eta^{LK} \varphi_{t-1}^K \Delta \log(C_t^L/C_t^K) - \eta^{LE} \varphi_(t-1)^E \Delta \log(C_t^L/C_t^E) - \eta^L \varphi_{t-1}^M \Delta \log(C_t^L/C_t^M)($$

Where $\eta^{LK}$, $\eta^{LE}$, $\eta^{LM}$ are the elasticities of substitution between labor and the other production factors respectively capital, energy, material (i.e. non-energy intermediate consumption). $\varphi^K$, $\varphi^E$, $\varphi^M$ are respectively the capital, energy and materials shares in the production costs. $C^K, C^L, C^E, C^M$ are respectively the unitary costs of production of capital, labor, energy and material. The next section provides more information on the derivation of factors demands. Finally, the adjustment mechanisms being defined according to the equations (1), (2) and (3), the three following relationships are used:

$$\log(L_t) = \lambda_0^L \ \log(L_t^n) + (1 - \lambda_0^L) \ (\log(L_{t-1}) + \Delta \log(L_t^e))$$

$$\Delta \log(L_t^e) = \lambda_1^L \ \Delta \log(L_{t-1}^e) + \lambda_2^L \ \Delta \log L_{t-1}) + \lambda_3^L \ \Delta \log(L_t^n) \tag{4.6}$$

$$SUBST_L_t = \lambda_4^L \ SUBST_L_t^n + (1 - \lambda_4^L) \ SUBST_L_{t-1}$$

## 4.2 The production function and the production factors demand

The production structure is decomposed into three levels (see Figure 4.1). The first one assumes a production function with 4 inputs (or production factors), often referred as KLEM (capital, labor, energy and materials). The first level has a fifth element: the transport and commercial margins. *Stricto sensu*, they cannot be considered as production factors since they intervene after the production process. Thus they are not substitutable with the production factors. But they are closely related to the level of production since once a good has been processed, it has to be transported and commercialized. At the second level, the investment, energy, material and margins aggregates are further decomposed by type of commodities (e.g. energy sources). At the third level, the demand for each factor or margin is either imported or produced domestically. The demands for production factors are derived from the minimization of the firm's production costs. We assume a production function with constant returns-to-scale more general than the CES (Constant Elasticity of Substitution) insofar as substitution elasticities may differ between different inputs pair (Reynès, 2019). The production costs minimization program leads to the following equations for the notional factors demand. This holds for every economic activity, but for algebraic simplicity the sector index is omitted here:

$$\Delta \log(FP^{n}_{j,t}) = \Delta \log(Y_t) - \Delta \log(PROG_FP_{j,t}) + \Delta SUBST_FP_{j,t} \tag{4.7}$$

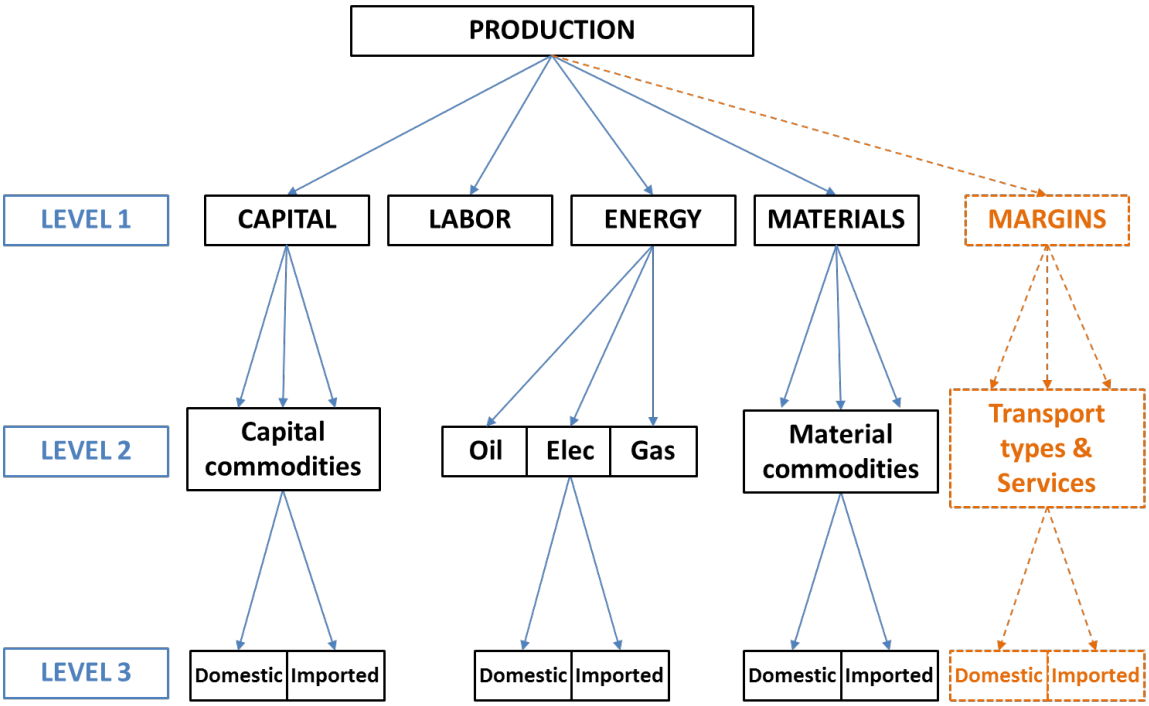
$$\Delta SUBST_FP^{n}_{j,t} = -\sum_{\substack{j'=1 \\ j \neq j'}} \eta_{j,j'}\ \varphi^{j'}_{t-1}\ \Delta \log(C_(j',t)^{FP} / C^{FP}_{j,t})) \tag{4.8}$$

with $\varphi_{j,t-1} = (C^{FP}_{j,t}\ FP_{j,t-1}) / (\sum_j C^{FP}_{j,t}\ FP_{j,t-1})$ and $j = \{K, L, E, M\}$

Where $FP^{n}_{j}$ is the notional demand of input $j$ (KLEM), $\eta_{j,j'}$ the elasticity of substitution between the pairs of inputs $j$ and $j'$, $PROG_FP_{j,t}$ the technical progress

related to input $j$, $C_j^{FP}$ the cost/price of input $j$ and $Y$ the level of production of the sector under consideration.

