

Distributional effects of carbon pricing on households: a case study for Brazil under the Paris Agreement goals

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ABSTRACT

This paper assesses the distributional effects of carbon pricing on Brazilian households. We apply a multi-regional Computable General Equilibrium (CGE) model with representation of multiple households according to a family expenditure survey. Questions of importance for policy makers in Brazil are addressed. What are the economic effects of introducing carbon pricing in Brazil? Is there a double dividend, with economic and environmental benefits, when carbon revenue is recycled through tax rebates? Could carbon revenue contribute to the financing of social spending and to income distribution improvements in Brazil? Results show that carbon pricing avoids further carbon intensive infrastructure lock-in by further promoting biomass in electricity generation and biofuels in the transportation sector. Lump-sum transfers from carbon revenue help boosting income of lower deciles up to +4.5%, while targeting transfers to most vulnerable groups leads to an income growth of +42.2% by 2030. Brazil has a large gap in terms of effective carbon pricing that could be addressed in the context of the ongoing tax reform debate, with carbon revenue contributing to the financing of social spending. Our analysis examines different policy design options and contribute to the policy debate about fiscal reform and socioeconomic effects of carbon pricing in Brazil.

Keywords: Carbon price; Household distributional impacts; General equilibrium; Paris agreement

JEL codes: D580; Q580; Q480

Highlights

- Carbon pricing can be a source of financing of social spending in Brazil. Lump-sum transfers would represent an additional source of income of nearly USD 60 to first-decile households under the poverty line and of around USD 140 to first-decile households under the extreme poverty line.
- Source-side impacts prevail, thus leading to progressive effects in lump-sum scenarios or neutralizing regressive effects of the carbon price.
- Welfare gains are found in lump-sum scenarios, but are restricted to a few low-income deciles when carbon revenues are recycled through rebates on labor income taxes, suggesting a double dividend in its weak form.
- Moderate GDP growth is found in Brazil, mainly driven by gains in its trade balance, as a consequence of worldwide carbon pricing.

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1. Introduction

There is a considerable debate about what is the mix of policy instruments to be used in meeting a desired greenhouse gases (GHG) mitigation goal. Carbon pricing is viewed by many politicians and economists as a cost-effective instrument to internalize the costs of climate damage into prices of goods and services (Fullerton and Metcalf, 2001; Fischer et al., 2001; Goulder and Parry, 2008; Goulder et al., 2019). By inducing agents to substitute the use of carbon-intensive products, carbon pricing reduces CO₂ emissions, being regarded as central in the design of a highly effective policy mix (Wang et al., 2016; Stiglitz et al., 2017; Baranzini et al., 2017).

Carbon pricing has important implications to households, because it changes the relative prices of goods and services (Goulder et al. 2019). The effects of climate-oriented policies are not homogenous across socio-economic groups within countries (Cronin et al., 2019, Goulder et al. 2019) and low-income groups are often the most vulnerable (Grainger and Kolstad, 2010). In particular, carbon pricing might raise consumer prices for energy goods, such as electricity or oil products, eventually with regressive effects due to the relatively larger share these products have in the lower-income households' budget (Böhringer et al. 2019).

Nevertheless, carbon pricing might lead to a double dividend, a theme vastly explored in the literature (Freire-González, 2018), but with a few studies focusing on Brazil (Bento and Jacobsen, 2007; Chen and Timilsina, 2012; Chisari and Miller, 2015). By improving the efficiency of the tax system, while reducing emissions to achieve environmental goals, the double-dividend hypothesis introduced by Pearce (1991) was further developed by Goulder (1995) in its 'weak' and 'strong' forms, where a 'weak dividend' means that cost savings² are found due to the environmental tax reform, whereas a 'strong dividend' implies a costless policy for the economic system, leading to welfare gains.

High-income countries have been historically leading the way in testing and implementing carbon pricing instruments. As a consequence, most studies in the literature that assess the double-dividend hypothesis after the introduction of carbon pricing focus in these countries (Freire-González, 2018), with a few studies dedicated to Brazil (Bento and Jacobsen, 2007; Chen and Timilsina, 2012; Chisari and Miller, 2015). Yet, an increasing number of developing countries is looking at carbon pricing as a potential instrument in their policy mix, and questions about the effects of introducing a carbon price in Brazil are timely (Mello and Silva, 2019), with tax reforms being currently under discussion in various spheres, from academia to Congress (The World Bank, 2019).

² Cost as a measure of the policy-induced changes in individual welfare, but abstracting from welfare effects associated with policy-related changes in environmental quality (Goulder, 1995).

The Brazilian tax system is nonetheless complex, with more than 85 taxes at the federal, state and municipal levels, sometimes compounding on each other in a 'cascade effect' (Higgins and Pereira, 2014). The system does not contribute to reduce income inequalities because it relies mainly on indirect taxes³ (Higgins and Pereira, 2014), promotes economic informality, especially in the labor market (Rocha, Ulyssea and Ratcher, 2017), and eventually fosters regressive taxation effects on consumption (The World Bank, 2018).

Therefore, depending on where carbon revenues are directed to, pre-existing distortions of the Brazilian tax system might be reinforced, leading to a trade-off between efficiency and equity, through distributional effects (Bovenberg and Goulder, 2002). Understanding how the costs and benefits of carbon pricing are distributed among disparate households is crucial (Rao et al. 2017; van Ruijven, O'Neill, and Chateau 2015), meaning that social heterogeneity must be incorporated into energy-economy models.

In this vein, Computable General Equilibrium (CGE) models are useful tools to evaluate climate-related policies effects on households and are widely used to assess economic shocks. By placing the energy system and emissions in an economy-wide context that considers their direct and indirect effects, CGE models also sketch possible climate change transition pathways (Faehn et al., 2020). Although the assessment of carbon pricing effects in the Brazilian economy have been considerably explored in the literature of CGE models (Tourinho, Seroa da Motta and Alves, 2003; Silva and Gurgel, 2012; Magalhães and Domingues, 2013; Gurgel and Paltsev, 2014; Grottera et al., 2020), most of the applications relied on national CGE models (Grottera et al., 2020; Magalhães and Domingues, 2013), or were based on Input-Output matrices methods (Silva Freitas et al, 2014; Grottera, C. et al., 2017), with few studies analysing distributional effects in multi-regional CGE models (van Ruijven et al., 2015).

Furthermore, the large majority of existing CGE models does not include any type of heterogeneity (Rao et al., 2017), and the ones that do so are mostly national models (e.g. Grottera, 2020; Rausch and Schwarz, 2016; Mathur and Morris, 2014; Magalhães and Domingues, 2013; Liang and Wei, 2012; Rausch et al., 2011), usually not accounting for eventual effects of introducing carbon pricing instruments in other countries or regions. Besides, the assessment of distributional impacts in developing countries through multi-regional CGEs has proven to be scarce in the literature (Ojha, Pradhan and Shosh, 2013; Bouet et al., 2013; Wang et al., 2016), with most applications dedicated to the analyses of developed regions (Böhringer et al. 2019; Mathur and Morris, 2014; Saveyn et al., 2011; Rausch et al, 2011).

This study aims to fill this gap by assessing the distributional effects of carbon pricing in Brazil through a multi-regional recursive dynamic CGE model. By disaggregating the single representative agent into multiple households, the relevant contributions of the study are the

³ According to Higgins and Pereira (2014), direct taxes represent 45 percent, whereas indirect taxes account for 55 percent of the taxes levied by the government.

assessment of introducing a carbon price and its distributional effects on Brazilian households. Different carbon revenue recycling schemes are simulated in a context of a worldwide carbon policy and government revenue neutrality in Brazil. In doing so, the study contributes to the policy debate about fiscal reform and carbon pricing by answering important questions related to the double dividend hypothesis and to the effects on income distribution and social spending in Brazil.

The rest of the paper is structured as follows: Section 2 contextualizes the Brazilian economy in the light of its National Determined Contributions (NDC) ambitions. Section 3 describes the research method and the design of the policy scenarios. Section 4 presents the simulation results and discusses its policy implications, whereas Section 5 summarizes the main findings.

2. Brazilian economy and climate policy targets

Between 2003 and 2014, the Brazilian economy went through several transformations that promoted social and economic gains, such as poverty eradication through income distribution (The World Bank, 2019). However, big economic setbacks were observed in the last years due to economic crises and cuts in social spending (IBGE, 2019). Millions of Brazilian households returned to poverty and extreme poverty conditions, bearing the burden, while other social groups were hardly unaffected or even became better-off⁴ (Neri, 2019; IBGE, 2019). Besides, further aggravated by the Covid-19 pandemic crisis (Silveira et al., 2020; The World Bank, 2020c), gross public debt is now close to 90% of Gross Domestic Product - GDP (BACEN, 2020), putting stronger pressure on the current fiscal policy.

Managing the trade-offs between socio-economic development and environmental conservation is crucial for sustainable growth in Brazil, especially in the oil and gas production, agriculture, and mineral sectors. As part of the Paris Agreement, the Brazilian NDC pledged to reduce emissions to 1.3 GtCO₂ by 2030, a 43% reduction compared to 2005 (BRASIL, 2015), and recently indicated the goal of achieving net-zero emissions by 2050. The largest source of Brazil's GHG emissions is land-use change and deforestation, accounting for more than 50% of total GHG emissions (SEEG, 2019). The country has rich environmental resources and biodiversity, including the Amazon biome – a natural carbon-sink of global climate importance –, and made substantial progress in reducing deforestation rates from 2005 to 2012 (INPE, 2020). Nonetheless, recent changes in environmental policy led to a rampant in deforestation, particularly in the Amazon and Cerrado (savanna) biomes (Rochedo et al, 2018; Rajão et al., 2020), threatening the achievement of the Brazilian NDC targets.

⁴ In 2018, the average monthly income obtained by the richest 1% of the Brazilian population reached the equivalent of 33.8 times the monthly income of the poorest 50% (IBGE, 2019). In terms of Gini coefficient, Brazil is in the top 10 most unequal economies in the world and is ranked as 79th in the Human Development Index – HDI (UNDP, 2019; IBGE 2019).

Likewise, a large renewable energy sector contributes to reduce carbon intensity in Brazil, with nearly two-thirds of its electricity supply coming from hydropower (EPE, 2019) and strong blending mandates of biofuels in road transport (27% of ethanol in gasoline and 11-15% of biodiesel in diesel blending). The Brazilian energy sector responds by around 20% of Brazil's GHG emissions (SEEG, 2019), but the current energy infrastructure planning, with increasing role of fossil fuels in the energy mix (EPE, 2020), might hinder its national climate policy ambitions.

