The distributional effects of CO_2 pricing at home and at the border on German income groups

Michael Hübler*, Malin Wiese †, Marius Braun ‡, Johannes Damster §

September 28, 2022

Abstract

While climate policy studies are widespread, fully fledged computable general equilibrium (CGE) model analyses of distributional policy effects are rare because the required data and approaches are usually unavailable. To fill this gap, we provide a step-by-step "recipe" for disaggregating a country-specific representative consumer of a CGE model. Using this "recipe", we implement German household survey data in a global CGE model by distinguishing three income groups of the German representative consumer. We find that the negative consumption effect of CO_2 pricing is highest for the low-income group, whereas the negative income effect is highest for the high-income group and exceeds the consumption effect. The low-income group benefits most from (per capita-based redistribution of) carbon pricing revenues and receives social transfers such that poor households can be better off with such climate policies than without them. Similarly, CO_2 pricing of imports at the EU border strengthens these distributional effects and is mainly beneficial for the low-income group.

JEL classifications: C68; F18; Q52; Q54

Keywords: distributional effects; consumer split; climate policy; border carbon adjustments; CBAM; Germany

*Corresponding author, email: michael.huebler@agrar.uni-giessen.de, phone: +49-641-99-37052, fax: +49-641-99-37059; Agricultural, Food and Environmental Policy, Institute for Agricultural Policy and Market Research, Center for International Development and Environmental Research (ZEU), Justus Liebig University Giessen, Senckenbergstr. 3, 35390 Gießen, Germany.

†University of Potsdam, Germany.

‡Justus Liebig University Giessen, Germany.

§Justus Liebig University Giessen, Germany.

1 Introduction

For public policy discussions, it has become increasingly important to extend the analysis of policy-induced welfare effects towards a deeper understanding of distributional (inequality) effects across households (consumers). Thus, recent economic studies have examined the distributional effects of climate policy on households with different income levels to obtain socially sensitive insights for policymakers with mixed results (see the review and the meta-analyses by Wang et al. (2016) and Ohlendorf et al. (2021)).

In this article, we make three contributions. First, we contribute to the literature by applying an elaborated method to the newest available data with a regional focus on Germany. Previous studies on distributional effects applied statistical methods to micro (household) data (Wang et al. (2016); Ohlendorf et al. (2021)), sometimes by combining macroeconomic data generated by numerical models with microeconomic (household) data (for an overview, see Bourguignon and Bussolo (2013)), e.g., via the integration of a microeconomic (household) approach in a macroeconomic model (e.g., Lanbandeira et al. (2009); Rausch et al. (2011); Dissou and Siddiqui (2014); Goulder et al. (2019)), particularly via so-called microsimulations (e.g., Landis et al. (2009); Buddelmeyer et al. (2012)).

The disaggregation of representative consumers in computable general equilibrium (CGE) models is a novel and still rare endeavor. Böhringer et al. (2021) summarize the distributional effects of climate policy for meeting the goals of the Paris Agreement in Germany (UOL model), Norway (SNoW model), Spain (BC3 model), India (IEG model), and 11 or 21 EU countries (JRC-GEM-E3-EUROMOD-ITT and CEPE model) (for results, see below). Cunha Montenegro et al. (2019) split consumers in EU countries into five income groups to study EU climate policies in a CGE model. In their CGE model, Kim and Kim (2003) distinguish among 14 Korean regions and ten income groups to study urban development strategies. In another CGE model, Jung et al. (2017) distinguish among 20 Korean income groups and show that skill- and capital-biased technical progress increases inequality. In a CGE model of China, Huang et al. (2019) combine income groups with a rural–urban distinction between households and find that the wise redistribution of climate policy revenues can reduce inequality.

Contributing to this literature, we derive consumer income groups from German household data and integrate them into a new straightforward CGE model calibrated to the newest GTAP 10[1] data (Aguiar et al., 2019) for the benchmark year 2014 (sector aggregation derived from Pothen and Hübler (2018)). As a result, complex general equilibrium (policy) effects are directly and explicitly included in the distributional analysis, and different from statistical micro data studies, consumption expenditure and income effects are calculated directly and simultaneously within the general equilibrium.

Second, as a methodological contribution that renders consumer disaggregation easily accessible, applicable and transparent, we introduce a model-independent step-by-step "recipe" for modelers who intend to implement different income groups of a representative consumer in an intuitive way.

Third, as a policy contribution, we not only investigate CO_2 pricing within Germany as a member of the European Union Emissions Trading Scheme (EU ETS) but also at the EU ETS border: the new Carbon Border Adjustment Mechanism (CBAM) planned for implementation in the EU in 2026 after a transition phase from 2023 to 2025.[2] In this way, we contribute to the model-based literature on carbon border adjustment policies (see the model comparison study summarized by Böhringer et al. (2012)), which has so far, to the best of our knowledge, not examined distributional effects across heterogeneous consumers within countries.

Based on the input-output data and the actual CO_2 emissions reductions in 2014, we find the following results for three German consumer groups: low, middle and high income. (We compute descriptive statistics for five and ten income groups too. Our approach can be used to generate any reasonable number of consumers.)

First, whereas domestic CO_2 pricing is beneficial for low-income households (1.3% welfare surplus), it is disadvantageous for high-income households (1.2% welfare loss) and to a smaller extent for middle-income households (0.5% welfare loss). While this distributional pattern (with negative relative welfare effects increasing in income) is in line with that in other studies (e.g., Siriwardana et al. (2013); Sajeewani et al. (2015)), it is surprising that the low-income group *gains* from climate policy. This occurs in our analysis because all income groups receive the same amount of revenue from CO_2 pricing on the basis of a fair per capita redistribution scheme (cf. Klenert et al. (2018) and the discussion/implementation of climate bonus payments in Germany and Austria), which dominates the expenditure and income effect (explained in the following section)

[1] Global Trade Analysis Project, consistent global input-output database, version 10.

[2] https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3661. Such a policy levies a CO_2 price on imports from countries without CO_2 pricing according to the imports' total CO_2 contents from all production steps and intermediate goods inputs. As a result, imports are subject to the same CO_2 price as if they were produced domestically under the established emissions pricing scheme.

in the low-income group. Additionally, low-income households receive substantial social redistribution transfers that dampen any climate policy-induced effects. A positive low-income effect also occurs in the CGE model analysis of the United States of America (USA) by Goulder et al. (2019). Likewise, Cunha Montenegro et al. (2019) find positive income growth effects for the low-income group of EU countries under specific EU climate policy scenarios. Lanbandeira et al. (2009) even find a positive effect of energy taxation for *all* income groups, with larger effects for poorer households in Spain.