Figure 4.1: Structure of production in ThreeME




According to national accounts data, ThreeME assumes that each commodity may be produced by more than one sector. For instance, electricity can be produced by several sectors such as nuclear or wind power. The production of each sector is defined by the following equations:

$$Y_{c,a} = \varphi_{c,a} YQ_c \tag{4.9}$$

$$Y_a = \sum_c Y_{a,c} \tag{4.10}$$

Where $YQ_c$ is the aggregated domestic production of commodity $c$. It is determined by the demand (intermediate & final consumption, investment, public spending, exports and stock variation). $\varphi_{c,a}$ is then the share of commodity $c$ produced by the sector $a$ (with $\sum_a \varphi(c,a) = 1$) and $Y_a$ is the aggregated production of sector $a$.

## 4.3 Equations for investment & capital

Investment in ThreeME depends on the anticipated production, on its past dynamic, on substitution phenomena and on a correction mechanism, which guaranties that companies reach their level of long-term notional capital stock. The stock of capital is deducted from the investment according to the standard capital accumulation equation:

$$\Delta \log(IA_t) = \theta_1^I A \; \Delta \log(IA_{t-1}) + \theta_2^I A \; \Delta \log(Y_t^e) + \theta_3^I A \; (\log(K_{t-1}^n) - \log(K_{t-1})) + \Delta SUBST_K_t (4$$

$$K_t = (1 - \delta^K) K_{t-1} + IA_t$$

Where $IA$ is the investment, $Y^e$ anticipated production, $K$ and $K^n$ the actual and notional stocks of capital, $SUBST_K$ a variable gathering substitution phenomena between capital and the other inputs, and $\delta^K$ the depreciation rate of capital. Moreover, we impose the constraint $\theta_1^I A + \theta_2^I A = 1$ in order to guaranty the existence of the stationary equilibrium path. This specification is a compromise between the short-term dynamics empirically observed and the consistency of the model in the long run. Like the MESANGE econometric model (Klein and Simon, 2010), it is common to estimate an investment equation rather than capital stock equation for several reasons. Firstly, time series capital stock data are often unreliable. Secondly, this approach better represents the short-term dynamics of investment. In particular, it avoids capital destruction phenomena (negative investment) that are in practice unusual, since companies generally prefer to wait for the technical depreciation of their installed capital. Unlike MESANGE, we assume in addition that investment depends on the difference between the actual and notional capital stock. This element ensures that the effective capital stock converges over time towards its notional level. In the long-term, the model is then consistent with the production function

theory that establishes a relationship between the levels of production and capital stock (and not with the flow).

## 4.4 Wage equation

Several studies have shown that the theoretical arguments and empirical estimates difficultly allow choosing between the two specifications. However, this difference of specification has important implications on the definition of the equilibrium unemployment rate (NAIRU) and thus on the inflationary dynamic and the long-term proprieties of a macroeconomic model (Blanchard and Katz, 1999). In ThreeME, we choose a general specification that includes the Phillips and WS curves. It assumes that the notional nominal wage ($W_t^n$) positively depends on the anticipated consumption price ($P_t^e$) and on the labor productivity ($PROG_L_t$), and negatively on the unemployment rate ($U_t$):

$$\Delta \log(W_t^n) = \rho_1^W + \rho_2^W \, \Delta \log(P_t^e) + \rho_3^W \, \Delta \log(PROG_L_t) - \rho_4^W U_t - \rho_5^W \Delta U_t \quad (4.12)$$

This relation can alternatively be identical, either to the Phillips curve, or to the WS curve depending on the value of the selected parameters (Heyer et al., 2007; Reynès, 2010). The Phillips curve corresponds to the case where $\rho_4^W > 0$ whereas the WS curve assumes $\rho_4^W = 0$. For the model to have a consistent steady-state in the long-run, the WS curve must also impose the constraints identified by Layard et al. (2005): a unit indexation of wages on prices and productivity: ($\rho_2^W = \rho_3^W = 1$) and $\rho_1^W = 0$.

## 4.5 Equation of households' consumption

In the standard version of the model, consumption decisions are modeled through a Linear Expenditure System (LES) utility function generalized to the case of a non-

unitary elasticity of substitution between the commodities Brown and Heien (1972). Households' expenditures for each commodity evolve (more or less) proportionally to their income:

$$(EXP_c^n - NEXP_c)\ PEXP_c = \beta_c^{EXP}[(1-MPS)\ DISPINC_VAL - \sum_c PEXP_c\ NEXP_c] \quad (4.13)$$

With $\sum_c \beta_c^{EXP} = 1$

Where $EXP_c^n$ corresponds to the volume of notional consumption (expenditures) in commodity $c$ and $PEXP_c$ to its price. $NEXP_c$ is the incompressible volume of expenditures in commodity $c$, $DISPINC_VAL$ is the households' disposable income and $MPS$ their marginal propensity to save. In the case of no incompressible expenditures ($NEXP_c = 0$), households aim at allocating a share $\beta_c^E XP$ of their total expenditure (in value), $(1 - MPS)\ DISPINC_VAL$, to commodity $c$. This share is constant if the elasticity of substitution between the commodities is equal to one (Cobb-Douglas assumption). In this case (Cobb-Douglas utility function without incompressible expenditures), commodity $c$ expenditures stay exactly proportional to income. In the case of a CES function where the elasticity of substitution is $\eta^{LES_CES}$, the marginal propensity to spend varies depending on the relative prices according to the following specification:

$$\Delta\beta_{c,t}^{EXP} = (1 - \eta^{LES_CES})\ \Delta PEXP_{c,t}/(PEXP_t^{CES}) \quad (4.14)$$

$$PEXP_t^{CES} = (\sum_c \beta_{c,0}^{EXP}\ PEXP_{c,t}^{(1-\eta^{LES_CES})})^{1/1-\eta^{LES_CES}} \quad (4.15)$$