Therefore, additional policies shall be required to meet Brazil's economy-wide NDC targets⁵, including market mechanisms (Gurgel and Paltsev, 2014). The Partnership for Market Readiness (PMR) Brazil Project (Mello and Silva, 2019) is currently analyzing the adoption of economic instruments to price carbon emissions as part of the policy package post-2020. In this regard, achieving feasible conditions to introduce a carbon pricing instrument in Brazil is a challenge, especially given the peculiarities of the Brazilian economy: a relatively clean energy matrix; the relevance of forestry and agricultural sector; the enduring fiscal context, with public budget under pressure due to increasing public expenditure; and the complex political-institutional conditions for the implementation of deeper tax reforms that directly affect Brazilian households.

3. Research Method

This section describes the research method used to assess the household incidence of carbon pricing schemes in Brazil. We apply a multiple household method, as described in van Ruijven et al. (2015), to increase the representation of the Brazilian households in a multi-regional CGE model with 14 regions and 10 sectors represented⁶, as designed in the regional aggregation of the EMF36 study.

In this method, the single representative household for Brazil is broken into ten households, making households' decisions integrally modeled within the CGE model. As a consequence, each household type becomes represented by a separate utility function, capturing heterogeneity in preferences and providing a broader view of the policy effects on the consumption side (e.g., higher energy prices). We cluster household types by income distribution, covering heterogeneity in factor endowments to capture the policy effects on the income side (e.g., wages, profits). By assessing changes from these two different perspectives – income (source) and consumption (use) sides –, the method allows for a comprehensive assessment of the distributional impacts of carbon pricing on welfare. We further explore results on welfare changes from these two perspectives by following the method described in Goulder et al. (2019),

⁵ Gurgel and Paltsev (2014) suggest that, although challenging because of the Measurement, Reporting and Verification (MRV) of GHG emissions mitigation in the land use sector, a carbon market (instead of a carbon tax) would be the preferable option for Brazil to achieve its NDC pledges.

⁶ *Regions* (14): Africa; Australia and New Zealand; Brazil; Canada; China; Europe; India; Japan; Middle East; Other America; Russia; South Korea; Other Asia; and United States. *Sectors* (10): Coal, Crude Oil, Electricity, Natural Gas, Oil Products, Agriculture, Energy Intensive Industry, Manufacturing, Services and Transport.

Also, the macroeconomic effects of carbon pricing policies worldwide are greatly captured by the multi-regional model. By valuating the marginal cost of carbon for different regions, the model captures to what extent changes in relative prices of carbon-intensive goods in other regions have distributional implications for Brazilian households, and how these changes affect international terms of trade, which is of particular importance for the Brazilian economy.

3.1 Computable General Equilibrium (CGE) model

The TEA (Total-Economy Assessment) model (Cunha et al., 2020) is a multi-regional and multi-sectorial CGE model that tracks the production and distribution of goods in a dynamic recursive setup for the global economy. The model follows the standard microeconomic optimization framework, assuming total market clearance (through price equilibrium), zero profit condition for producers (with constant-returns-to-scale) and perfect competition, to reach general equilibrium. Consumers maximize welfare subject to a budget constraint, while producers minimize the cost of production using intermediate inputs and primary factors (labor, capital, land, and resources) for a given sector/technology. Full employment of production factors is assumed⁷. Capital and labor are mobile across sectors but not across regions, while land and resources are treated as sluggish factors. Land is endogenously calculated by a land supply curve, also adding biophysical information on land productivity, for each region. Consumer preferences and production functions are described as multi-level nested Constant Elasticity of Substitution (CES) functions calibrated by share parameters of their inputs.

The TEA model static structure is based on GTAPinGAMS (Rutherford, 1997), and its dynamic structure and parameters are based on other CGEs and Integrated Assessment Models (IAM), such as GTAPinGAMS (Rutherford, 1997), the MIT EPPA model (Paltsev et al., 2005; Yang et al., 1996) and the COFFEE model (Rochedo, 2016). The TEA model is formulated as a Mixed Complementary Problem (MCP) and is solved through Mathematical Programming System for General Equilibrium – MPSGE (Rutherford, 1999) within GAMS. The TEA model currently uses the GTAP9 Data Base (Aguiar et al., 2016), with base year 2011, and includes a detailed representation of the energy sector that is based on the COFFEE model⁸ (Rochedo, 2016) – a

⁷ Capital and labour productivity are endogenously defined, assuming that Total-Factor Productivity (TFP) meets an exogenous GDP level in the baseline. Labor supply follows exogenous population growth rates, while capital stock evolves with capital additions that depend on: (i) the investment level in the current period and (ii) depreciation of investment in the previous period. See more assumptions in Cunha et al. (2020).

⁸ Data for energy production and consumption (in energy physical units), share parameters of the factors of production (capital, labor, resources and land), technological change, penetration trends for alternative technologies, and efficiency improvements assumptions from COFFEE are inputted into TEA. Biofuels production combines intermediate inputs with the fixed factor based on an elasticity of substitution, which has a different value for Brazil compared to the rest of the world. This elasticity makes it possible to represent a gradual penetration when the prices of oil products rise continuously, as well as via mandates or fuel substitution. For a more comprehensive description of the energy and land-use systems in the TEA model, please refer to Cunha et al. (2020).

multi-regional partial equilibrium bottom-up model, that provides rich technological information for the energy and land-use systems.

In the current version of the TEA model, government and consumers were disaggregated in order to capture direct transfers from/to households' deciles, accordingly. Governments (public agent) collect taxes and spend their revenue on consumption of goods and services, and on direct transfers⁹ to households and firms. The government and the tax system represent a combination of federal, state, and local levels, which, in the case of Brazil, is of particular importance because income taxes are mostly under federal jurisdiction, whereas sales taxes are mostly state and local.

We focus on carbon revenue recycling scenarios that include lump-sum transfers, income tax or sales tax recycling, in addition to the case in which carbon revenue is kept within government budget (no revenue recycling). In all policy scenarios, we assume government revenue neutrality in the sense that public expenditure is kept fixed at the baseline level, thus allowing for full carbon revenues to be recycled directly to households or rebated through tax reduction.

In addition, international trade follows Armington's aggregation (Armington, 1969), in which a composite CES function differentiates consumers' preferences between imported and domestic goods. In the macroeconomic closure, an endogenous real exchange rate clears the current accounts, and we assume that the regional capital accounts converge exogenously in the long run. We set the price numeraire of the model as the United States dollar (USD), thus all prices are measured relative to the numeraire. We also assume that investment equals total savings, with marginal propensity to save constant over time, according to savings' endowments from the GTAP9 Data Base (Aguar et al., 2016).

3.2 *Creating representative multiple household types*

Micro-dataset from POF 2008-2009 (*Pesquisa de Orçamentos Familiares* - IBGE, 2010) was used to disaggregate the Brazilian single average representative household in the TEA model by income deciles. The survey has a sample of 55,970 households, representing a universe of 57.6 million households and 190 million people around the country in 2008, and it accounts for the whole national income distribution. The households were clustered into income deciles¹⁰ to create 10 multiple household's types. Households with income equal to zero were not considered in the analysis.

⁹ In this study, direct transfers are indexed to the consumption level, keeping the reference case level in real terms based on the Consumer Price Index (CPI) in all simulations.

¹⁰ Income decile is a relative measure that stratifies households into ten groups, from lowest to highest income values, each of them representing ten percent of the total amount of households. The first decile represents the poorest 10%, whereas the tenth decile represents the wealthiest 10% households. Total annual household income was the selected variable used in the clustering process.

First, we took 475 income sources from POF and grouped them into 4 factors of production, as represented in the TEA model (capital, labor, land/resources, and transfers). *Erro! Fonte de referência não encontrada.* shows the share of income sources by income decile compared to the national average ("BR"). The share of capital income increases in the same direction of growing affluence, whereas transfers decrease (from 32% in the first decile to 13% of total income share in the tenth decile), since high income households need less governmental assistance than the lower income ones and the current transfer schedule is indeed progressive (Higgins and Pereira, 2014). However, the share of transfers for the higher deciles is still high as compared to other economies (Goulder et al., 2019), especially due to transfers from the Brazilian public pension system (Medeiros and Souza, 2015).

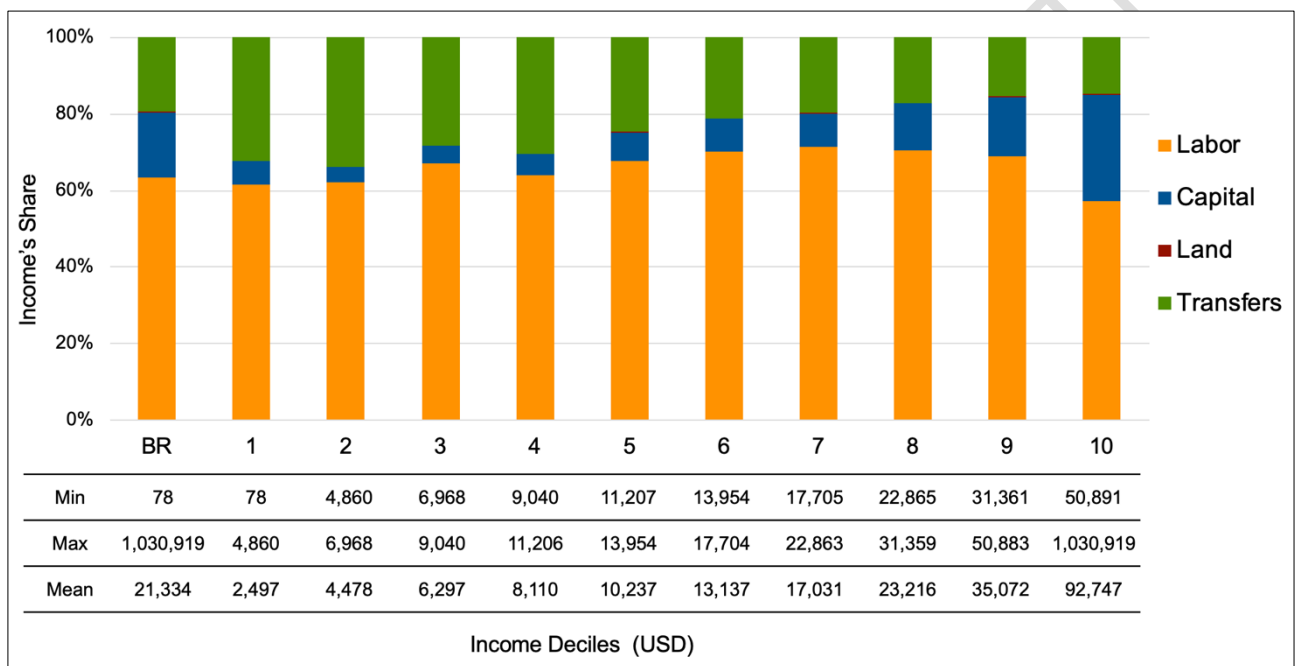


Figure 1. Share of income by source and decile in Brazil

Note: 1 BRL = 0,7329 USD and the values are annual income by households

Source: own elaboration based on IBGE (2010)

Then, we classified 13,255 commodities from POF into 10 sectors, as represented in the TEA model¹¹. **Figure 2** presents the share from the expenditure side for 8 sectors (Coal and Crude Oil were omitted because their final consumption is negligible). As the Brazilian households get wealthier, demand for Services increases, reaching nearly 60% of the final consumption in the tenth decile. Also, there is a clear trade-off between the share of Oil products and Transportation sectors across deciles, with a greater share of oil being consumed by higher income deciles, which indicates their preference for individual rather than public transport.