Second, in accordance with the outcomes for the EU, Canada and the USA (Böhringer et al. (2021); Dissou and Siddiqui (2014); Goulder et al. (2019)), in our results, consumption expenditure effects are regressive. In particular, domestic climate policy causes a slightly stronger consumption price index increase for low-income German households than for middle-income German households, whose consumption price index increase is in turn slightly stronger than that for high-income households (across all groups, approximately 0.8%). Feindt et al. (2021), by contrast, find a neutral or progressive effect of carbon pricing within EU countries.

Third, (factor) income effects, on the contrary, are progressive, as shown for the EU, Canada and the USA (Böhringer et al. (2021); Dissou and Siddiqui (2014); Goulder et al. (2019)). This occurs because richer households own a larger portion of the production factors than poorer ones do, and factor prices are often dampened by climate policy. In our study, natural resource rents, including rents from fossil fuel ownership, drop sharply (by approximately 48.1%) due to CO_2 pricing. Labor income and, to a slightly larger extent, capital income decline moderately (by approximately 0.8% each). Land rents, on the other hand, increase significantly (by approximately 3.8%): one can imagine that renewable energy expansion requires land and raises land rents, although this is not directly observed in the model. The land rent increase, however, is dominated by declining prices for the remaining factors.

Fourth, similar to domestic CO_2 pricing, additional CO_2 pricing of imports at the EU border (CBAM) (with equal per capita-based distribution of CBAM revenues across the income groups and without CO_2-content-related subsidies for exports) is more beneficial for the low-income group (approximately 0.1 percentage point gain) than for the middle-income group and the high-income group (no clear improvement). Overall, it strengthens the distributional effects of domestic CO_2 pricing and dampens the climate policy-induced welfare losses of Germany and the EU ETS countries.

Fifth, if policymakers were to redistribute the revenues from domestic CO_2 pricing between high-, middle- and low-income groups such that all groups become roughly equally compensated and the welfare loss is close to the economy-wide loss (approximately 0.5%) in all groups, then ceteris paribus, the low-income group will receive 13% of the revenues, the middle-income group will receive 30% and the high-income group will receive 57%.

The article proceeds as follows. Section 2 explains our model-independent approach to disaggregating a typical representative consumer based on household data. We choose Germany, 17 goods and three income groups for an exemplary application. Section 3 describes a new corresponding CGE model with consumption, production, trade, complex intermediate goods linkages and CO_2 emissions. The consumer split derived in Section 2 enters this model here. Section 4 analyzes the distributional effects of CO_2 pricing in Germany and at the EU border based on this model. It discusses the robustness and the implications of the results. Section 5 concludes the article. Appendix A provides further details and statistics illustrating consumer disaggregation. Appendix B provides further details, numbers and figures characterizing the model.

2 Disaggregation

The following procedure can be applied to analyze the distributional effects of policies on income groups in a country or region of a (macroeconomic) model. We start with a formal definition of consumption and relevant sectors. Then, we explain the disaggregation of consumer income groups and present the disaggregation results for Germany as an illustrative example. For further details on the data sources, data aggregation, sector correspondences and descriptive results, please see Appendix A.

2.1 Foundation

This subsection describes a standard general description of consumption that can be part of any economic model. This will be the foundation of the consumer disaggregation procedure.

Following standard microeconomic theory and the model setup in Pothen and Hübler (2018), ch. 2.2, in each region s, a representative consumer chooses the optimal consumption bundle C_s of m goods and services (in the following, goods always include services) indexed as i and measured as output quantities $Y^{DM}_{C,s,i}$ to maximize utility derived from consumption C_s. P_s indicates a corresponding price index for the consumption bundle of goods. The bundle $Y^{DM}_{C,s,i}$ contains goods that are domestically produced in the same region/country s or imported from other countries/regions r. Domestically produced and imported goods are usually combined via a constant elasticity of substitution (CES) function. Hence, the consumer has implicit (nested) CES preferences over goods i. The exemplary CES functions used for the model application of this article are displayed in Appendix Figures B1 and B2.

According to the Solow growth model philosophy, the representative consumer spends a fixed fraction ξ_s of her total income I_s on consumption, while the remaining fraction $(1-\xi_s)$ is saved, i.e., savings expressed in pecuniary terms read $P_s S_s = (1-\xi_s) I_s$. Thus, the value of total consumption is maximized, and the balanced budget condition *expenditures = income* always holds.

$$\max_{Y^{DM}_{C,i,s}} \; C_s, \; C_s = CES_i(Y^{DM}_{C,s,i}) \tag{1}$$
$$\text{s. t.} \;\; P_s C_s = \xi_s I_s$$

The representative consumer of each region s is endowed with region-specific quantities of the production factors (inputs), for example, capital $\bar{K}_s$, labor $\bar{L}_s$, land $\bar{N}_s$ and (natural) resources $\bar{R}_{i,s}$ (where resources are available only in relevant sectors i, such as the mining of fossil fuels). The consumer supplies them inelastically and receives (factor income) Θ_s depending on the corresponding endogenous factor prices P^K_s, P^L_s, P^N_s and $P^R_{s,i}$ (Pothen and Hübler, 2018):

$$\Theta_s = P^K_s \bar{K}_s + P^L_s \bar{L}_s + P^N_s \bar{N}_s + \sum_i P^R_{s,i} \bar{R}_{s,i} \tag{2}$$

The consumer also receives net transfers Ξ_s (from the government). The revenues for the transfers are increased by levying taxes or selling emissions allowances and decreased by granting subsidies. Furthermore, a given (current account) deficit Δ_s can be taken into account (Pothen and Hübler, 2018):

$$I_s = \Theta_s + \Xi_s + \Delta_s \tag{3}$$

Real consumption $\frac{\xi_s C_s}{P_s}$ reflects utility. Its change can be used as a welfare measure of a policy or shock compared with the benchmark situation, where P_s can be interpreted as a true-cost-of-living index (Pothen and Hübler, 2018). Consequently, a welfare effect includes a change in consumption combined with a change in the price level and composition of the consumed goods.

2.2 Approach

To disaggregate a representative consumer into n consumption groups, we need to split all relevant parameters of equations 1 to 3 into n parts. For this purpose, let us define the set of n consecutive integer numbers $\Phi_s = \{1, .., n\}$ and the consumer group dimension ϕ.