## 4.6 Equations of prices and of the mark-up rate

The production price for each sector is set at the lowest level by applying a mark-up over the unit cost of production (which includes labor, capital, energy and other

intermediate consumption costs) :

$$PY_t^n = CU_t \left(1 + TMD_t\right) \tag{4.16}$$

$$\Delta \log(1 + TM_t^n) = \sigma^{TM} \left(\Delta \log(Y_t) - \Delta \log(Y_{t-1})\right) \tag{4.17}$$

$$TMD_t = \lambda^{TM} \, TM_t^n + (1 - \lambda^{TM}) \, TMD_{t-1} \tag{4.18}$$

Where $PY_t^n$ is the notional price, $CU_t$ the unitary cost of production and $Y_t$ the level of production. $TMD_t$ and $TM_t^n$ are respectively the desired and notional mark-up. The equation of notional price is a behavioral equation: by assuming that the addressed demand to a firm is a negative function of its price, one can easily demonstrate that the optimal price corresponds to a mark-up over the marginal cost of production. The mark-up equation reflects the fact that the returns-to-scale are decreasing in the short-term. Therefore, a non-expected increase in production results into a higher marginal cost of production and therefore into a higher notional price. The other prices are calculated according to their accounting definition and are therefore (directly or indirectly) a function of the producer price. The price of the domestically produced commodity c is a weighted average of the production prices of activities (indexed by a) producing that commodity. For example, the price of electricity is a weighted average of the production prices of the sectors producing electricity. The price paid by the final user (consumer, government, sector, rest of the world) integrates in addition the commercial and transportation margins, and the taxes net from subsidies. Combined with the price of imports, we get the average price for each commodity paid by each end user.

## 4.7 Equations of foreign trade

Exports are determined by the external demand addressed to domestic products and the ratio between the export and world prices:

$$\Delta \log(X_{c,t}) = \Delta \log(WD_{c,t}) + \Delta SUBST_X_{c,t} \tag{4.19}$$

$$\Delta SUBST_X^n_{c,t} = -\eta^X \ \Delta \log(P^X_{c,t}/P^W_{c,t}/TC_t)$$

Where $WD_{c,t}$ is the world demand, $P^W_{c,t}$ its price. $P^X_{c,t}$ is the export price that depends on the production costs and which reflects the price-competitiveness of the domestic products. $TCt$ is the exchange rate; $\eta^X$ is the price-elasticity (assumed constant). We assume imperfect substitution between domestic and imported goods (Armington, 1969). The demand for domestic and imported products is :

$$\Delta \log(A^D_{c,t}) = \Delta \log(A_{c,t}) + \Delta SUBST_AD_{c,t}$$

$$\Delta SUBST_AD^n_{c,t} = \eta^A_c \ \Delta \log(P^{AD}_{c,t}/P^A_{c,t}M) \ \frac{(P^A_{c,t-1} MA^M_{c,t-1})}{(P^A_{c,t-1} \ A_{c,t-1})} \tag{4.20}$$

$$A^M_{c,t} = A_{c,t} - A^D_{c,t}$$

Where $A_{c,t}$ represents the demand for each type of use (intermediary consumption, investment, consumption, public spending, exports, etc.), $P^A_{c,t}$ is its price. $A^M_{c,t}$ and $A^D_{c,t}$ are the imports and the domestic products demanded for each type of use $A$, $P^A_{c,t}M$ and $P^A_{c,t}D$ are their respective prices. The elasticity of substitution $\eta^A_c$ by type of use $A$ of a given commodity $c$ can potentially be different, which allows a high degree of flexibility. The full description of the model can be found online at www.threeme.org

Essais sur l'évaluation macroéconomique de la transition bas-carbone

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## Résumé

La menace que le changement climatique représente pour le bien-être des humains devient de plus en plus précise, tangible et alarmante, comme l'exposent les dernières publications du Groupe d'experts intergouvernemental sur l'évolution du climat (IPCC, 2022) ou l'augmentation de la fréquence des événements météorologiques extrêmes tels que les vagues de chaleur, les sécheresses, les ouragans, les inondations ou les tempêtes que nous avons enregistrés ces dernières années. Après près de 30 ans de négociations internationales, débutant officiellement en 1992 avec le Sommet de Rio, la communauté internationale a fini par s'accorder en 2015 sur des engagements visant à limiter l'augmentation des températures d'ici la fin du siècle à 1,5 degré Celsius, bien en dessous de 2 degrés Celsius. Cet objectif ambitieux était un signe de soulagement que les dirigeants mondiaux puissent faire passer l'intérêt global avant les intérêts privés, même si les voies pour l'atteindre restent floues. En effet, en l'état actuel des promesses nationales, reconduites en 2021 lors de la COP 26, l'augmentation des températures serait de 2,1°C (dans une fourchette de 0,5°C). 5°C) et *les politiques & actions actuelles* à 2,7°C (dans une fourchette de 0,9°C) (UNEP, 2021), ce qui reste bien supérieur à ce que les parties ont convenu au départ. La réduction attendue des émissions nécessaire pour limiter le changement climatique est considérable. Selon le PNUE, pour atteindre l'objectif de 1,5°C, les émissions doivent diminuer à l'échelle mondiale à un taux annuel moyen de 7,6% et d'au moins 4,5% pour un objectif de 2°C. Par comparaison, les émissions de CO2 ont augmenté de 1,4% par an au cours de la décennie 2010-2019 et ont atteint leur pic historique en 2019 avec 36,81 $GtCO_2$. Si l'on considère les pays développés qui se sont engagés à atteindre des émissions nettes nulles d'ici à 2050, la tendance attendue est encore plus forte[1].

L'épisode de la pandémie de COVID est un cas intéressant pour apprécier

[1] A cette date, les États membres de l'UE, le Royaume-Uni, le Japon, le Canada et la Nouvelle-Zélande se sont légalement engagés à atteindre la neutralité carbone d'ici à 2050 (extrait de Net Zero Tracker).

l'ampleur de la transformation sous-jacente que les économies modernes doivent entreprendre pour suivre cette tendance à la décarbonisation. Pour 2020, les émissions mondiales de GES ont enregistré une baisse annuelle sans précédent de 5,4% au niveau mondial (Friedlingstein et al., 2022). Les différents épisodes d'enfermement et de restriction de la mobilité qui bouleversent le monde ont conduit les gens à consommer moins, notamment les biens et services à forte intensité de carbone comme les transports. Par conséquent, les émissions ont considérablement baissé, avec une estimation moyenne d'une réduction mondiale quotidienne de 17% par rapport au niveau moyen des émissions en 2019 [2]. (Le Quéré et al., 2020). Cependant, cette baisse de la consommation est portée par des comportements individuels contraints et reste purement mécanique puisqu'un changement brutal du comportement de la population n'a que peu d'impact sur l'infrastructure basée sur les énergies fossiles. Elle se caractérise par un contexte sanitaire spécifique et ponctuel où les activités sont strictement contrôlées, ce qui ne peut perdurer *ad vitam*. Sans changement structurel affectant les prix relatifs par le biais de la tarification du carbone et sans perte de revenu pour les agents économiques, il n'y a aucune raison qu'un choc sur la demande stimule une baisse des émissions (Malliet et al., 2020; Eichenbaum et al., 2021; Mintz-Woo et al., 2021).