¹¹ Importantly, the definition of commodities in POF relies on the consumer's standpoint (household survey), while in CGE models it comes from the supply side (I-O matrices).

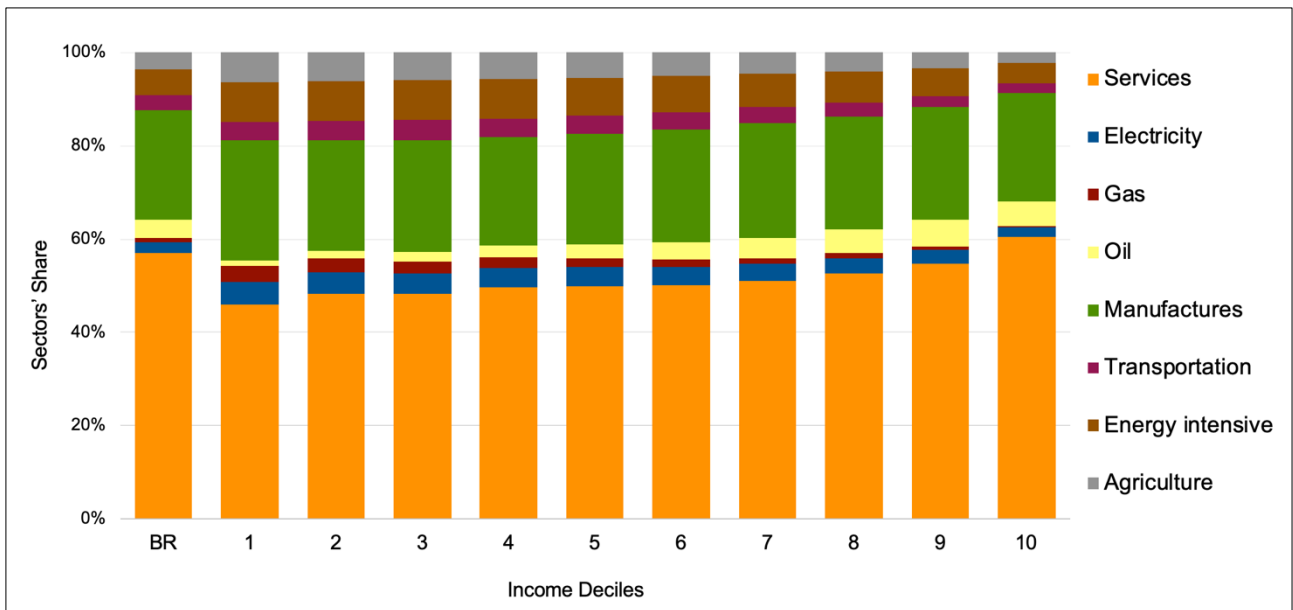


Figure 2. Share of expenses by sector and decile in Brazil.

Note: Coal and Crude Oil omitted due to negligible shares in final consumption.

Source: own elaboration based on IBGE (2010)

Finally, in the TEA model, total income for each factor of production and total expenditure derived from the GTAP9 Data Base (Aguilar et al., 2016) were distributed according to the share for each household decile (as shown in **Figure 1** and **Figure 2**, respectively). Total expenditure comprises consumption and savings, and the share of capital income from POF was used to break down savings by household decile in the TEA model¹². The share of land/resources income from POF was used to split the income from resources by household type in the TEA model. Transfers among government and households were a result of the difference between total income and total expenditure (including savings), with the Brazilian government being a net transferrer to households in the base year 2011. Data from the Brazilian Ministry of Economy (SEAE/MF, 2017) and the share of the transfers by household decile from POF were used to check the adherence of the estimates.

3.3 Carbon pricing and policy scenarios

Baseline GDP projections for 2030 (measured at market exchange rates – MER) follow the International Energy Outlook – IEO (EIA, 2019), and do not account for the effects of Covid-19 pandemic on economic activity. Regional CO₂ emissions indexes provided by the Energy Modelling Forum (EMF) 36 on Carbon Pricing After Paris (Böhringer et al., this issue) were also used in the baseline projection. To calibrate the baseline in the TEA model a top-down approach was adopted, with technological change mainly induced through three mechanisms: (i) changes in

¹² Savings initial endowment from the GTAP9 Data Base (Aguilar et al., 2016) was distributed according to the share of capital income by household decile obtained from POF micro-dataset (IBGE 2010).

elasticities of substitution between non-fossil and fossil fuel sources; (ii) cost penalties for fossil fuels; and (iii) exogenous energy efficiency, as described in the Supplementary Material.

A carbon pricing was set up as an emission allowance market, in which the permits start to be negotiated in 2020 between regions and/or sectors under a cap-and-trade system. The government has endowments of emissions permits that are freely traded under a perfectly competitive carbon market. When any segment of the carbon market is active, the corresponding CO₂ permit becomes a required input in the production function for the emitting sectors, therefore changing its relative cost of production, according to the indirect marginal abatement cost (MAC) curve faced by that particular sector.

The carbon pricing policy simulated in this paper considers regional carbon markets that are subject to a global carbon budget (consistent with a likely chance to achieve a maximum 2°C increase in the average surface temperature of the Earth over pre-industrial levels by 2100). In this set-up, each region enters the market with a number of permits equal to their total CO₂ emissions in the baseline scenario in 2020. Then, following the regional CO₂ emissions indexes provided by the EMF36 scenario protocol, the number of permits is constrained at every period, forcing CO₂ energy-related emissions¹³ to decrease relatively to the baseline scenario.

The target for Brazil is a 27% reduction to the baseline by 2030, which, along with other regional targets¹⁴, implies a global decrease of 21.5% in CO₂ energy-related emissions, within a carbon budget¹⁵ of 1,000 GtCO₂. Regional targets are based on the 2°C scenarios of Kitous et al. (2016), which translates regional NDC pledges to NDC-2C scenarios, as additional efforts to meet the 2°C temperature target.

As a straight result of this carbon pricing setup, the ‘first dividend’ of the double dividend hypothesis is entirely achieved in the simulations, with the pollutant reaching the targeted levels by definition. Importantly, welfare gains derived from the reduction of the air pollution – i.e., the first dividend of reducing the negative externality – are not captured in the TEA model, so we further investigate if carbon revenue recycling through labor or sales taxes rebates leads to the second dividend in the form of a ‘weak dividend’ or a ‘strong dividend’ as presented by Goulder (1995).

In addition to the baseline scenario (BASE), six policy-relevant scenarios are simulated in the context of the carbon pricing (**Table 1**). First, a scenario without revenue recycling (GOV) with

¹³ Simulations in the EMF36 scenario protocol only include CO₂ emissions from fossil fuels combustion. Including CO₂ emissions from land-use would substantially increase the number of CO₂ permits traded in Brazil, eventually affecting carbon prices, according to the indirect MAC curve.

¹⁴ Targets for other regions relatively to the baseline by 2030 are: United States (-27%); China (-15%); India (-15%); Europe (-33%); Canada (-30%); Japan (-18%); South Korea (-40%); Russia (-12%); Australia and New Zealand (-15%); Middle East (-15%); Africa (-20%); Other America (-19%); and Other Asia (-30%).

¹⁵ van Vuuren et al. (2020) derive budgets of 837 GtCO₂ and 1,600 GtCO₂ for the +1.5°C and 2°C temperature targets, respectively, while the IPCC SR1.5 (IPCC, 2018) derives 746 GtCO₂ and 1,496 GtCO₂ for the 2010-2100 period.

carbon revenues being kept within the public budget; then, different revenue recycling schemes are introduced, including: a direct method, in which carbon revenues are recycled through lump-sum transfers to households (TRF, POV and EXT); and two indirect methods, in which carbon revenue rebates on labor taxes (LAB) and on sales taxes (VAT) are applied. As a counterfactual to disentangle national from international effects of the worldwide carbon pricing policy, we simulate an additional scenario (No BRA) where Brazil has no carbon pricing mechanism, whereas all other regions do.

Table 1. Summary of policy scenarios

Tag	Scenario description (Carbon revenue condition)
GOV	Kept within the public budget
TRF	Directly and equally transferred to households (lump-sum)
POV	Directly transferred to households below poverty line (lump-sum)
EXT	Directly transferred to households below extreme poverty line (lump-sum)
LAB	Rebates on labor taxes
VAT	Rebates on sales taxes
NoBRA	No carbon revenue for Brazil (all other regions do)

The social acceptance of a carbon price is of paramount importance for its success. As such, while regressiveness concerns of the Brazilian tax system are addressed by simulating carbon revenue rebates, the scenarios also include direct carbon revenue transfers to households, which is more likely to be positively perceived by society, when carbon pricing is introduced. In all revenue recycling scenarios, the totality of the revenue is rebated or transferred, under a ‘equal-yield’ constraint that assumes government neutrality, with public revenue kept at the baseline level.