By drawing on (household) data for all region-specific goods consumption expenditures $Y^{DM}_{C,s,i}$, we will need to find n share parameters $\lambda^{C}_{s,i,\phi}$ $\forall$ $\phi \in \Phi_s$ with $\sum_\phi \lambda^{C}_{s,i,\phi} = 1$ that allow us to split $Y^{DM}_{C,s,i}$ into n parts. Furthermore, we need to split savings $(1-\epsilon)I_s$ with $\lambda^{\epsilon}_{s,\phi}$ $\forall \phi \in \Phi_s$ such that $\sum_\phi \lambda^{\epsilon}_{s,\phi} = 1$. Similarly, on the income side, we need to find $\lambda^{K}_{s,\phi}$ with $\sum_\phi \lambda^{K}_{s,\phi} = 1$, which allows us to split $\bar{K}_s$ into n parts. Likewise, we need to determine $\lambda^{L}_{s,\phi}$ with $\sum_\phi \lambda^{L}_{s,\phi} = 1$ for $\bar{L}_s$, $\lambda^{N}_{s,\phi}$ with $\sum_\phi \lambda^{N}_{s,\phi} = 1$ for $\bar{N}_s$, and $\lambda^{R}_{s,i,\phi}$ with $\sum_\phi \lambda^{R}_{s,i,\phi} = 1$ for $\bar{R}_{s,i}$. Finally, we need to identify $\lambda^{\Xi}_{s,\phi}$ with $\sum_\phi \lambda^{\Xi}_{s,\phi} = 1$ for net transfers Ξ_s and $\lambda^{\Delta}_{s,\phi}$ with $\sum_\phi \lambda^{\Delta}_{s,\phi} = 1$ for deficits Δ_s.

As a result, equations 1 to 3 can be rewritten n times for all $\phi \in \Phi_s$ in each region s subject to a consumer split. The aggregate expenditures and income replicate the original situation with just one consumer.

2.3 Sectors

Table 1
Sectors covered by the analysis

Sector	Description
$AGRI$	Agriculture
$COAL$	Coal
$CRUD$	Crude oil
$NGAS$	Natural gas
$PETR$	Refined petroleum
$FOOD$	Food production
$MINE$	Mining
$PAPR$	Paper and pulp
$CHEM$	Chemicals, rubber and plastic
$NMMS$	Mineral products nec.
$IRST$	Iron and steel
$NFMS$	Non-ferrous metals
$MANU$	Manufacturing
$ELEC$	Electricity
$TRNS$	Transport
$CONS$	Construction
$SERV$	Services
($INVS$	Investment)

Sectors (goods and services) i or, alternatively, j defined by Pothen and Hübler (2018), Table A2.

For the following exemplary disaggregation procedure based on household data, we refer to the 18 sectors (goods and services) defined by Pothen and Hübler (2018). Each sector produces one good or service that the representative consumer purchases. The investment ($INVS$) sector is essential for any economic general equilibrium model. Consumers (households), however, do not spend money on investment. Instead, they save part of their income, which will be converted into investments by financial intermediaries, such as banks. Consequently, the investment sector is not included in the household data.

2.4 Data

We use the 2013 household income and expenditure survey for Germany ("Einkommens- und Verbrauchsstichprobe", EVS) from the Research Data Centre (RDC) of the Federal Statistical Office and Statistical Offices of the Federal States (FDZ, 2021), as it includes very detailed information on income and its use in various expenditure categories. This survey covers 52,421 German households, which are extrapolated to 38,559,825.4 households with the provided extrapolation factors so that the survey is representative of Germany. The data are defined according to the SEA (German: "Systematik der Einnahmen und Ausgaben der privaten Haushalte") classification (FDZ, 2019) following the Classification of Individual Consumption by Purpose (COICOP) of the United Nations and the more deeply differentiated European version (Statistisches Bundesamt, 2013).

For the global input-output structures with (intermediate and final goods) trade flows, international transport margins, CO_2 emissions, subsidies, taxes, tariffs, and so forth, we use the latest version 10 of the Global Trade Analysis Project (GTAP) data (Aguiar et al., 2019) for the year 2014 covering most countries in the world.[3] The aggregation of the GTAP 10 sectors to our model sectors is detailed in Appendix Table A1.

2.5 Procedure

This subsection provides a "recipe" for modelers who aim to disaggregate a representative consumer to conduct a distributional policy analysis. The consumption data of each household are transferred from the utilized classification based on the purposes of product (goods) categories to the classification based on production sectors, which are then aggregated to the production sectors in the model. To obtain data on income and consumption for different income groups, a consumption and expenditure survey (such as the EVS) is required. Drawing on such a survey, the following procedure can

[3] More information can be found at https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx.

be applied to any country or region. For a (macroeconomic) model implementation, a consistent (macroeconomic) database (such as GTAP) is required. Another prerequisite is a country- or region-specific consumption interdependence table that links the aggregate consumption pattern to the available production sectors.

To disaggregate the representative consumer, we proceed in eight steps:

1. First, we need to transfer the data on consumption by purpose into product (goods) categories by sector. To this end, we apply the consumption interdependence table of the German Federal Statistical Office (Statistisches Bundesamt, 2020) to transfer the product categories from the SEA classification (used in the EVS) to the Statistical Classification of Products by Activity (CPA) based on economy-wide input-output data.[4] As the consumption interdependence table includes only 42 consumption categories (SEA classification), the consumption data are first aggregated to these categories and then transformed into the 85 production categories (CPA classification) resulting from the consumption interdependence table.

For each region s with a representative consumer that we would like to split, following Kronenberg (2010), we define $Y^G_{C,s,j}$ as the total consumption by purpose j (SEA) and $Y^H_{C,s,i}$ as the total consumption of goods category i (CPA). The given consumption interdependence table consists of the matrix $\mathbf{A}$, where the respective element $a_{s,i,j}$ contains the absolute amount of $Y^G_{C,s,j}$, which is mapped onto $Y^H_{C,s,i}$. We assume that the consumption of each household by purpose is distributed across goods categories with the same conversion coefficients.[5] To calculate the goods consumption $Y^H_{C,s,i,\psi}$ of each household ψ, we proceed in two steps. First, we determine the conversion coefficients $\bar{a}_{s,i,j}$, i.e., the shares of consumption by purpose j that can be mapped onto goods category i:

$$\bar{a}_{s,i,j} = \frac{a_{s,i,j}}{\sum_j a_{s,i,j}} \tag{4}$$

Second, we apply these conversion coefficients to the consumption by purpose j. This yields the consumption of household ψ in each goods category i:

$$Y^H_{C,s,i,\psi} = \sum_j \bar{a}_{s,i,j} Y^G_{C,s,j,\psi} \tag{5}$$

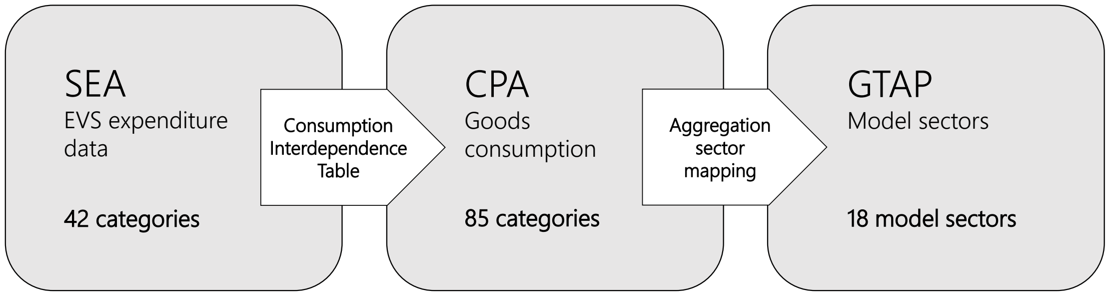
[4] See Kronenberg (2010), who also uses the consumption interdependence table to transform the consumption data into sectoral data for Germany.