Quelle que soit l'évolution du contexte macroéconomique international, les économies mondiales, et en premier lieu les pays développés, doivent mener une réduction régulière, permanente et significative de leurs émissions. Toutefois, un tel objectif ne peut être atteint qu'au moyen d'une feuille de route solide et complète, capable de surmonter le problème de la *tragédie des horizons*[3].

[2]Localement, les baisses estimées des émissions ont été plus nettes car les périodes de confinement n'étaient pas totalement synchronisées à l'échelle mondiale. On estime qu'en avril 2020, les émissions françaises étaient 30% inférieures à la normale (on Climate, 2020)

[3]La tragédie des horizons fait référence à un discours prononcé par l'ancien gouverneur d'Angleterre Mark Carney en 2015 sur la façon dont l'impact catastrophique du changement climatique imposera aux générations futures un coût que la génération actuelle n'a aucun intérêt à réparer.

D'un point de vue de la science économique, le changement climatique résulte d'une mauvaise allocation intertemporelle des ressources, due à l'incapacité des marchés privés à évaluer correctement les externalités négatives des gaz à effet de serre sur le bien-être humain. Pour corriger cette mauvaise allocation, la politique climatique la plus rentable, largement encouragée par les économistes, consisterait à imposer une taxe pigovienne (Pigou, 1932) sur les émissions de carbone, reflétant le coût social du carbone (CSC). Le CSC, et donc le prix optimal de cette taxe carbone, est une estimation de la valeur actuelle des dommages, exprimée en valeur économique, de l'émission d'une tonne supplémentaire de dioxyde de carbone dans l'atmosphère. Cette taxe augmente le prix des combustibles fossiles proportionnellement au carbone qu'ils émettent et incite donc les agents économiques à modifier l'allocation de leurs ressources en fonction des nouveaux prix relatifs, pour finalement atteindre l'optimum social (ce qu'on appelle le résultat de premier ordre). Il convient de noter que ce mécanisme prend différentes formes dans les politiques du carbone : taxe indirecte sur les produits énergétiques, système de plafonnement et d'échange associé à des permis d'émission, ou prix interne dans la prise de décision en matière d'investissement.

L'augmentation du coût des combustibles fossiles stimulerait également l'investissement dans des activités moins intensives en carbone et modifierait donc la structure du stock de capital, en remplaçant le capital à forte intensité de carbone par du capital moins intensif en carbone. D'un point de vue purement technique, cela signifie : investir dans plusieurs technologies et actions, comme l'augmentation des sources d'énergie renouvelables dans la production d'électricité, la modernisation des bâtiments résidentiels et commerciaux, le développement de systèmes de transport public ou l'accélération de l'électrification du parc automobile. Ce processus de décarbonisation est généralement appelé "transition énergétique", car il implique une

modification de la consommation d'énergie, soit par des mesures d'efficacité énergétique, soit par l'élimination progressive des combustibles fossiles du bouquet énergétique. Afin de reconnaître l'existence d'autres sources d'émissions non énergétiques (telles que des processus industriels spécifiques dans les industries du ciment et de l'acier, des choix d'utilisation des sols ou certaines pratiques agricoles), on parle de *transition bas-carbone*.

La tarification du carbone est également un choc idiosyncratique où les agents économiques sont affectés de manière hétérogène par la politique climatique. Pour les entreprises, l'impact dépend principalement de leurs spécificités sectorielles en matière d'activité, de fonction de production et de structure du capital, qui déterminent leur consommation d'énergie : (Martin et al., 2014; Dechezleprêtre and Sato, 2020). Concernant les ménages, l'impact d'une politique climatique sera différent en fonction de leur structure de consommation et de l'intensité carbone moyenne des biens couverts par une taxe carbone. La littérature montre que ces effets sont régressifs avec le niveau de revenu (Ohlendorf et al., 2021), mais aussi que l'hétérogénéité provient d'autres facteurs tels que les lieux de résidence et de travail ou leur statut d'occupation du logement.

La macroéconomie a commencé à s'intéresser aux profondes implications d'une politique de décarbonisation sur l'activité économique à la fin des années 1960 (Ayres and Kneese, 1969). Un large éventail de classes de modèles macroéconomiques a été développé pour étudier l'économie du climat (Farmer et al., 2015). En particulier, les modèles d'évaluation intégrée (Integrated Assessment Models - IAMs) ont été largement utilisés dans le travail du GIEC pour produire des analyses de scénarios. Ils jouent un rôle central dans la détermination des trajectoires socio-économiques (*Social Sustainable Pathways* - SSP), qui sont des scénarios examinant des récits contrastés des tendances socio-économiques qui pourraient façonner la société future et sont destinés à couvrir l'éventail des futurs plausibles (Riahi et al., 2017). Contrairement à

ces IAMS, qui peuvent devenir très complexes en raison des nombreuses combinaisons entre les modules économiques et techniques, les *simple* IAMS - tels que PAGE (Hope, 2006), utilisé pour le rapport Stern (Stern, 2006), FUND (Waldhoff et al., 2014) et le modèle DICE (Nordhaus, 1991, 2013) sont souvent utilisés pour calculer le SCC et informer sur la politique carbone intertemporelle à mener pour maximiser le bien-être intertemporel.

Aussi séduisants que puissent être ces outils de politique publique, plusieurs voix éminentes se sont élevées pour critiquer leur utilisation dans la conception des politiques publiques. Une partie des économistes, tout en reconnaissant leur intérêt scientifique dans l'évaluation qualitative de leur dynamique, les considère comme trop incertains et sensibles aux hypothèses pour fournir des indications quantitatives fiables et donc peu adaptés à l'évaluation et au service des politiques climatiques : (Arrow et al., 1996; Heal, 2017; Pindyck, 2020; Stern and Stiglitz, 2022).