When rebated, the carbon revenue reduces labor and sales taxes (LAB and VAT scenarios). When transferred, carbon revenues are uniformly distributed across all households (TRF) or targeted to more vulnerable groups (POV and EXT scenarios). In POV and EXT, carbon revenues are only distributed to households with total income below the poverty line (PPP USD₂₀₁₁ 5.50/day) and below the extreme poverty line (PPP USD₂₀₁₁ 1.90/day), as classified in The World Bank (2020b). **Table A.1** in the Appendix presents the share of households under poverty and extreme poverty condition, while **Table A.2** presents the share of carbon revenue lump-sum transfers directed to each decile, which is kept constant throughout the period 2020-2030.

4. Results and discussion

This section presents the results of the simulations and discusses their implications. First, the macroeconomic impacts of carbon pricing are presented, followed by the results of distributional impacts on households, as well as the welfare and inequality analyses.

4.1 Carbon pricing macroeconomic impacts

Results suggest a carbon price of nearly 4 USD/tCO₂ in all scenarios, in 2020; reaching 12 USD/tCO₂ by 2025; and ranging from 26.4-27.1 USD/tCO₂, in 2030, depending on the scenario¹⁶ (**Figure A.1** in the Appendix). The average carbon market size is estimated at USD₂₀₁₁ 10.4 billion/year, with 390 MtCO₂ of carbon permits being traded annually. Brazil has a relatively low-carbon intensive energy system, but the estimated carbon revenues could represent up to 1.6% of the government budget, considering a GDP growth projection of +2% p.y. between 2020 and 2030. In this regard, carbon pricing influences economic activity and **Table 2** presents the results for macroeconomic effects in Brazil, by scenario.

In terms of welfare changes to baseline (Equivalent Variation - EV), without revenue recycling (GOV), welfare losses of -0.14% are found with similar effects coming from the income and consumption sides. Nonetheless, the income effect prevails in most scenarios with revenue recycling, being strong enough to make an overall positive effect in lump-sum scenarios (+0.18%), but not in tax rebates scenarios, with welfare losses found in LAB (-0.14%) and VAT (-0.17%). In LAB, similar effects coming from the income and consumption sides are found (-0.07%), but in VAT, the income effect (-0.58%) overcomes the expenditure effect (+0.41%).

More importantly, when assessing welfare results through the lens of the double-dividend hypothesis, a comparison with the lump-sum scenarios reveals that a 'strong dividend' is not found in GOV, LAB or VAT scenarios, with welfare losses found in 2030. The absence of a 'strong dividend' is not surprisingly, and is in line with most studies in the literature, including the few ones focusing on Brazil, such as Chen and Timilsina (2012), and Chisari and Miller (2015).

In this vein, results in **Table 2** do not add clear evidence of the presence of a 'weak dividend' -- despite the welfare losses found in GOV, LAB and VAT, a moderately GDP growth is found in all scenarios. Nonetheless, the results for GDP come mainly as a consequence of positive trade balances that are achieved because of greater net exports (around +16% than the baseline in most scenarios). So, the existence of a 'weak dividend' should be interpreted with caution, and is further investigated by disentangling national from international effects of carbon pricing (as discussed when presenting the results of the NoBRA scenario below).

Interestingly enough, the international effects of carbon pricing in LAB and VAT scenarios are stronger enough to boost the Brazilian trade balance by +35.25% and +30.16%, respectively, mainly through imports substitution, with a stronger decrease in imports is found. Therefore, our results suggest that Brazil might benefit from economy-wide (but worldwide) carbon pricing, with

¹⁶ In this paper, the results for the carbon market reflect regional carbon markets, with permits being traded solely by sectors within regions. For the EMF36 runs, however, other types of cooperation were simulated, with a global carbon market roughly cutting costs by 50% when compared to regional markets. Carbon price estimates for Brazil range from 25.50 to 295.14 USD/tCO₂ across the models of the EMF36 study.

the country adjusting its international trade basket and achieving moderate GDP gains. Naturally, changes in terms of trade could influence these results, so we performed a robustness check based on the Paasche's price index¹⁷, where no substantial changes in terms of trade were found (positive effects up to +0.05% in GOV, LAB and VAT scenarios).

Relative growth in GDP, although moderate, is however not expected after carbon pricing is introduced. For instance, Magalhães and Domingues (2013), Gurgel and Paltsev (2014) and Grottera et al. (2020) suggest GDP losses after introducing a carbon price in Brazil. However, differently from these previous studies, our simulations in a multi-regional model consider that every region, including Brazil, introduces a price on carbon¹⁸, thus valuating the marginal cost of carbon for different regions.

Table 2. Macroeconomic effects and terms-of-trade index in Brazil. Values in USD₂₀₁₁ billion and relative changes to BASE in 2030 (%)

	GOV	TRF	POV	EXT	LAB	VAT	BASE
Welfare (EV)	-0.14%	0.16%	0.18%	0.18%	-0.14%	-0.17%	
EV source	-0.07%	0.43%	0.45%	0.45%	-0.07%	-0.58%	
EV use	-0.07%	-0.27%	-0.27%	-0.27%	-0.07%	0.41%	
GDP	3,251.8	3,254.5	3,254.4	3,254.4	3,269.0	3,269.8	3,238.5
% BASE	0.41%	0.49%	0.49%	0.49%	0.94%	0.96%	
Consumption (C)	1,910.6	1,911.8	1,912.2	1,912.1	1,906.7	1,906.6	1,909.3
% BASE	0.07%	0.13%	0.15%	0.15%	-0.14%	-0.14%	
Investment (I)	621.6	622.7	622.0	622.1	622.3	625.3	624.1
% BASE	-0.40%	-0.22%	-0.34%	-0.32%	-0.29%	0.18%	
Government (G)	602.6	603.1	603.1	603.1	604.3	607.2	604.7
% BASE	-0.35%	-0.27%	-0.27%	-0.27%	-0.08%	0.41%	
Exports (X)	379.0	377.3	377.3	377.3	378.9	380.1	385.4
% BASE	-1.66%	-2.10%	-2.09%	-2.09%	-1.67%	-1.38%	
Imports (M)	260.5	260.4	260.2	260.2	243.2	249.4	285.0
% BASE	-8.58%	-8.64%	-8.68%	-8.70%	-14.68%	-12.49%	
Trade Balance (X-M)	118.4	116.9	117.1	117.1	135.8	130.7	100.4
% BASE	17.97%	16.48%	16.61%	16.67%	35.25%	30.16%	
Terms of trade (Index)	1.0585	1.0603	1.0603	1.0603	1.0585	1.0583	1.0580
% BASE	0.05%	0.22%	0.22%	0.22%	0.05%	0.03%	

¹⁷ The Paasche index is the price index for the current period, with terms of trade (TOT) described as $TOT = EXP_t / IMP_t$, where $EXP_t = Qexp_t \cdot Pexp_t / Qexp_t \cdot Pexp_{2011}$ and $IMP_t = Qimp_t \cdot Pimp_t / Qimp_t \cdot Pimp_{2011}$ are the Paasche price indexes for exports and imports in time t, respectively; $Qexp_t$ and $Qimp_t$ are the quantities of imported goods and services in time t, respectively; and $Pexp_t$ and $Pimp_t$ are the prices of imported goods and services in time t. Prices in the denominator are fixed in the base year 2011 to compute the Paasche index.

¹⁸ We also run a counterfactual scenario in which carbon pricing is solely introduced in Brazil (only BRA). Results in this scenario indicate a change of -0.20% in GDP, relatively to BASE in 2030, under a USD₂₀₁₁ 20.27/tCO₂. Results of another counterfactual scenario (No BRA) where Brazil is the only region to not put a price on carbon are reported in Tables 4 and 5 below.

In terms of consumption, in GOV scenario, losses are not found (+0.07%) due to the effects of carbon pricing. Consumption is kept relatively similar to BASE (+0.15%) in all direct transfer scenarios (TRF, POV and EXT), thus suggesting that lump-sum transfers contribute to reduce the effects of carbon pricing on consumption, as discussed below. Nonetheless, there are consumption losses found in LAB and VAT scenarios (-0.14%). Investment and government spending decrease in all scenarios, except in VAT (+0.18% and +0.41%, respectively), further contributing to GDP gains relatively to the baseline (+0.96%).

Table 3 presents the impacts on total income by income source, relatively to baseline, in 2030. In GOV, changes in total income reach +0.41%, mainly because of the increase in net transfers from government to households (+22.74%). Capital income (-0.41%), labor income (-0.43%) and resource income faces losses (-1.90%) relative to the baseline.

Table 3. Income sources impacts. Relative change to Baseline in 2030 (in %)

Source	GOV	TRF	POV	EXT	LAB	VAT
Capital	-0.41	-0.18	-0.19	-0.19	-0.41	-0.46
Labor	-0.43	-0.20	-0.22	-0.22	0.42	-0.48
Resource	-1.90	-1.70	-1.70	-1.70	-1.90	-1.62
Transfer ¹	22.74	34.32	34.18	34.19	0.44	0.24
Total Income ²	0.41	0.49	0.49	0.49	0.94	0.96

Note: ¹ Net transfers from government to households. Includes lump-sum transfers from carbon revenue in TRF, POV and EXT scenarios.

² Total Income includes private and public revenue, which is kept at the baseline level (revenue-neutral).

In lump-sum scenarios (TRF, POV and EXT), gains in total income (+0.49%) come as a consequence of direct money-transfer from carbon revenue, with net transfers from government to households increasing by +34%. Lower-income deciles are the most benefited, whereas the ninth and tenth deciles remain net transferrers to government. Capital income (-0.19%), labor income (-0.22%) and resources income (-1.70%) losses are found in lump-sum scenarios. When carbon revenue is directed to tax rebates on labor income (LAB), total income increases by +0.94%, led by an increase in labour income and net transfers (+0.42% and +0.44%, respectively). In VAT, net transfers (+0.24%) also contribute to the increase in total income, which is led by the growth in government spending and savings. Distributional impacts are however distinct, as discussed in the next section.

Regarding market prices, an expected result of introducing carbon pricing is an increase in the price of carbon intensive sectors. As such, Coal and Natural Gas sectors are the most affected by carbon pricing, followed by Electricity and Transport sectors (**Table A.3** in the Appendix). However, carbon pricing is often passed forward to final consumers, eventually affecting long-term growth due to regressive effects, since low-income households spend a greater share of their budget on electricity and natural gas, for example. Carbon pricing increases the consumer prices

index in GOV (+0.08% relatively to BASE), while in lump-sum scenarios, consumer prices increase up to +0.27%. Consumer prices in LAB and VAT scenarios face different effects from carbon pricing (+0.08% and -0.41%), because of tax rebates from sales taxes (**Table A.3** in the Appendix).