[5] We assume that these structural differences in the consumption linkage (not in the consumption structure itself) between households average out, as they are aggregated to relatively large groups.

In step 7, we will aggregate households into income groups.

2. In the next intermediate step, we aggregate the obtained values for the goods categories into the corresponding model sectors; see Section 2.3 and Appendix Table A2 for the sector mapping. In this procedure, we follow Rueda-Cantuche et al. (2020), who discuss how to transfer the input-output tables of the EU classification to GTAP and the concordance tables provided by GTAP.[6] Figure 1 illustrates steps 1 and 2.

Figure 1
Conversion and aggregation of sectors (goods)



Conversion and aggregation steps from the consumption (goods) expenditures data of the household survey to the required model sectors. EVS denotes “Einkommens- und Verbrauchsstichprobe”, SEA denotes “Systematik der Einnahmen und Ausgaben der privaten Haushalte”, CPA denotes “Statistical Classification of Products by Activity”, and GTAP denotes “Global Trade Analysis Project”.

3. Now, we calculate the available income categories in the EVS: labor income, capital income and net transfers (transfers with deducted taxes). All data items used to calculate the disposable income[7] are distributed to these three categories following the suggestions by the UNECE (2011). The household data (EVS) usually contain various income sources that can be attributed to factor income from providing labor or capital. Net transfers include tax revenues generated by the government minus subsidy payments redistributed to the households.[8] Appendix Table A3 displays the assignment of the EVS data to income categories.

4. Next, we calculate the savings of each household based on the respective EVS data. For details, see Appendix Table A4.

5. To render the data household size-independent, we follow Statistisches Bunde-

[6]The concordance tables can be accessed here: https://www.gtap.agecon.purdue.edu/databases/contribute/concordinfo.asp. In our case, the CPA goods categories can in general be distributed to one model sector and do not need to be divided into more sectors. Crude petroleum and natural gas (no. 06), as an exception, is distributed to the model sectors of crude oil ($CRUD$) and natural gas ($NGAS$). The required consumption data are usually available in the household data (here, available in the EVS). For more details, see Appendices A.2 and A.3. Furthermore, as no consumption is assigned to the non-ferrous metals ($NFMS$) sector, 50% of the resulting iron and steel ($IRST$) sector data are assigned to the $NFMS$ sector, assuming that the $NFMS$ consumption is distributed in the same way as the $IRST$ consumption.

[7]Available income after deducting taxes.

[8]The EVS data also contain specific minor income types that can be assigned neither to capital nor to labor income. These income types are assigned to net transfers.

samt (2018) and draw on the Organisation for Economic Co-operation and Development (OECD) equivalence scale (OECD, 2013) to obtain per capita values; see Appendix Section A.4. With the help of this equivalence scale, we calculate household-specific weighting factors that will be used in the next step.

6. Next, we create the desired number of n income groups.[9] For the creation of income groups, the households are sorted from low to high by their equivalent income, i.e., the households' disposable income divided by the weighting factors obtained in the previous step. Then, we create n groups with equal size (sum of the OECD weighting factors multiplied with the extrapolation coefficients) such that each group represents the same equivalent number of people. In our exemplary application, we distinguish between three German income groups representing low-, middle- and high-income.

7. Building on the previous steps, we are now able to aggregate the total consumption and income values and shares for each income group. In this aggregation procedure, we determine the sum of the resulting income $X_{s,f,\phi}$ from sources indexed f and consumption $Y^{DM}_{C,s,i,\phi}$ of goods indexed i over income groups indexed ϕ in country (region) s. We add up the indexed households ψ weighted with their extrapolation factors μ_ψ within each income group:[10]

$$X_{s,f,\phi} = \sum_{\psi \in \phi} X_{s,f,\psi}\ \mu_\psi\ , \quad Y^{DM}_{C,s,i,\phi} = \sum_{\psi \in \phi} Y^{DM}_{C,s,i,\psi}\ \mu_\psi\ , \quad S_{s,\phi} = \sum_{\psi \in \phi} S_{s,\psi}\ \mu_\psi \tag{6}$$

This sum can, in general, differ from the total values of the database (GTAP) underlying the model under scrutiny. For this purpose, we calculate the share parameters $\lambda^X_{s,f,\phi}$ and $\lambda^C_{s,i,\phi}$ for the n income groups for each of the k income sources f and each of the m goods (sectors) i as defined in Section 2.2. Based on the absolute savings values $S_{s,\phi}$, the calculation of the savings shares $\lambda^S_{s,\phi}$ across income groups ϕ is straightforward. This yields the *vertical distribution* of income and expenditures:

$$\lambda^X_{s,f,\phi} = \frac{X_{s,f,\phi}}{\sum_{\phi=1}^{n} X_{s,f,\phi}}\ , \quad \lambda^C_{s,i,\phi} = \frac{Y^{DM}_{C,s,i,\phi}}{\sum_{\phi=1}^{n} Y^{DM}_{C,s,i,\phi}}\ , \quad \lambda^S_{s,\phi} = \frac{S_{s,\phi}}{\sum_{\phi=1}^{n} S_{s,\phi}} \tag{7}$$

The household data (EVS), however, usually do not provide information on income from

[9] In general, any number of income groups can be created.

[10] We do not need to apply the OECD weighting factors here as all groups have the same size. Therefore, multiplying each data position by the corresponding OECD weighting factor results in the same shares as dividing the absolute numbers by the equivalent size (which is the sum of the weighting factors). Furthermore, because households are assigned to only one income group, the (equivalent) sizes of the groups differ slightly. Therefore, we correct the values by multiplying them with the number of people that should be in each group and divide by the number of people that are actually in each group.

the production factors of land or natural resources. Likewise, we lack macroeconomic information on the distribution of these production factors across public and private consumers and across income groups. Therefore, by default we distribute them in the same way we distribute total consumption expenditures (referring to subsection 2.2, $\sum_i \lambda^C_{s,i,\phi} = \lambda^N_{s,\phi} = \sum_i \lambda^R_{s,i,\phi}$). Then, we vary the distribution of land and resources income shares across the income groups in a sensitivity analysis (see Section 4.4).