Dès lors, comment pouvons-nous, en tant qu'économistes, déterminer un prix du carbone qui puisse servir l'action publique et le processus de transition vers une économie sobre en carbone ? La question de la mesure de ce prix du carbone qui rend compte du compromis entre le développement économique et le respect de la protection de l'environnement peut être résolue à l'aide de deux approches. La première, intrinsèquement liée aux IAMs, est l'analyse coûts-bénéfices (ACB), qui adopte une approche normative. Elle mesure le prix du carbone qui égalise les bénéfices marginaux qu'il apporte (réduction des dommages causés par le changement climatique en diminuant les émissions de carbone) à son coût marginal (l'augmentation du prix des biens et services à forte intensité de carbone). La seconde approche, appelée analyse coût-efficacité (ACE), est plus positive par essence et n'intègre pas l'analyse du bien-être, en particulier le bien-être intergénérationnel, et ne nécessite donc pas l'évaluation des dommages actualisés de la dynamique du changement climatique. Au contraire, elle examine quel prix du carbone serait nécessaire pour déclencher une réduction des

émissions sur la base de leur coût marginal de réduction (alternativement, le coût fictif de la contrainte carbone) et de l'objectif global de réduction des émissions (ou de limitation de l'augmentation de la température) tel qu'il est donné. La publication de budgets carbone mondiaux (IPCC, 2018) compatibles avec les objectifs de 1,5 °C et 2 °C [4], car la promulgation de voies et de stratégies nationales à faible émission de carbone correspond à cette approche et permet de se concentrer sur de multiples dimensions techniques et sociales. La complexité des interactions économiques entre les agents économiques et leur hétérogénéité soulèvent plusieurs questions.

Comment augmenter la précision et l'opérationnalité des modèles macroéconomiques dans le cadre d'un outil d'aide à la décision pour la mise en œuvre de la transition bas carbone ? Quelles informations sont nécessaires pour intégrer l'interdépendance d'une économie nationale avec son environnement économique ? Comment mieux représenter l'hétérogénéité qui caractérise une économie entre les ménages et les activités et leurs comportements respectifs attendus pour mettre en œuvre des politiques carbone ? Quelles politiques complémentaires pourraient être mises en œuvre pour modérer les distorsions qu'elles induisent et assurer une répartition équitable du coût ?

Ces questions font finalement partie du problème du choix du cadre représentatif pertinent pour l'analyse des politiques de transition. Ce cadre doit pouvoir intégrer les effets d'équilibre général et les interactions entre les activités de production et de consommation tout en garantissant une représentation suffisante de l'hétérogénéité.

Aujourd'hui, la macroéconomie du climat est à la croisée des chemins. Les modèles d'IAMs deviennent plus maniables et plus précis, continuent d'alimenter les travaux du GIEC, et sont particulièrement utiles pour construire des scénarios climatiques. En outre, en encadrant la transition vers une économie à faible émission de carbone par une analyse coûts-avantages, les économistes ont déplacé le débat vers le coût

[4]Pour tenir compte de l'incertitude, les estimations des budgets carbone sont associées à une distribution de probabilité de rester sous un seuil d'augmentation maximale de la température.

social optimal du carbone, avec toutes ses limites. L'analyse coût-efficacité, à laquelle contribue la littérature sur l'équilibre général calculable (EGC), semble bien adaptée pour accompagner la transformation progressive de l'économie sur une trajectoire compatible avec les budgets carbone.

Les modèles EGC, dans cette perspective, offrent un cadre intéressant. S'appuyant sur le modèle d'entrées-sorties de Leontief (1937) et adoptant un cadre d'équilibre général (Johansen, 1960a), ils cherchent à résoudre numériquement le problème des offres, des demandes et des prix qui soutiennent l'équilibre à travers un ensemble spécifié de marchés. Au lieu d'identifier des politiques optimales pour l'environnement, ils s'intéressent davantage à la compréhension et à la quantification des effets de décisions spécifiques de politique économique. L'extension du cadre de l'équilibre général aux questions environnementales remonte à Maler (1974), mais les modèles EGC ont commencé dans les années 1990 à intégrer ces dimensions dans leur cadre analytique (Wing, 2009). Parmi les exemples notables de modèles EGC, citons le modèle multipays ENV-Linkages de l'OCDE (Château et al., 2014) ; le Centre for Global Trade Analysis (Corong et al., 2017) ; GEM-E3 (Capros et al., 2013) ; et le modèle multirégional RHOMOLO (Brandsma et al., 2015).

Bien qu'ils aient une représentation plus granulaire de l'économie avec une large décomposition sectorielle, les comptes nationaux sur lesquels ces modèles *top-down* sont calibrés n'offrent pas une représentation suffisante des secteurs à forte intensité énergétique et, par conséquent, ne peuvent pas englober l'hétérogénéité des technologies, qui est essentielle pour intégrer une voie de décarbonisation par la substitution des sources d'énergie. En ce sens, il plaide pour l'hybridation des modèles économiques : que ce soit pour améliorer la connaissance technique du processus de production ou entre les dimensions macroéconomique et microéconomique pour évaluer pleinement l'hétérogénéité existante. L'hybridation cherche à compléter la richesse économique des modèles *top-down* par une représentation plus détaillée

d'activités économiques spécifiques essentielles à l'analyse des scénarios de transition que les modèles *bottom-up* fournissent. Elle a été principalement développée pour coupler des modèles d'ingénierie décrivant l'approvisionnement énergétique à partir de sources primaires avec des modèles EGC (Fortes et al., 2014) et utilisée sur différentes applications telles que les systèmes énergétiques, le transport (Helgesen et al., 2018) ou le secteur résidentiel (Drouet et al., 2005). Plus généralement, ces développements visent à représenter plus précisément les coûts marginaux de réduction des émissions des technologies liées à l'énergie afin de cerner les effets de substitution hétérogènes. Fournir des estimations robustes pour les paramètres de la fonction de production dépend non seulement de la richesse dans la représentation des technologies que permet l'hybridation entre les modèles mais aussi du choix de la forme de la fonction de production, qui est retenue dans les modèles EGC. Les fonctions de production à élasticité constante de substitution (CES) (Arrow et al., 1961) ont été largement utilisées à cette fin car elles peuvent représenter un continuum de possibilités de substitution entre les intrants tout en s'appuyant sur des fondements théoriques cohérents. Cependant, des hypothèses supplémentaires doivent être faites sur la structure d'imbrication (Sato, 1967) pour représenter pleinement les processus de production associés à l'utilisation d'un grand nombre d'intrants, ce qui affecte à son tour les résultats des estimations économétriques des élasticités de substitution (van der Werf, 2008).