The effects of carbon pricing on final consumers are also related to substitution possibilities of goods and services¹⁹. In Brazil, substituting oil products (for biofuels) and natural gas (for biomass or electricity) are quite frequent outcomes due to changes in relative prices, but electricity is relatively inelastic to price changes (Pereira Uhr et al., 2019). As a consequence, final consumption of electricity is not significantly affected by carbon pricing, whereas a stronger decrease in coal and oil consumption for electricity generation is found, with an increased share of renewables and biomass in electricity generation (88.6% in policy scenarios against 85.4% in baseline), as shown in **Figure 3**.

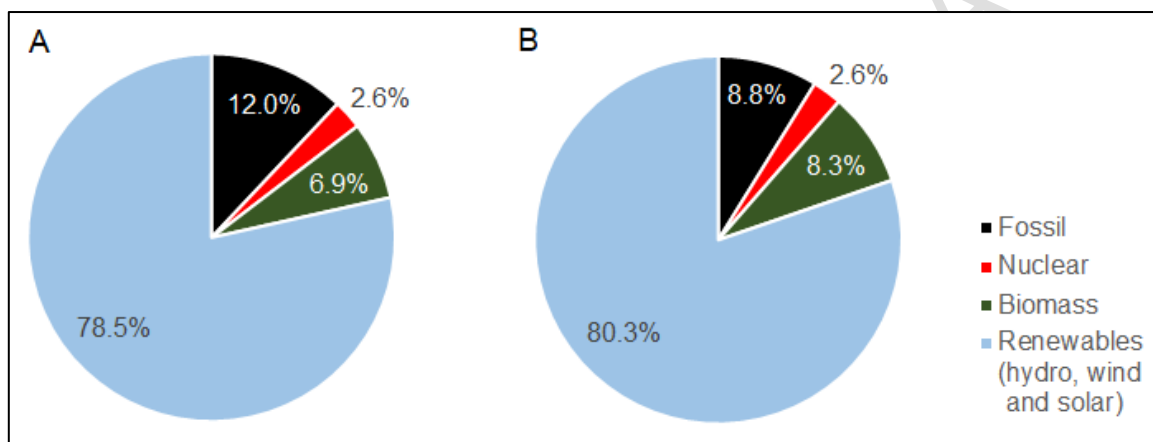


Figure 3. Electricity generation by energy source in 2030. Share of total (%) in baseline (A) and in all scenarios (B).

Moreover, in most scenarios, consumption of biofuels increases up to +1.6% relatively to the baseline, in 2030, displacing oil products. In VAT, however, rebates on sales taxes lead to a greater consumption of oil products (+4.5%) to the detriment of biofuels, in a typical rebound effect. Because a cap-and-trade system is assumed as the carbon pricing instrument, CO₂ emissions are quantitatively constrained, thus transmitting the rebound effect to the carbon price, and leading to a difference of +0.7USD/tCO₂ in the carbon price for VAT relatively to GOV (see **Figure A.1** in the Appendix). Conversely, in the presence of a carbon tax, a rebound effect in VAT would be expected, with emissions increasing due to greater consumption of oil products.

The effects of carbon pricing on final consumption are not homogeneous across household deciles (**Table 4**). In GOV, there are moderate regressive effects found due to carbon pricing, with some of the lower-income deciles being relatively more affected than higher ones, while total

¹⁹ The elasticities of substitution are represented in the nested CES structure of the model, as shown in Figures SM.1 to SM.4 in the Supplementary Material.

consumption decreases (-0.13% on average). Carbon revenue recycling schemes however affect final consumption, in many cases by neutralizing the effects of carbon pricing on low-income deciles. Results for lump-sum scenarios (TRF, POV and EXT) indicate progressive effects and small growth in total consumption (up to +0.15% on average). In LAB, final consumption decreases in all deciles (-0.14% on average), whereas rebates in VAT are not strong enough to keep final consumption at the baseline level (-0.14% on average), following the income effects observed in **Table 2**.

Table 4. Final consumption by decile. Relative change to Baseline in 2030 (in %)

Income decile	GOV	TRF	POV	EXT	LAB	VAT	NoBRA
1	-0.05	4.39	18.52	44.03	-0.10	-0.14	-0.08
2	0.01	2.55	7.57	1.64	-0.04	-0.13	-0.10
3	-0.03	1.57	3.21	-0.27	-0.05	-0.11	-0.08
4	-0.02	1.11	0.90	-0.43	-0.05	-0.12	-0.08
5	-0.08	0.67	-0.01	-0.47	-0.08	-0.11	-0.05
6	-0.10	0.40	-0.32	-0.46	-0.08	-0.11	-0.04
7	-0.10	0.23	-0.42	-0.44	-0.06	-0.11	-0.03
8	-0.13	0.04	-0.41	-0.41	-0.10	-0.12	-0.01
9	-0.13	-0.08	-0.37	-0.37	-0.11	-0.14	0.00
10	-0.17	-0.22	-0.31	-0.31	-0.19	-0.16	0.04
Average	-0.13	0.13	0.15	0.15	-0.14	-0.14	0.00

Results in NoBRA scenario provide a more comprehensive interpretation about the effects of the worldwide carbon pricing policy on Brazilian households and contribute to the assessment of the double-dividend hypothesis. By disentangling national from international effects of carbon pricing, when compared to GOV, LAB and VAT, results in NoBRA suggest no evidence of the presence of a second dividend (at least in the form of a 'strong dividend'). Nonetheless, in LAB, consumption losses in second, third and fourth deciles are lower than those in NoBRA, which suggests the presence of a second dividend in its weak form, as further discussed in Section 4.3.

4.2 Effects on income distribution

Table 5 shows the relative change in total income by household decile in Brazil compared to the baseline scenario in 2030. In GOV, the effects of carbon pricing on income are not homogeneous across deciles – income increases up to the fifth decile, whereas income decreases around 0.2% in higher deciles. In lump-sum scenarios (TRF, POV and EXT), targeted direct money transfers lead to income growth. In TRF, carbon revenue is equally transferred across households, representing a direct money-transfer of around USD₂₀₁₁180 per household on an annual basis – in

other terms, nearly an additional minimum wage per year per household²⁰. Income gains in TRF are found even up to the ninth decile, illustrating how income distribution is highly concentrated on higher deciles. In LAB, income gains are generally perceived by low- and middle-income household deciles, suggesting that the tax rebate has potentially progressive effects, while in VAT the effects are strongly homogeneous (-0.49% on average).

Table 5. Total income by household decile in Brazil. Relative change to Baseline in 2030 (in %)

Income decile	GOV	TRF	POV	EXT	LAB	VAT	NoBRA
1	0.08	4.58	17.98	42.20	0.09	-0.50	-0.10
2	0.14	2.79	7.51	1.93	0.15	-0.50	-0.13
3	0.09	1.85	3.38	0.12	0.14	-0.50	-0.11
4	0.09	1.42	1.22	-0.05	0.12	-0.50	-0.11
5	0.02	0.98	0.33	-0.11	0.08	-0.50	-0.09
6	-0.01	0.70	0.01	-0.13	0.07	-0.50	-0.08
7	-0.03	0.51	-0.11	-0.14	0.06	-0.50	-0.07
8	-0.08	0.28	-0.15	-0.16	0.00	-0.49	-0.05
9	-0.12	0.12	-0.17	-0.17	-0.04	-0.49	-0.03
10	-0.20	-0.08	-0.19	-0.19	-0.19	-0.49	0.01
Average	-0.12	0.28	0.26	0.26	-0.08	-0.49	-0.02

By targeting social groups under the poverty and extreme poverty lines, lump-sum transfers in POV and EXT scenarios improve income distribution, promote equality, and address poverty issues. In POV, nearly 2/3 of the carbon revenue is transferred to the first and second deciles, helping to boost their income in real terms by nearly +18% and +7.5%, respectively (**Table 5**). Targeting becomes even more stringent in EXT, with social groups under the extreme poverty line from the first and second deciles receiving 99% of the carbon revenue transferred to households – as a consequence, income grows by nearly +42% and +2% in the first two deciles, relatively to the baseline, in 2030 (**Table 5**).

Therefore, a key message of our results is that carbon pricing can be a source of financing for social spending in Brazil, thereby boosting welfare gains for the poorest, while keeping government revenue neutrality. On a monthly basis, lump-sum transfers would represent, in 2030, an additional source of income of nearly USD₂₀₁₁ 60 to first-decile households under the poverty line and of around USD₂₀₁₁ 140 to first-decile households under the extreme poverty line. Otherwise, when kept within government budget, the estimated carbon market revenue (USD₂₀₁₁

²⁰ The current monthly minimum wage at federal level in Brazil is BRL 1,100. Taking the average exchange rate in 2020 (USD 5.1/BRL), this is equivalent to USD 205 (BACEN, 2020).

10.4 billion, in 2030) could partially or even fully cover the total cost of *Bolsa Família* program²¹ – a conditional cash transfer program for reducing poverty in Brazil (Higgins and Pereira, 2014) --, helping to alleviate public budget pressures.

4.3 Welfare and inequality analysis

Results for welfare impacts are presented according to Atkinson Equally Distributed Equivalent (EDE) index (Atkinson, 1970), derived from the social welfare function. The equally distributed equivalent income (y_{EDE}) is the level of income that, if equally distributed, would enable society to reach the same welfare level as the current income distribution. The EDE index is presented in **Equation 1**:

$$y_{EDE} = \left(\frac{1}{N} \sum_{i=1}^N y_i^{1-\varepsilon} \right)^{\frac{1}{(1-\varepsilon)}} \quad (1)$$

where, N is the population; ε is the parameter of inequality aversion, with $\varepsilon = 0$ representing no inequality aversion in society and $\varepsilon = +\infty$ fully inequality aversion in society; and y_i is the real income level of each household decile i .

Results in **Figure 4** reveal interesting insights in terms of efficiency and equity considerations to policy design. Results do not suggest efficiency gains in LAB and VAT scenarios, however progressive effects are found in lump-sum scenarios, particularly in EXT and POV scenarios where revenue is strongly targeted to lower-income household groups (as presented in the smaller graph in the left upper corner in **Figure 4**). When accounting for full inequality aversion ($\varepsilon = +\infty$), an expected result is that social welfare is greater in EXT, followed by POV and TRF, because of targeted money-transfers and as a consequence of equity considerations.