8. Finally, we apply these share parameters to the model summarized in Section 3. Each corresponding absolute value of income, savings or expenditure in the model data is split into n values for n income groups. As a result, the disaggregated model data will exactly add up to the original absolute values, and the underlying (general) model equilibrium is restored, including across the new income groups.

Referring to the nomenclature of Section 2.1, we apply the share parameters $\lambda^X_{s,f,\phi}$ and $\lambda^S_{s,\phi}$ obtained from the household data (EVS) to each income source, capital and labor income (K, L) as well as net received transfers (Ξ) and to savings ($(1-\xi_s)I_s$) given by the data in the model.[11] Likewise, we apply the share parameters $\lambda^C_{s,i,\phi}$ to each expenditure type $Y^{DM}_{C,s,i}$ of each good i in the model. The remaining components required for a (macroeconomic) model implementation, such as current account deficits (Δ_S), need to be taken from a separate (macroeconomic) database (GTAP).[12]

In a similar vein, we calculate the share parameters $\iota^X_{s,f,\phi}$ and $\iota^C_{s,i,\phi}$ referring to equations 1, 2 and 3 that represent the distribution of expenditures across various goods i and income across several income sources (horizontal distribution). In our application, these share parameters do not enter the model but are displayed for illustrated purposes in the next subsection. In other applications, they may enter the model calibration. Furthermore, drawing on the household data on total income, total expenditures and total savings, we can easily calculate the fixed fraction of total income that the representative consumer spends on consumption $\xi_{s,\phi}$, while the remaining fraction $(1-\xi_{s,\phi})$ is saved. This yields the *horizontal distribution* of income and expenditures:

$$\iota^X_{s,f,\phi} = \frac{X_{s,f,\phi}}{\sum_{f=1}^k X_{s,f,\phi}}, \quad \iota^C_{s,i,\phi} = \frac{Y^{DM}_{C,s,i,\phi}}{\sum_{i=1}^m Y^{DM}_{C,s,i,\phi}}, \quad \xi_{s,\phi} = \frac{P_s C_{s,\phi}}{I_{s,\phi}} \tag{8}$$

[11]In our exemplary model application, net received transfers $\xi_{\phi,s}$ are implemented in the model in absolute terms and adjusted to add up to zero across income groups ϕ. As a result, the transfers are neutral with regard to the benchmark model equilibrium.

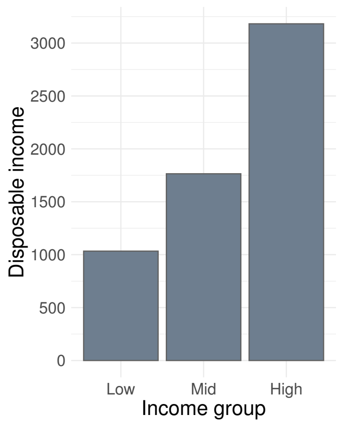
[12]In our implementation, the data on current account deficits (surpluses) are taken from GTAP and held constant throughout the analysis.

2.6 Results

For the interpretation of (macroeconomic) policy results, it is helpful to understand the underlying (microeconomic) household characteristics first. For this purpose, in the following illustrations, we present the distribution of (private) disposable income across income groups (ϕ), the vertical and horizontal distribution of income sources that are available in the EVS: capital income, labor income and net received transfers ($f \in \{K, L, \Xi\}$), and the distribution of income across consumption and savings. Then, we present the vertical and horizontal distribution of consumption across the 17 consumption goods (sectors i) defined in Section 2.3.

In the following application, we distinguish three income groups ($n = 3$), for which Appendix A.7 provides further descriptive results. We calculate the distribution of income and private consumption across goods (sectors) i for five and ten income groups ($n = 5$, $n = 10$); see Appendix A.8. According to the descriptive results, the distribution pattern is qualitatively similar when there are more than three income groups and is therefore omitted in the following model application and policy analysis for the sake of simplicity.

Figure 2
Distribution of total German income



Distribution of the mean equivalent disposable income (total disposable income divided by the number of equivalent people based on the OECD scale) per month of the 52,421 German households in the survey across income groups in euros. Data source: authors' own calculation drawing on data from the Research Data Centre (RDC) of the German Federal Statistical Office and Statistical Offices of the Federal States, "Einkommens- und Verbrauchsstichprobe" 2013, base file 5 (FDZ, 2021).

Figure 2 displays the mean equivalent disposable income of each income group. Notably, the increase in disposable income from the middle- to the high-income group is larger than that from the low- to the middle-income group.

Figure 3 shows the horizontal distribution of income sources (Appendix Table A5 provides the corresponding numbers). The low-income group receives 36% of its income via net transfers from the government. A small share (7%) is obtained from capital, while the largest share (57%) is earned from labor. By contrast, the value of the taxes the middle-income group pays is slightly higher than the value of the governmental support it receives (net transfers share of –2%). The group's share of capital income (14%) is more than twice as large as that of the low-income group, while the former's labor income contributes by far the largest share to overall income (88%). The capital income share of the high-income group (17%) is slightly higher than that of the middle-income group. In absolute values, however, it is substantially larger because the former's disposable income is nearly twice as high as that of the latter (see Table A5). As expected, the high-income group is a significant net transfer payer (–18%).[13]

Figure 3
German income sources by income group

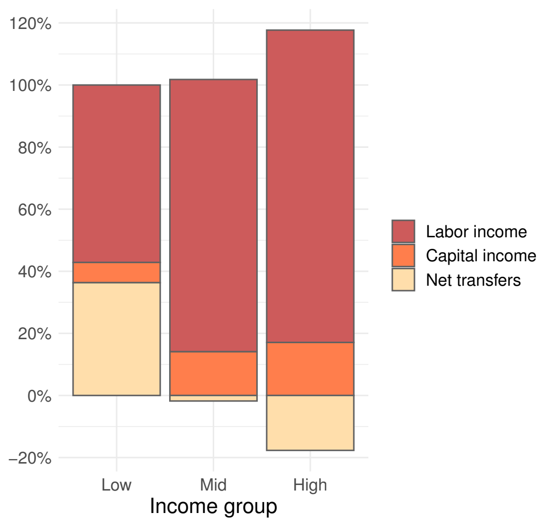
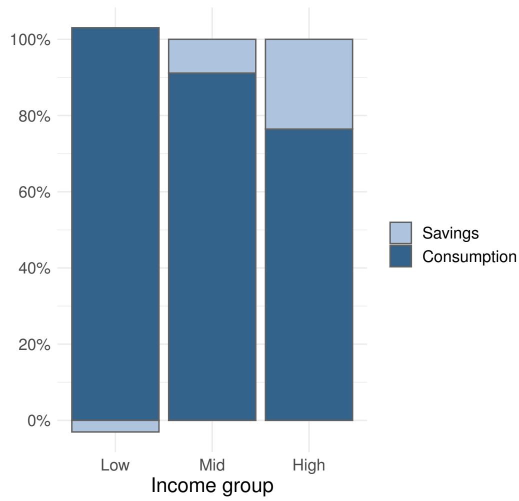


Figure 4
German savings/cons. by income group



Horizontal distribution of income sources (left) and their use in savings versus consumption expenditures (right) within each income group in Germany in percent. Data source: authors' own calculation; FDZ (2021), see above.