Autant il est important pour ces développements de spécifier les interrelations entre l'offre et l'utilisation d'énergie et leur traduction économique, autant il est essentiel d'intégrer l'hétérogénéité qui caractérise les composantes de la demande finale et les ménages, notamment pour rendre compte des effets distributifs induits par les politiques carbone.

Dans cette optique, plusieurs méthodologies de couplage entre un EGC et un modèle de microsimulations ont été proposées dans la littérature (Cockburn et al.,

2014) pour exploiter l'hétérogénéité individuelle dans un cadre intégré. En effet, l'hétérogénéité des comportements de consommation et de production est l'une des questions clés de l'analyse des effets des politiques carbone. Les ménages diffèrent en termes de revenus et d'autres caractéristiques importantes, telles que leur lieu de résidence, leur type de mobilité ou leur structure familiale, ce qui entraîne des différences dans leurs habitudes de consommation. Il est donc essentiel de dresser un tableau clair de l'hétérogénéité réelle de leurs émissions de carbone et de leur comportement de substitution entre les produits de consommation lorsque les prix relatifs varient. D'un point de vue méthodologique, cela revient à enrichir les modèles EGC en y ajoutant des modèles bottom-up (avec une représentation plus fine des technologies de production ou une distinction des ménages en plusieurs groupes), mais aussi à y associer une calibration des paramètres comportementaux (élasticités de substitution dans la fonction de production, élasticités-prix de la consommation finale des ménages) qui reflètent cette hétérogénéité. Le deuxième axe de recherche que j'explore porte sur les effets redistributifs induits par une politique économique de tarification du carbone. En prolongeant les résultats du chapitre précédent et en adoptant un cadre d'équilibre général, nous pouvons tirer des résultats de simulations numériques. Le troisième et dernier axe de recherche que j'explore concerne la substituabilité entre les facteurs de production, ce qui renvoie à la souche de la littérature relative à la substitution capital-énergie et à la controverse qui l'entoure sur la question de savoir si ces facteurs de production sont complémentaires ou substituables : Griffin and Gregory (1976); Berndt and Wood (1979); Koetse et al. (2008). Je contribue à ce domaine en effectuant des estimations économétriques des paramètres d'élasticité de substitution d'une fonction de production KLEM et en fournissant des estimations pour tous les facteurs de production. Les différents chapitres de ma thèse visent à combler un vide en contribuant à ces axes de recherche liés à l'évaluation empirique de la transition bas-carbone et éventuellement à soutenir des politiques publiques

assurant son efficacité et son acceptabilité.

De plus, comme l'illustre l'impact sur le cadre économique mondial de la guerre de la Russie contre l'Ukraine, l'évolution des prix de l'énergie est sujette à à incertitude radicale et pourrait complètement oblitérer notre compréhension du contexte macroéconomique. Les récents développements géopolitiques, qu'ils soient liés à la pandémie de COVID ou au conflit armé en Ukraine, soulignent la nécessité de disposer d'outils économiques capables d'intégrer les dynamiques de court terme et d'éclairer la décision publique dans un contexte incertain et fragile. Tout choc dans l'économie mondiale peut modifier de manière significative les conclusions d'une analyse coût-efficacité, qu'il s'agisse d'un changement soudain des prix internationaux de l'énergie, d'une perturbation de la chaîne d'approvisionnement ou d'un manque de main-d'œuvre qualifiée dans certains secteurs. Dès lors, la transition vers une économie à faible émission de carbone doit être considéré davantage comme un course d'obstacles que comme une course de demi-fond traditionnelle. Des obstacles inattendus peuvent entraîner des changements de cap, et la nécessité d'envisager des chocs soudains et imprévisibles est inévitable.

En ce sens, il semble essentiel qu'un cadre d'évaluation suffisamment complexe et réactif émerge dans les années à venir pour s'adapter à des chocs généralement difficiles (voire impossibles) à anticiper. La prise en compte de ces obstacles potentiels, ainsi que l'incertitude entourant la contribution du progrès technique à la réduction des émissions, réduit considérablement les conclusions à tirer pour un horizon de long terme. Restreindre l'analyse aux impacts à court et moyen terme associés aux étapes intermédiaires sur la voie du zéro émission net semble plus pragmatique et de fait préférable. Elle nécessiterait des évaluations actualisées, intégrant de nouvelles informations pour mettre à jour la calibration des modèles sur les données statistiques et estimer la valeur des paramètres. Une analyse approfondie de la transition bas-carbone nécessite des connaissances empiriques approfondies : de la structure du stock

de capital, de la disponibilité des technologies de réduction, de leur état actuel et de leur potentiel de développement, d'une cartographie précise des flux d'émissions au sein de l'économie, de la structure du tissu productif à une granularité suffisante, mais également intégrer l'hétérogénéité des comportements qui caractérise nos économies, tant du côté de la production que des consommateurs.

**Chapitre 1 : Quantifier les aspects globaux et distributifs de l'empreinte carbone française.**

Dans ce premier chapitre, je m'intéresse aux questions liées à la comptabilité carbone, notamment à la mesure de l'empreinte carbone de la France et à la répartition de la population. En effet, les considérations liées à la justice climatique qui animent une partie du débat scientifique, notamment celui de la responsabilité des émissions requière une connaissance plus approfondie des approche de comptabilité carbone. Cela nécessite tout d'abord de collecter des connaissances sur le circuit des émissions le long de la chaîne de valeur mondiale et sur la consommation finale à laquelle elles sont associées (Steininger et al., 2016). La question sous-jacente étant *in fine* de savoir si l'on peut observer un découplage (du moins en termes relatifs) entre le niveau des émissions et le niveau des revenus (Churchill et al., 2018) et dans quelle mesure ces deux variables sont corrélées. Je m'appuie sur la méthodologie de référence basée sur la consommation pour la comptabilité carbone des émissions (Peters, 2008) associée à la base de données multi-régionale d'entrées-sorties EXIOBASE (Stadler et al., 2018) à partir de laquelle je détermine un ensemble d'indicateurs d'intensité carbone pour plusieurs produits et selon plusieurs périmètres de couverture des émissions.