²¹ There is strong evidence, in Brazil, that lump-sum transfers targeting lower income households are administratively feasible. The best example so far is *Bolsa Família*, a well-succeeded program of targeted transfers to lower-income households under Federal administration. In 2019, the total cost of *Bolsa Família* program was USD₂₀₁₁ 7.4 billion, or BRL₂₀₁₁ 29.1 billion. The annual cost of the program has been historically reported as under 0.5% of the GDP (BRASIL, 2020).

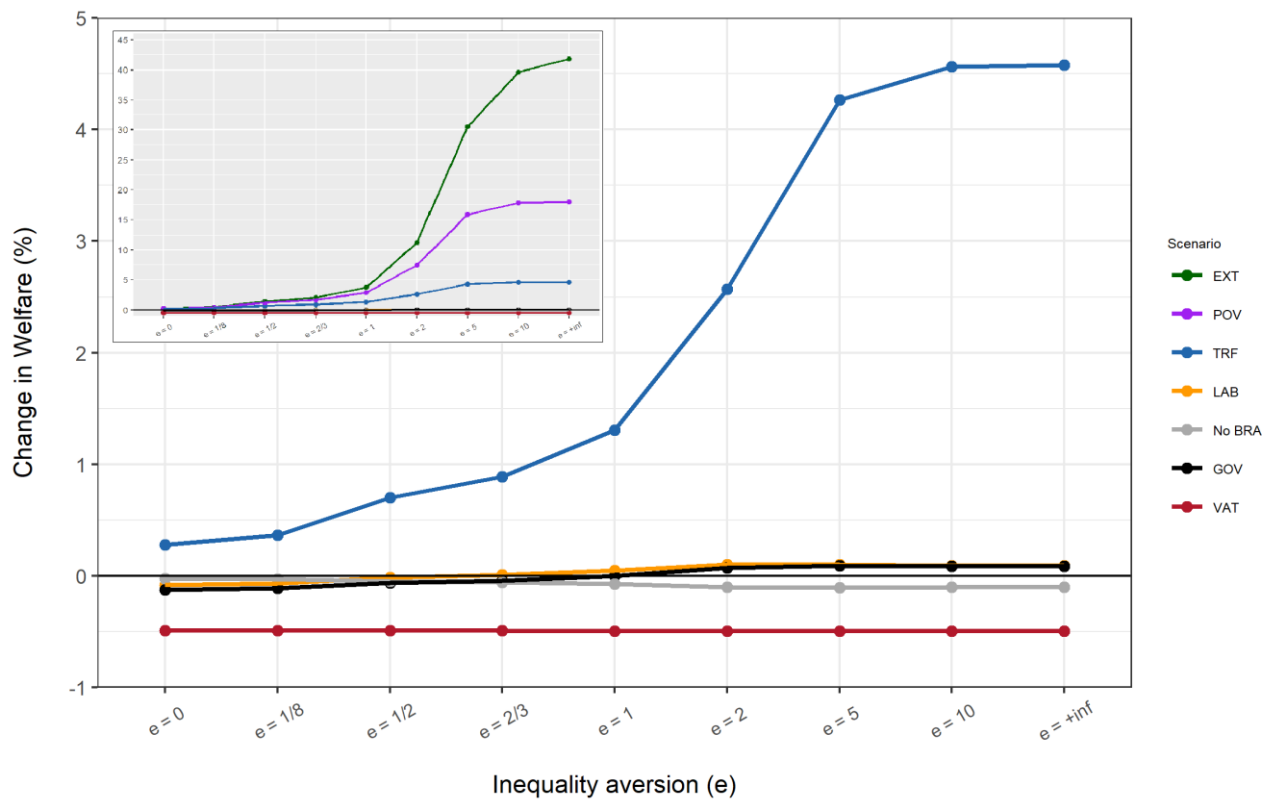


Figure 4. Atkinson Equally Distributed Equivalent (EDE) index by scenario in Brazil. Relative change in welfare to Baseline in 2030 (in %)

Interestingly, when compared to the NoBRA scenario, results in **Figure 4** do not add evidence of the presence of a second dividend, except when higher levels of inequality aversion are accounted. While VAT shows welfare losses for all levels of inequality aversion, LAB shows greater welfare gains than in NoBRA, from the level $\epsilon = 1$ onwards, which indicates a second dividend in its weak form, at least for lower deciles, as seen in **Table 4**. Evidence from the literature of double-dividend in Brazil shows mixed findings -- while Chivari and Miller (2012) found no evidence of a double dividend, Chen and Timilsina (2015) found a second dividend for Brazil when carbon revenue is used to cut labor taxes. When the second dividend is interpreted as GDP gains, our results are in line with the latter, but when interpreted as welfare gains, our results show mixed evidence, with a weak dividend found solely in lower deciles.

Finally, **Table 6** presents the relative changes to baseline scenario for different inequality indexes (Gini and the ratio S80-S20). The Gini index compares the cumulative distribution of the population relatively to the cumulative distribution of income, ranging between 0 (perfect equality) and 1 (perfect inequality). The S80-S20 ratio is the mean income received by the 20% of the higher income households to that received by the 20% lower income ones.

Table 6. Inequality Indexes. Relative change to Baseline in 2030 (in %)

Index	GOV	TRF	POV	EXT	LAB	VAT
Gini	-0.07	-0.45	-0.91	-1.06	-0.08	0.00
S80-S20 ratio	-0.30	-3.37	-10.41	-14.63	-0.28	0.01

As discussed in Silva Freitas et al. (2016), carbon pricing leads to an uneven burden because lower-income households are disproportionately affected. Overall, our results suggest that direct recycling contributes the most to reduce inequality. In GOV, the Gini is roughly affected (-0.07%), while the S80-S20 ratio decreases (-0.30%). In TRF, POV and EXT, the Gini index show greater decrease (-0.45%, -0.91% and -1.06%, respectively), along with the S80-S20 ratio decreases (-3.37%, -10.41% and -14.63%, respectively). In LAB, both Gini and S80-S20 ratio indexes decrease (-0.08% and -0.28%, respectively), while inequality is not reduced in VAT, with both indexes remaining at baseline levels.

Interestingly, these results are in line with Magalhães and Domingues (2013) that found regressive effects of carbon pricing in Brazil and suggest lump-sum transfers as a progressive policy instrument to curb these effects. In addition to the results found in Magalhães and Domingues (2013), this paper shows that slightly progressive effects are also found when recycling is done through rebates on labor taxes, as in LAB scenario.

5. Conclusions

Brazil has a large gap in terms of effective carbon pricing (OECD, 2018) that could be addressed in the context of the ongoing tax reform debate. In our simulations, carbon revenue contributes to the financing of social spending in Brazil, boosting welfare gains, especially for lower income deciles. Differently from previous literature, by valuating the marginal cost of carbon for different regions, we found a moderate GDP growth in Brazil, mainly driven by gains in its trade balance, as a consequence of worldwide carbon pricing.

While assessing for welfare impacts, we note that the source-side impacts prevail, thus leading to progressive effects in lump-sum scenarios or neutralizing regressive effects of the carbon price. In line with most of the literature of double-dividend, a second dividend in its weak form is found when revenue recycling is done through tax rebates on labor income taxes. Although the lack of a more comprehensive representation of the Brazilian tax system is a caveat, results are robust and suggest that this (weak) second dividend is limited to lower income deciles. In none of the scenarios herein simulated a second dividend in its strong form is found.

In this paper we applied a multiple household method, as described in van Ruijven et al. (2015), to increase the representation of the Brazilian households in the multi-regional TEA model.

Our results confirm that the method captures the distributional effects on Brazilian households in the context of a worldwide carbon pricing policy. Heterogeneity within income groups is however not addressed in the current framework, meaning that only the vertical income dimension (across income groups) is captured in the model. Properly accounting for the horizontal dimension (within income groups) would require coupling with microsimulation models or ideally developing an intergenerational framework.

We showed that, although Brazil already has a relatively clean energy mix, carbon pricing helps avoiding lock-in on carbon intensive infrastructure by further promoting biomass in electricity generation and biofuels in the transportation sector. In this paper, only CO₂ energy-related emissions were assessed. Accounting for non-CO₂ gases emissions, which are of paramount importance in Brazil, could be considered in future research. In addition, technological representation is modeled in an aggregated way, with technological change addressed exogenously, a focus of future improvements as well.

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Appendix

Table A.1. Share of households under poverty and extreme poverty condition in each decile (in %)

Households / Income decile	1	2	3	4	5	6	7	8	9	10
POV	78.8	54.6	37.1	18.0	8.5	3.5	0.9	0.1	-	-
EXT	27.3	2.1	0.3	0.1	-	-	-	-	-	-

Note: As in Brazil 1% of the richest concentrate 28,3% of the total income (second higher income concentration in the world), poor households can be found in deciles that are commonly seen as middle/rich (5-8).

Table A.2. Carbon revenue lump-sum transfers. Share of total revenue directed to each decile (in %)

Scenario / Income decile	1	2	3	4	5	6	7	8	9	10
TRF	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
POV	39.1	27.1	18.4	9.0	4.2	1.7	0.4	0.1	-	-
EXT	91.6	7.1	1.1	0.2	-	-	-	-	-	-

Table A.3. Consumer prices and market prices by sector. Relative change to Baseline in 2030 (in %)

	GOV	TRF	POV	EXT	LAB	VAT
Consumer Prices	0.08	0.27	0.27	0.27	0.08	-0.41
Market Prices						
<i>Coal</i>	13.8	14.1	14.2	14.2	13.8	14.2
<i>Oil</i>	0.8	1.0	1.0	1.0	0.8	0.8
<i>Crude Oil</i>	-2.4	-2.4	-2.4	-2.4	-2.4	-1.9
<i>Natural Gas</i>	3.8	4.0	4.0	4.0	3.8	3.9
<i>Electricity</i>	2.2	2.2	2.2	2.2	2.2	2.7
<i>Energy Intensive Industry</i>	0.3	0.3	0.3	0.3	0.3	0.8
<i>Transport</i>	1.2	1.3	1.3	1.3	1.2	1.8
<i>Agriculture</i>	0.1	0.1	0.1	0.1	0.1	0.5
<i>Manufacturing</i>	0.0	0.0	0.0	0.0	0.0	0.5
<i>Services</i>	-0.3	-0.3	-0.3	-0.3	-0.3	0.1

Note: Relative changes to baseline for market prices in real terms based on the Consumer Price Index (CPI).