Figure 4 illustrates the corresponding use of income for savings versus consumption in each income group (see Appendix Table A5).[14] The low-income group's consumption share (103%) exceeds its income. Hence, the remaining part is financed via a debt reflected by a negative savings share. The middle-income group exhibits a positive savings share (9%). The savings share in the high-income group is more than twice that in the middle-income group (24%).

Figure 5 depicts the vertical distribution of each income source across income groups (Appendix Table A6 provides the corresponding numbers). The vertical shares of labor

[13] Because the paid transfers slightly exceed capital income, the high-income labor share slightly exceeds 100%.

[14] In the EVS data, a statistical difference remains regarding the equation income = consumption + savings, which is disregarded here to create the consumption and savings shares.

and capital income also enter the calibration of the model described in the next subsection. Accordingly, the labor and capital income shares rise from low- to middle-income groups and from middle- to high-income groups, mimicking the distribution of disposable income, as displayed in Figure 2. Net transfers are shown in absolute numbers as they enter the model calibration.[15]

Figure 5
German income sources by source type

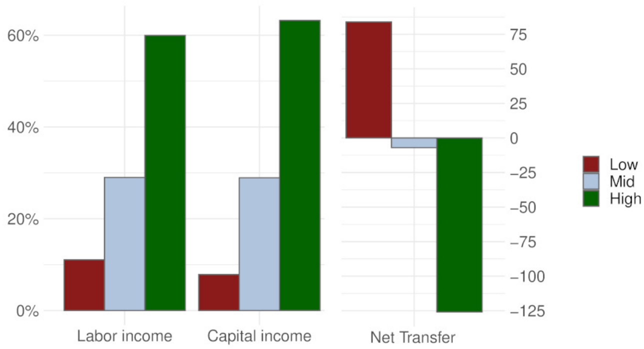
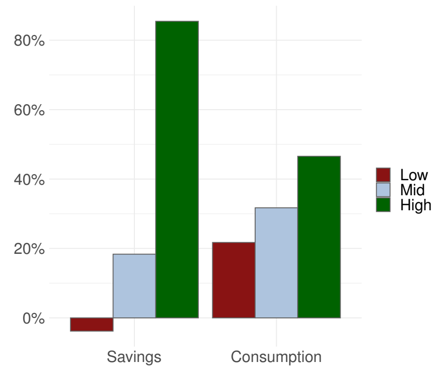


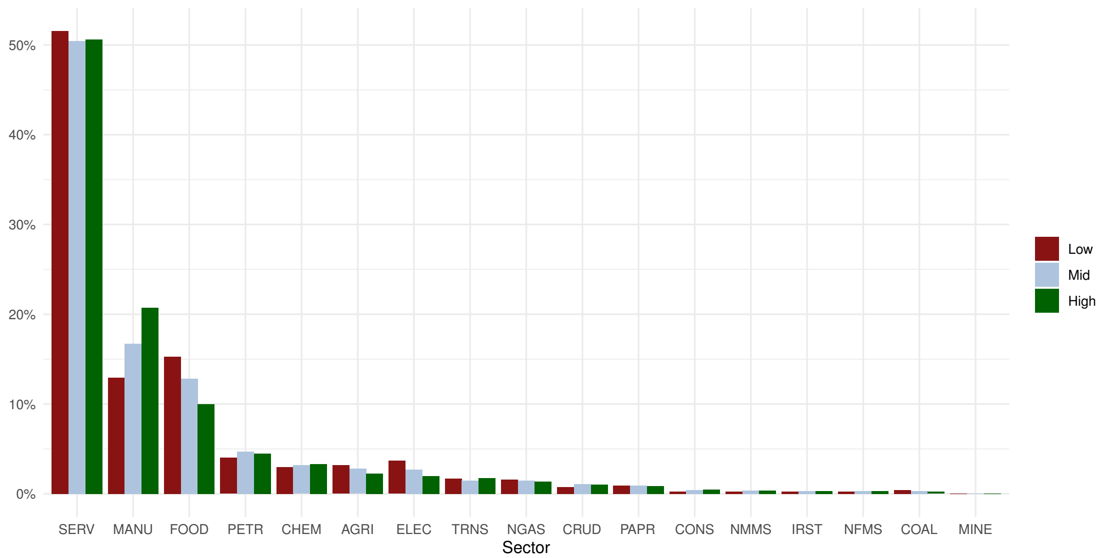
Figure 6
German savings vs. consumption



Vertical distribution of income sources (left) and their use in savings versus consumption expenditures (right) across income groups (low, middle, high) in Germany; net transfers in billions of euros, other sources in percent. Data source: authors' own calculation; FDZ (2021), see above.

Figure 6 sketches the corresponding income use across income groups (see Appendix Table A6). As expected, the shares of savings and consumption increase from low- to middle-income groups and middle- to high-income groups.

Figure 7
Horizontal distribution of German consumption expenditures of each group across goods



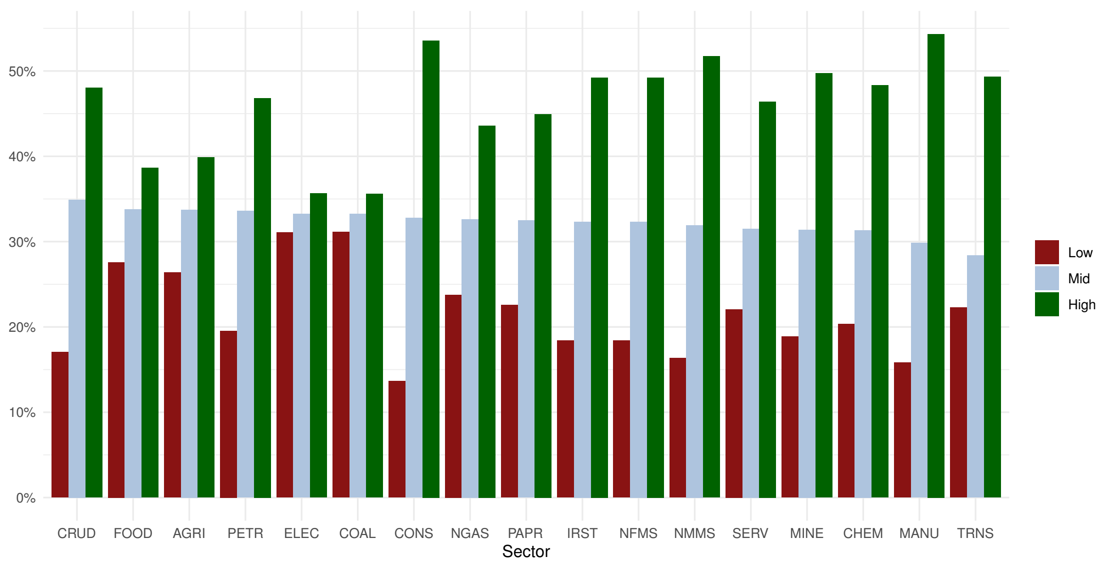
Horizontal distribution of each income group's consumption expenditures across types of goods (sectors) in Germany. Data source: authors' own calculation; FDZ (2021), see above.