A partir de cette cartographie, et en mobilisant une enquête de l'INSEE *Budget des Familles* (BNF) qui collecte sur un échantillon de plus de 15 000 ménages des observations sur les dépenses de consommation, je construis une distribution de l'empreinte carbone entre ménages et à partir d'indicateur de revenu de niveau de vie et montre par quelle dimension l'hétérogénéité qui la caractérise s'explique selon la sources des émissions (directes et indirectes), le type et la localisation de la résidence principale, ou en core la structure familiale. La répartition des émissions au sein de la population conduit à deux conclusions principales. La première est que les inégalités d'empreinte carbone sont moins critiques que les inégalités de revenus. Les instru-

ments de taxation du carbone sont donc régressifs. Je trouve une élasticité entre les émissions directes et le revenu de 0,533 contre 0,455 entre les émissions indirectes et le revenu. Cette hiérarchie est inversée lorsqu'on regarde les élasticités des émissions avec les dépenses, dans ce cas les émissions directes sont moins élastiques que les émissions indirectes (0,693 pour les émissions directes contre 0,762 pour les indirectes). Je montre également qu'il y a moins d'hétérogénéité horizontale pour les émissions indirectes au sein d'une même classe de revenu que pour les émissions directes, pour lesquelles des dimensions telles que le type de résidence ou la possession d'un véhicule privé sont significativement plus corrélées.

**Chapitre 2 : Une analyse distributive de la taxe carbone en France : des micro-simulations à un cadre d'équilibre général**

Dans le deuxième chapitre de cette thèse, je me concentre sur les effets redistributifs des politiques de tarification du carbone sur les ménages français et ce dans différents cadres d'analyse. L'acceptabilité des politiques de tarification du carbone a été largement étudiée dans la littérature, avec une attention généralement limitée aux émissions directes et sans aborder systématiquement les effets d'équilibre général au niveau des jeux (Rausch et al., 2011). Il est désormais largement établi dans la littérature que les politiques de tarification du carbone ont tendance à être régressives avec le revenu dans les pays développés (Ohlendorf et al., 2021) et sont donc susceptibles d'augmenter le risque de rejet par le public (Klenert et al., 2018). La mise en oeuvre de systèmes connexes de redistribution des recettes de taxe carboe par le biais de remises directes peuvent atténuer ces impacts régressifs (Pomerleau and Asen, 2019) mais sont moins efficaces que d'autres systèmes de recyclage, plus ciblés (Rausch et al., 2011; Rausch and Reilly, 2015; Klenert et al., 2018), faisant ainsi état d'un arbitrage clair entre efficacité de la mesure et équité dans la répartition de son coût. La prise en compte des effets dits d'équilibre général, notamment sur la façon dont les rétroactions sur la structure du revenus des ménages et le niveau des prix permet notamment d'intégrer la dimension d'offre d'une économie et d'inclure ses interactions sur le niveau de la demande. Il est dès lors légitime de se demander comment l'intégration des effets d'équilibre général affecte-t-elle les résultats associés aux impacts redistributifs des politiques de tarification du carbone ?

Avant de conduire cette analyse, je réalise des micro-simulations sur un échantillon large d'observations de ménages tiré de l'Enquête Budget des Familles 2011. Je montre ainsi dans quelle mesure les effets d'une taxe sur les émissions directes et indirectes affectent la distribution des ménages. Ainsi, si en moyenne et par décile

de niveau de vie, la distribution est globalement comparable selon les deux assiettes, une taxe carbone sur les émissions indirectes se traduit également par une dispersion moindre, et donc une hétérogénéité horizontale moins forte que pour des émissions directes. J'estime par ailleurs les élasticités-prix directes et compensées pour une variété de 12 produits, issue de la nomenclature COICOP, et compatible avec la nomenclature retenue dans l'enquête BDF, à la fois pour l'ensemble de la population, et pour chaque décile de revenu de niveau de vie. Nos résultats montrent que plus un ménage dispose d'un revenu élévé, plus son comportement présente une plus grande sensibilité aux prix Je présente également les effets associés à la prise en compte de la réponse en prix des ménages selon que leur comportement est considéré comme similaire pour l'ensemble de la population ou dépendant de la classe de revenu. A cette fin, je montre qu'une politique de redistribution basée sur un critère de revenu peut inverser la régressivité initiale et être considérée comme suffisamment ciblée en prenant le critère de revenu pour les classes de ménages. Une redistribution qui retient des critères individuelles de revenu pour déterminer le montant reversé permet certes de réduire la proportion des ménages les plus pauvres pour qui la taxation du carbone reste un coût malgré les montants redistribués, mais cela s'accompagne par la hausse du même indicateur pour les classes de revenu intérmédiaires, pour qui le montant redistribué est relativement moindre que dans le cas d'une dotation égale. Enfin je m'attache à intégrer la prise de comportements estimés sur données de panel pour l'ensemble des ménages et individuellement pour chaque sous-population de décile de revenu de niveau de vie. Nos simulations montrent qu'en fonction de la prise en compte de comportements, homogènes ou hétérogènes, les conclusions tirées différent sensiblement. Nous faisons un exercice similaire de taxation du carbone un cadre EGC. Cette taxe carbone affecte directement les ménages (sur la base de leur émissions directes) mais également les entreprises (la composante indirecte de l'empreinte carbone, du moins pour sa dimension domestique). Nous intègrons une

distinction des ménages en plusieurs classes de revenus. En utilisant un modèle de système de demande presque idéal (Deaton and Muellbauer, 1980) calibrés avec les résultats de nos estimations économétriques, et qui permettent d'intégrer les comportements différenciés dans le cadre macroéconomique du modèle EGC. A cet effet, je montre qu'un mécanisme de redistribution par rabais direct peut compenser les effets régressifs de court terme associés à l'introduction d'une taxe carbone mais qu'à long terme, les changements technologiques dans le secteur productif et l'adaptation des ménages au nouveau système de prix les annulent. Ces résultats introduisent deux dimensions supplémentaires par rapport à une analyse effectuée dans un modèle de micro-simulations. Tout d'abord les effets de substitution dans le secteur productif entre les facteurs de production conduit à accroître la demande en emploi, ce qui par rétroaction conduit à une hausse du revenu des ménages. Ensuite les capacités de substutions des ménages permettent de modérer leur taux d'effort de financement de la taxe carbone par une réallocation de leurs dépenses de consommation.