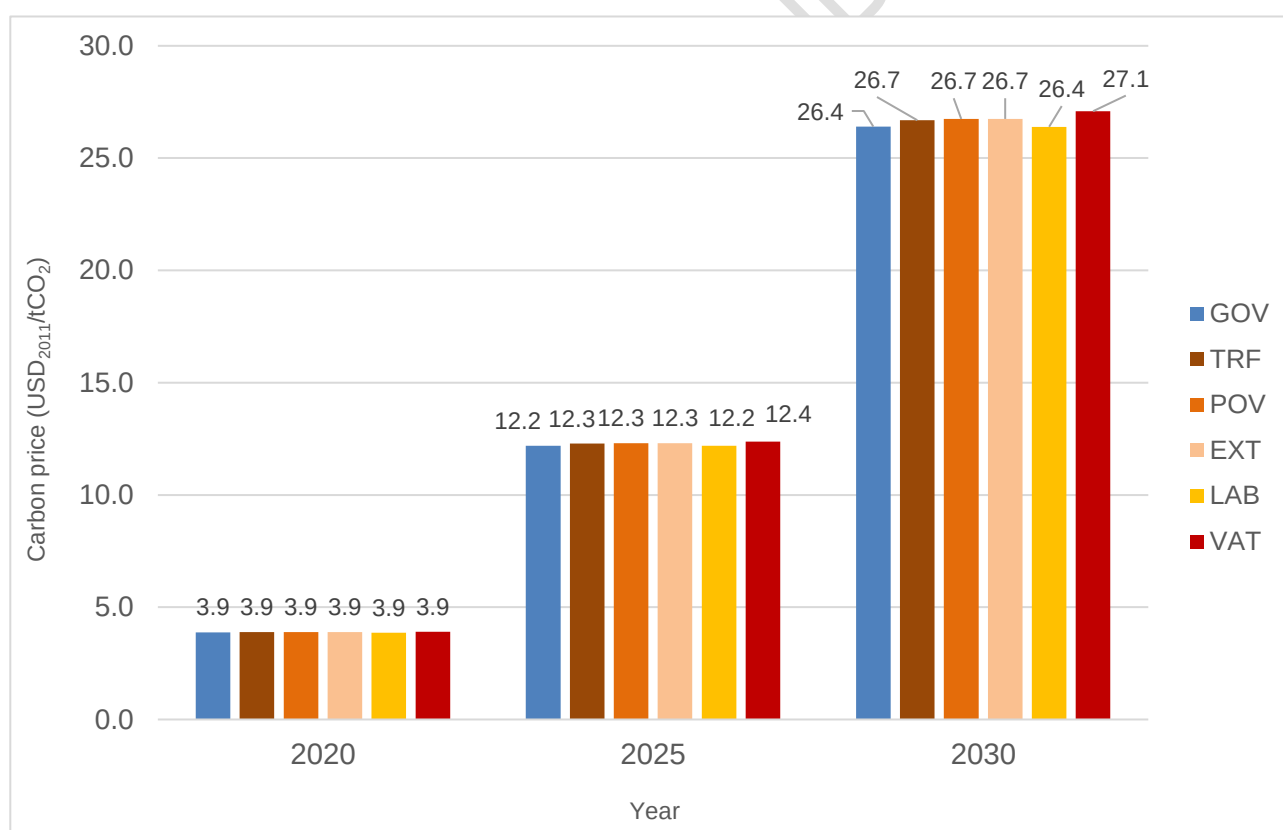


Figure A.1. Carbon prices by scenario (2020-2030). Values in USD₂₀₁₁/tCO₂.

Supplementary Material – Baseline calibration and schematic representation of nestings

The baseline calibration followed a top-down approach. First, we performed runs for the IEO baseline only including the GDP trends. Then, we started calibrating the baseline to achieve the regional emission targets of the IEO projections. To do so, we induced technological change mainly through three mechanisms: (i) changes in elasticities of substitution between non-fossil and fossil fuel sources; (ii) cost penalties for fossil fuels; and (iii) exogenous energy efficiency.

Regarding changes in elasticities, we had to triple the elasticity of substitution between wind and solar power generation and the other sources (it changed from 2 to 6) to increase the model flexibility towards low-emission technologies in the power sector. Trade is modelled in a two level Armington nest with elasticities between 1.25 and 6.00 for the domestic/import trade-off. We usually double these values for trade-offs between different countries. The nested CES structures for each sector are presented in the end of this Supplementary Material (**Figures SM.1 – SM.4**).

In addition to changes in elasticities, cost penalties were assumed in order to limit the use of coal in the power sector and the use of oil in the transport sector for some regions. The parameters for cost penalties are shown in **Table SM.1**. We have also introduced subsidies (negative penalties) for natural gas in China to favor its penetration in the power sector. This was particularly necessary to achieve a consistent representation of the natural gas demand in China in the base year calibration of the GTAP9 Data Base (Aguilar et al., 2016).

Table SM.1: Cost penalty for coal and oil in the IEO baselines

Fuel	Parameter
Coal	$\text{colcost_t}(\text{"usa"}, t) = (1 - 0.10 * (\text{ord}(t)))$;
	$\text{colcost_t}(\text{"chn"}, t) = (1 - 0.08 * (\text{ord}(t)))$;
	$\text{colcost_t}(\text{"eur"}, t) = (1 - 0.02 * (\text{ord}(t)))$;
	$\text{colcost_t}(\text{"ind"}, t) = (1 - 0.12 * (\text{ord}(t)))$;
	$\text{colcost_t}(\text{"anz"}, t) = (1 - 0.08 * (\text{ord}(t)))$;
	$\text{colcost_t}(\text{"oas"}, t) = (1 - 0.01 * (\text{ord}(t)))$;
Oil	$\text{oilcost_t}(r, t) = (1 - 0.05 * (\text{ord}(t)))$;
	$\text{oilcost_t}(\text{"bra"}, t) = (1 - 0.01 * (\text{ord}(t)))$;
	$\text{oilcost_t}(\text{"oam"}, t) = (1 - 0.04 * (\text{ord}(t)))$;
	$\text{oilcost_t}(\text{"afr"}, t) = (1 - 0.08 * (\text{ord}(t)))$;

These changes led us to achieve overall emission targets for 2030, but there were still differences after the runs, with some regions showing different emission paths than the ones from IEO. To replicate the CO₂ emission target for every region of the IEO and WEO projections, we kept the AEEI constant at 1% p.y. for all regions and then introduced an exogenous energy efficiency (gain/loss) parameter (**Table SM.2**).

Table SM.2: Energy efficiency exogenous adjustments in the IEO baseline calibration.

Region	Years				
	2011	2015	2020	2025	2030
USA	1.00	0.94	0.91	0.85	0.83
CAN	1.00	1.06	1.04	1.06	1.02
JPN	1.00	1.03	1.00	1.04	1.01
KOR	1.00	1.04	1.10	1.09	1.10
RUS	1.00	1.07	1.04	1.08	1.07
CHN	1.00	0.88	0.77	0.71	0.72
IND	1.00	1.10	1.02	0.96	1.03
ANZ	1.00	0.99	0.94	0.96	0.97
BRA	1.00	1.21	1.21	1.27	1.34
EUR	1.00	0.90	0.89	0.85	0.87
MEA	1.00	1.06	1.08	1.08	1.08
AFR	1.00	1.05	1.13	1.11	1.00
OAM	1.00	1.05	1.05	1.06	1.01
OAS	1.00	1.07	1.09	1.10	1.05

In **Table SM.2**, the parameters with values lower than 1 represent an increase in energy efficiency, so that the region reduces its energy consumption and emissions. Alternatively, regions with parameters greater than 1 will end-up increasing their energy consumption and emissions. This led us to precisely replicate the emission pathways and to achieve consistent representations of the energy mix for every region. In the end, the level of emissions was achieved by technological change, energy efficiency and fossil fuel penalization.

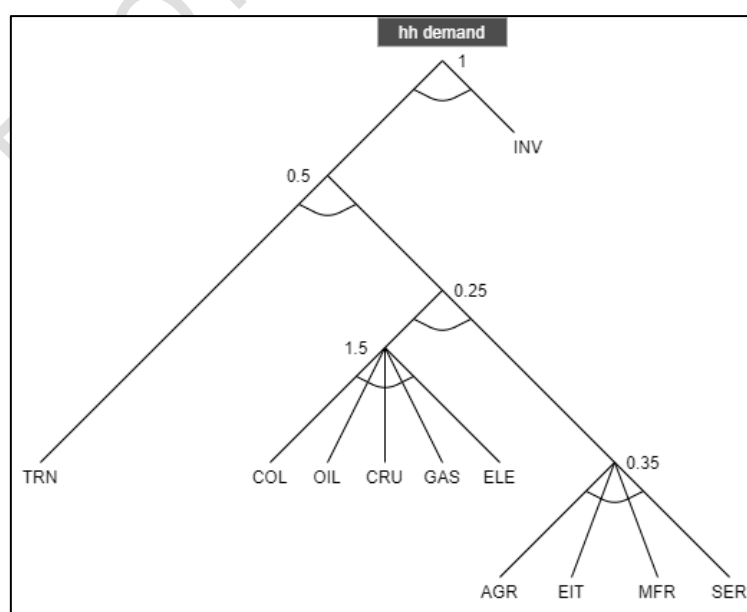


Figure SM.1. Nestings – Household demand.