[15]The net transfers of the high-income group are adjusted such that the sum of net transfers over income groups adds up to zero and the original general equilibrium is restored.

Figure 7 illustrates the horizontal distribution of each income group's consumption expenditures across the various types of goods (i.e., the sums across the goods equal 100%; see Appendix Table A7.). Interestingly, the consumption pattern varies across income groups. With a share of approximately 50%, the services sector ($SERV$) sees the highest expenditures. Here, the low-income group contributes the largest expenditure share of all income groups, while the middle-income group spends the smallest share, which is very close to the high-income group's share. In the sectors food production ($FOOD$), agriculture ($AGRI$) and electricity ($ELEC$), the low-income group exhibits the largest expenditure shares as well, while the high-income group exhibits the smallest shares. This pattern differs, for example, in the manufacturing sector ($MANU$), where the high-income group has the largest expenditure share and the low-income group the smallest. In the refined petroleum ($PETR$) sector, the middle-income group exhibits the largest expenditure share and the low-income group the smallest.

Figure 8

Vertical distribution of German consumption expenditures on each good across groups



Vertical distribution of consumption expenditures on each type of goods (sector) across income groups (low, middle, high) in Germany. Data source: authors' own calculation; FDZ (2021), see above.

Figure 8 visualizes the corresponding vertical distribution of (private) consumption expenditures on each type of goods (sector) across income groups (i.e., the sums across the three income groups equal 100%; see Appendix Table A7.) These vertical shares also enter the model calibration. Obviously, the distribution is more uneven for some sectors, such as construction ($CONS$) or manufacturing ($MANU$), than for others, such as food production ($FOOD$) or electricity ($ELEC$), where the expenditure shares are similar across income groups. Nonetheless, the high-income group pays the largest share on all goods, and the low-income group the smallest share on all goods.

3 Model

This section provides a nontechnical model summary. The basic model builds on Thomas Rutherford's approach[16] and has been extended according to the requirements of this study. To illustrate the application of our consumer split approach, we use a typical basic computable general equilibrium (CGE) model. It is designed to be as compact as possible to make it transparent and straightforward and to avoid any unnecessary uncertainty in model functions and parameters. The model represents the world economy in the benchmark year 2014 according to the most recent GTAP 10 data. Appendix B contains further model details.

Each of the 17 model regions (s or alternatively r) (see Table 2) includes one representative consumer that is split into three groups (low-, middle- and high-income) in Germany (DEU). Each representative consumer has Cobb-Douglas preferences over a range of 17 consumption goods bundles (see Appendix Figure B2). Each bundle encompasses domestically produced and imported varieties of the same good (see Appendix Figure B1). Each consumer owns the production factor endowments of the corresponding region and receives factor income by supplying them to the producers. Additionally, a consumer may receive income from (public) transfers or a regional (current account) deficit. Each consumer spends a major fraction of her income on consumption, while the remaining fraction is saved, such that disposable income always equals expenditures plus savings.

International trade flows from region r to region s. Trade is modeled following the standard approach introduced by Armington (1969) (Figure B1). This approach implies that varieties of the same good originating from different regions are imperfect substitutes. Parameter values governing the substitutability of these varieties are transferred from Pothen and Hübler (2018) according to the trade model unification theory of Arkolakis et al. (2012).

Each region contains 18 production sectors (i or j) (see Table 1). Overall, each sector produces one corresponding good (or service), 17 consumption/intermediate goods and one investment good. Investments match savings. Each sector uses intermediate goods

[16] Our model is programmed with the General Algebraic Modeling System (GAMS) and the interface Mathematical Programming System for General Equilibrium (MPSGE), https://www.gams.com/latest/docs/UG_MPSGE.html, https://www.gams.com/latest/docs/mpsge.pdf. A similar model can be found at GTAPinGAMS, https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=409.

Table 2
Countries and world regions distinguished by the global model

Region	Description	Split	ETS	Region	Description	Split	ETS
DEU	Germany	Yes	Yes	CAN	Canada	No	No
FRA	France	No	Yes	CHN	China	No	No
GBR	United Kingdom	No	Yes	IND	India	No	No
ITA	Italy	No	Yes	JPN	Japan	No	No
EUR	Rest of EU ETS	No	Yes	KOR	South Korea	No	No
ROE	EU non-ETS	No	No	MEX	Mexico	No	No
FSU	Former Soviet Un.	No	No	OCE	Austral. & Ocean.	No	No
ROA	Rest of Asia	No	No	USA	United States	No	No
ROW	Rest of the World	No	No				

Model regions s or alternatively r defined by Pothen and Hübler (2018). "Split" indicates whether the representative consumer is split in a region, "ETS" indicates whether a region is part of the European Emissions Trading System (EU ETS). Other regions are assumed not to impose a price on CO_2.

and production factors (capital, labor, land and natural resources including fossil fuels) as inputs (see Appendix Figure B3). There is perfect competition ruling out positive profits in all sectors.

Consumers and producers emit CO_2 directly when they burn fossil fuels. To reflect these emissions, the consumption of each fossil fuel, coal ($COAL$), crude oil ($CRUD$), natural gas ($NGAS$) and refined petroleum ($PETR$), is associated with fuel-specific CO_2 emissions (Figure B1). When climate policy imposes a price on CO_2 emissions (via emissions trading or a tax), these emissions reflect a corresponding cost of buying emissions permits or paying a tax bill.