**Chapitre 3 : Estimations empiriques de l'élasticité de substitution d'une fonction de production KLEM sans contraintes d'imbrication : Le cas de l'élasticité variable de la production-Cobb Douglas.**

Dans le troisième et dernier chapitre de cette thèse, j'explore - avec mon co-auteur - la question de l'estimation empirique de la substituabilité des intrants au sein de la fonction de production et son impact sur les résultats de simulation des modèles EGC. Dans ce chapitre, je tente d'exposer le biais que le choix d'une fonction de production emboîtée spécifique apporte aux résultats des estimations économétriques des élasticités de substitution et, par conséquent, aux résultats des simulations réalisées avec un EGC et calibrées sur ces paramètres. En effet, les résultats des modèles EGC sont très sensibles aux hypothèses formulées sur la distribution des paramètres exogènes, notamment les élasticités de substitution entre l'énergie et les autres intrants (Jacoby et al., 2006; Antimiani et al., 2015). Un ensemble d'études économétriques appliquées a tenté de fournir des estimations empiriques du niveau de substitution entre les facteurs de production en utilisant différentes formes de fonctions de production, telles que Translog (Koetse et al., 2008) ou, plus récemment, les formes CES (Lagomarsino, 2020). Pour surmonter cette limite, nous tirons parti de la spécification VOE-CD (*Variable Output Elasticity-Cobb Douglas*) de la fonction de production (Reynès, 2019). Il s'agit d'une forme flexible de la fonction de production Cobb-Douglas, qui fournit une généralisation de la forme fonctionnelle CES où les élasticités de substitution (ES) entre chaque paire d'intrants ne sont pas nécessairement égales. En ce sens, elle présente des propriétés qui sont bien adaptées au cas de la fonction de production CES multifactorielle à plus de deux facteurs sans supposer une structure d'imbrication spécifique. Dans ce chapitre, nous effectuons des estimations empiriques des élasticités de substitution pour une forme KLEM de la fonction de production VOE-CD en utilisant des procédures d'estimation de type SUR

(*Seemingly Unrelated Model*) (Zellner, 1962). Cette méthode permet d'imposer des contraintes sur la symétrie de l'estimation pour chaque élasticité entre deux intrants et résout simultanément le système d'équations de demande. L'originalité de cette approche est double. Premièrement, nous nous appuyons sur un ensemble de données de panel original et cohérent issu de la publication WIOD 2016 et à partir duquel toutes les variables (prix et quantités) utilisées dans l'estimation sont dérivées. Deuxièmement, nous introduisons une nouvelle spécification de la fonction de production, qui n'a pas encore été testée dans une analyse empirique. Ainsi, nous contribuons à la littérature économétrique appliquée sur la relation de substitution entre les facteurs de production en proposant la première estimation empirique des élasticités de substitution de la spécification VOE-CD entre les facteurs de production et pour 54 secteurs économiques. Nous estimons et comparons trois spécifications de la fonction de production, parmi lesquelles deux formes principales de la structure d'imbrication de la fonction de production CES, à savoir [[[KL]E]M] et [[[KE]L]M][5], et pour lequel nous obtenons des résultats hautement significatifs pour la plupart des secteurs. Par ailleurs nous complétons cette analyse par un travail de simulations de scénario de fiscalité carbone à l'aide d'un modèle EGC pour illustrer les impacts sur les propriétés dynamiques du modèle. Nous retenons le cas central précedement estimé pour calibrer les élasticités de substitution dans le modèle et le comparons avec deux trois cas standards où la calibration des mêmes paramètres est homogènes. Le premier retient une calibration de ces ES à -1, afin de reproduire le cas Cobb-Douglas. Le deuxième et troisième cas de comparaison traduisent des configurations nuancées, la première retenant une valeur de -0.5 tandis que la seconde -2 pour la calibration de ces paramètres, illustrant respectivement un cadre relativement inélastique et élastique aux variation de prix. Ces configurations conduisent à des résultats largement

[5]Les parenthèses indiquent dans quel ordre les intrants sont imbriqués. [[[KL]E]M] indique que $[KL]$ forme un premier emboîtement, qui est ensuite combiné avec $E$ ($[[KL]E]$), qui est enfin combiné avec M pour produire la bien final.

différenciés sur des indicateurs macroéconomiques, tant dans l'amplitude observée (notamment sur les effets de substitution avec les facteurs de production travail et capital, mais également sur son effet sur l'activité générale). Une comparaison des différentes spécifications permet de tirer trois conclusions principales. En premier lieu, la forme imbriquée a des implications directes sur les résultats de l'estimation puisqu'elle impose des contraintes sur les estimations. Ensuite, le comportement de substitution Capital-Energie dépend fortement de la structure d'emboîtement puisqu'il conduit à la conclusion inverse : soit la substitution, soit la complémentarité selon le choix de la structure d'emboîtement. Enfin, la spécification VOE-CD indique une substituabilité entre ces deux facteurs de production, ce qui suggère que la structure d'imbrication [[[KE]L]M] est plus proche de la réalité. Ces résultats apportent un éclairage sur la controverse Capital-Energie. La spécification VOE apparaît comme une forme fonctionnelle pertinente et flexible de la fonction de production. Elle présente l'avantage de la tractabilité linéaire tout en relâchant la contrainte imposée par la fonction de production CES.

Par conséquent, elle pourrait être considérée comme une alternative pertinente pour les modèles EGC. Appliquée à l'évaluation des politiques énergétiques et carbone, la fonction VOE-CD montre que le choix de la structure d'imbrication affecte les résultats économétriques.