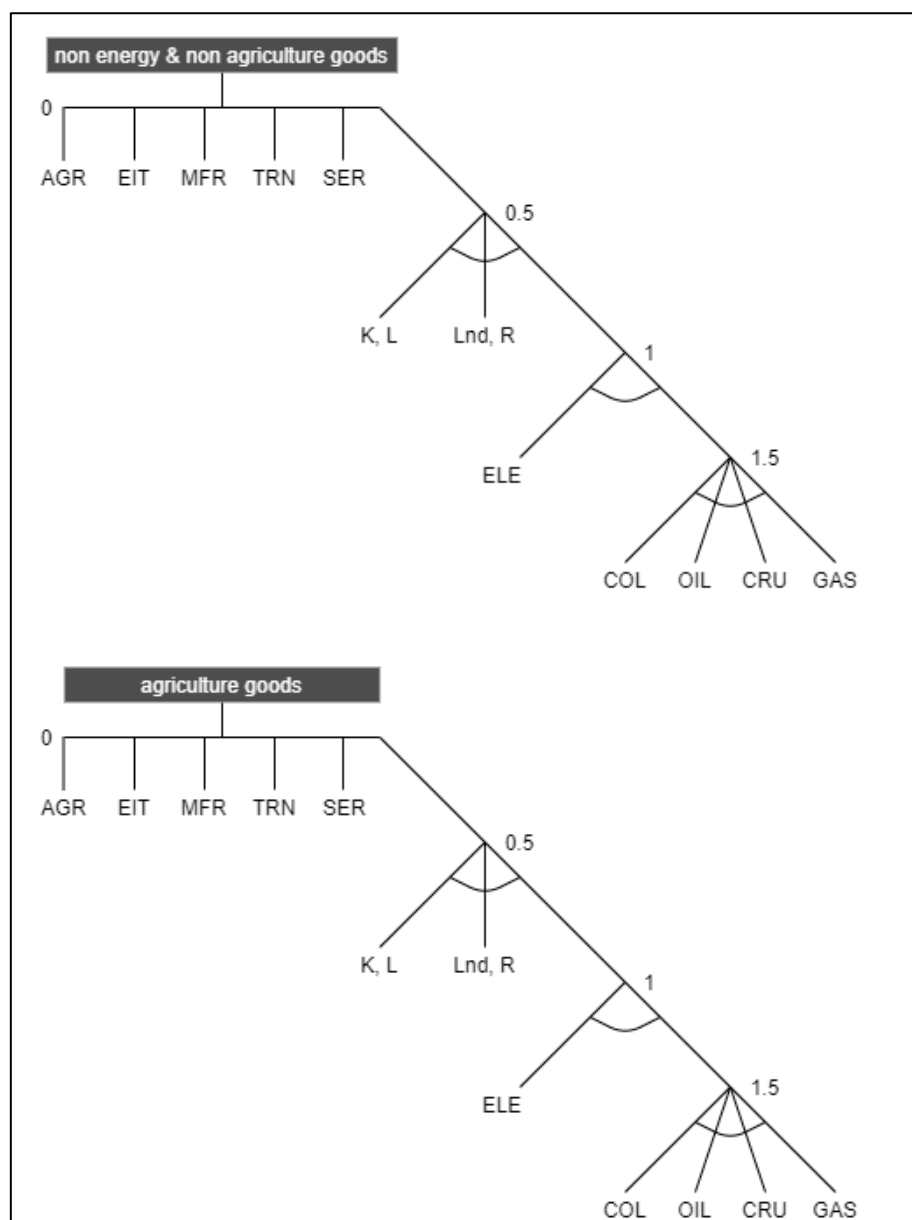


Figure SM.2. Nestings – Goods & Services (Agriculture and other goods).

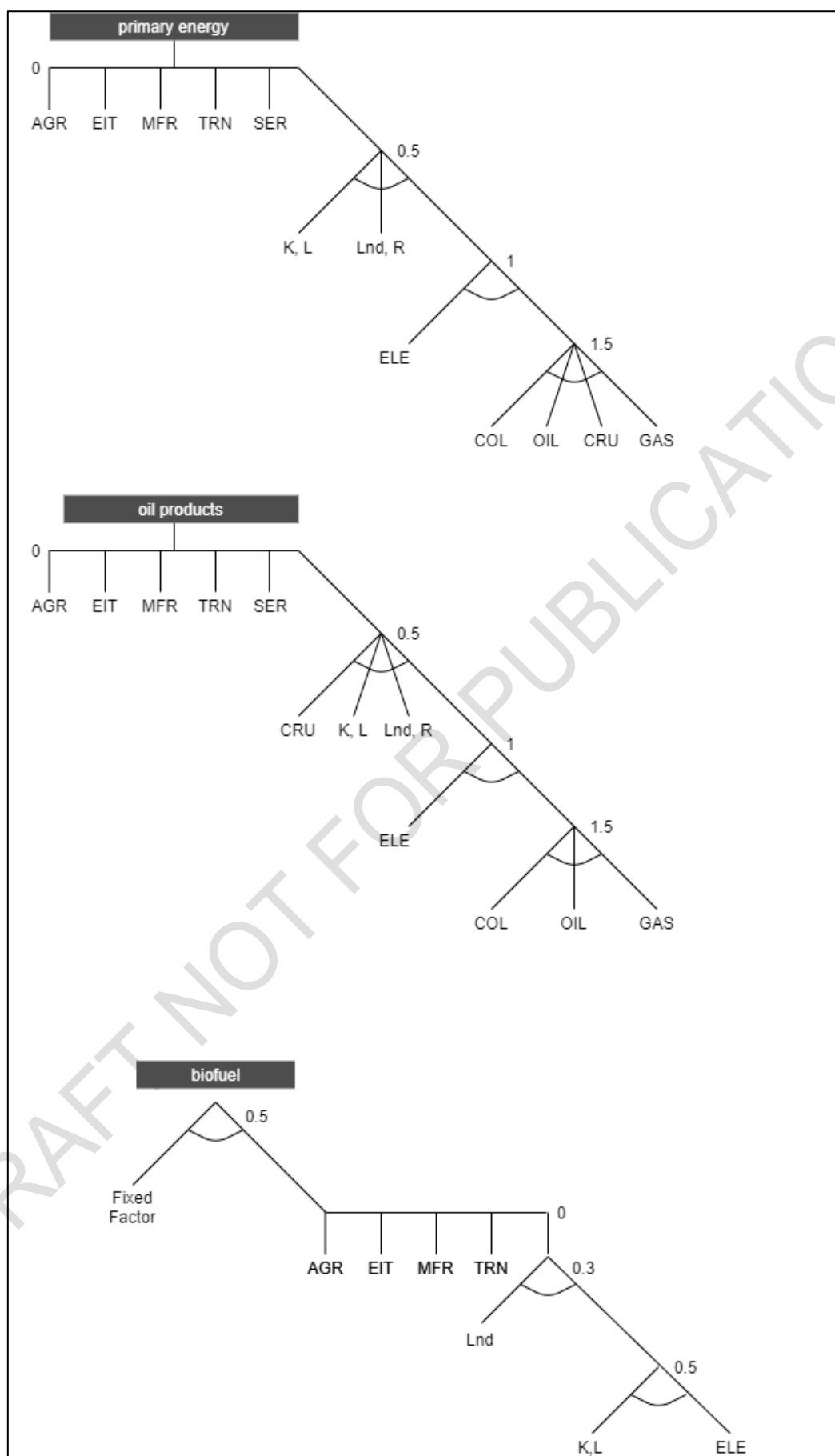


Figure SM.3. Nestings – Primary Energy, Oil products and Biofuels

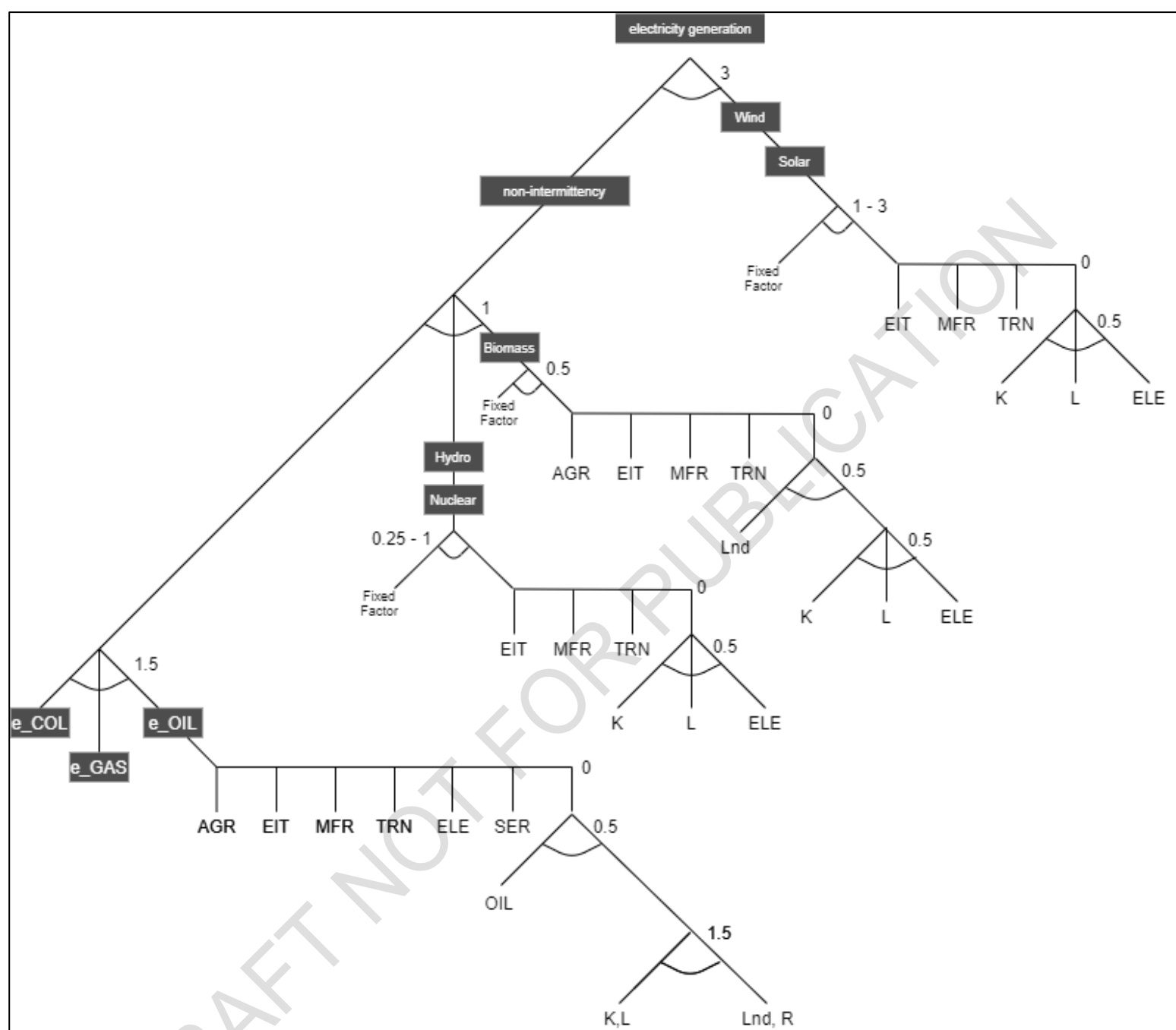


Figure SM.4. Nestings – Electricity generation