Consumers and producers in all sectors cause CO_2 emissions indirectly when they consume electricity or other goods (with embodied CO_2 footprints). Electricity consumption, for example, is associated with CO_2 emissions released during power generation in the power sector ($ELEC$). These emissions are taxed in the power sector within the European Emissions Trading Scheme (EU ETS) in the countries that are EU ETS members (see Table 2). If goods are imported into the EU, neither fossil fuels nor fossil fuel inputs in any sector are taxed. Therefore, CO_2 pricing at the EU border can put a price on these emissions (both direct emissions and indirect emissions according to the goods' CO_2 footprints, see Section 4).

4 Policy

This section describes the policy scenarios, presents the results and discusses the method used herein.

4.1 Scenarios

To keep the application simple and straightforward and to avoid uncertainty in the choice of future developments and model parameters governing model dynamics, we refer to the situation in the benchmark year 2014 with regard to consumption, production, CO_2 emissions and changes to these factors. Based on that, we carry out a comparative static policy analysis, in which we compare each policy scenario with this *benchmark* scenario without the policy. Market failures are not explicitly modeled. Because climate change impacts are not included either, we carry out a cost-effectiveness analysis, i.e., the optimal implementation of a specific reduction in CO_2 emissions. Because the benchmark data incorporate taxes and subsidies that were in place in 2014, we are in a second-best world, which can result in more complicated outcomes than a first-best world.

We consider the following two policy scenarios reflecting EU climate policy:

1. *Domestic CO_2 price (Dom):* CO_2 pricing encompasses the EU ETS member countries, whereas CO_2 pricing in other model (sub-)regions (such as California) is ruled out. To exploit the full potential of consumption-side consumer disaggregation and to emulate emission reduction policies in all parts of the EU ETS economies, we explicitly include all sectors and private consumption in CO_2 pricing without explicitly distinguishing between ETS and non-ETS sectors. This situation mimics the German CO_2 taxation in non-ETS sectors (transport and housing) and an EU ETS 2 with assumed equalized CO_2 prices across the pricing systems. Compared with a situation with heterogeneous CO_2 prices, substantial efficiency gains from having a common CO_2 price can be expected (Pothen and Hübler (2021)). Therefore, the implemented policy addresses all CO_2 emissions from burning fossil fuels in production and consumption, whereas other greenhouse gases are not included. Referring to the CO_2 emissions and their reductions around 2014, we assume a 10% CO_2 reduction in Germany and each EU ETS member country/region as the default policy.[17] The revenues of CO_2 pricing are redistributed across income groups in

[17] In Germany (*DEU*), which is in the focus of our analysis, greenhouse gas emissions increased by 1.9% between 2012 and 2013, decreased by 4.2% between 2013 and 2014 and increased slightly by 0.4% between 2014 and 2015. Between 2005 and 2014, greenhouse gas emissions decreased by 9.3%; between 2014 and 2020, they decreased by 18.5% (Umweltbundesamt, UBA, accessed 01-2022, https://www.umweltbundesamt.de/en/data/environmental-indicators/indicator-greenhouse-gas-emissions#at-a-glance). Against this background, a 10% CO_2 reduction in 2014 is feasible and realistic. Drastic CO_2 reductions, however, would overcharge the model for three reasons: 1. the model is calibrated to the sectoral and technological situation in 2014 with corresponding consumer preferences, 2. we abstain from modeling uncertain future development scenarios, including a transition of the energy (electricity) system and energy efficiency gains, and 3. the energy input system is relatively inflexible in terms of substitution possibilities, and the electricity sector captures fossil, renewable, nuclear and other power generation technologies only implicitly.

a fair per capita-wise way (cf. Klenert et al. (2018)). This assumption is in line with climate bonus discussions and implementations in Germany, Austria and other countries. Given that all income groups contain the same number of households, each group receives the same share and amount of the CO_2 pricing revenues. To check the robustness of the results, we vary the distribution of the CO_2 pricing revenues across the income groups in a sensitivity analysis (see Section 4.4).

2. *Border CO_2 price (Bor):* includes *Domestic CO_2 price*. Additionally, CO_2 pricing occurs at the border of the EU ETS member countries and is imposed on all imports, ruling out any regional or subregional CO_2 pricing elsewhere in the world (such as in California) for simplicity. CO_2 pricing covers all direct and indirect emissions that occur during all stages of producing a good (or service) and its intermediate inputs. (We do not grant CO_2-content-related subsidies for exports.) This policy follows the EU Carbon Border Adjustment Mechanism (CBAM), currently planned to be implemented in the EU beginning in 2026 after a transition phase from 2023 to 2025.[18] We calculate the required total CO_2 contents of goods following the standard Leontief inverse method (see, e.g., Peters and Hertwich (2008), Hübler (2012)). The CO_2 contents of each good are differentiated by the country/region of origin.[19] The resulting CO_2 price is the same as if the goods were produced domestically within the EU ETS. Such a policy has two aims: first, to encourage emissions reductions abroad, and second, to level off the carbon playing field among competitors within and outside the EU ETS. The second aim is to reduce the negative effects of CO_2 pricing for EU producers and reduce carbon leakage from the EU to the rest of the world. As before, the revenues of CO_2 pricing are redistributed per capita by default and varied in a sensitivity analysis (see Section 4.4).

To express policy effects, such as welfare effects, we compare either the first or the second policy scenario with the *benchmark* scenario in 2014 and compute relative (percentage) changes, such as changes in real consumption (the consumption value divided by the consumer price index; see the end of Section 2.1), for each income group and the sum of these changes across all income groups.

4.2 Results

This subsection presents the results of the policy scenario simulations with regard to the EU policy effects on the model countries/regions as well as the distributional effects on

[18] https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3661.

[19] The set of countries/regions in the Leontief inverse matrix and in the model calibration is the same and is applied to the same GTAP 10 dataset.

the three German consumer income groups. Table 3 reports the regional results. Figures 9 and 10 summarize and illustrate the policy effects on Germany.

Table 3
EU policy effects on countries and world regions

Region	Description	*Dom*	*Bor*	Region	Description	*Dom*	*Bor*
DEU	German tot. welf.	–0.59	–0.57	ROA	Rest of Asia	–0.01	–0.02
	Low-income	**1.30**	**1.39**	ROW	Rest of the World	–0.26	–0.30
	Mid-income	**–0.50**	**–0.47**	CAN	Canada	–0.08	–0.09
	High-income	**–1.20**	**–1.21**	CHN	China	0.29	0.27
FRA	France	–0.51	–0.49	IND	India	0.13	0.12
GBR	United Kingdom	–0.46	–0.46	JPN	Japan	0.08	0.09
ITA	Italy	–0.67	–0.65	KOR	South Korea	0.10	0.12
EUR	Rest of EU ETS	–0.49	–0.44	MEX	Mexico	0.11	0.12
ROE	EU non-ETS	–0.53	–0.56	OCE	Austral. & Ocean.	–0.67	–0.72
FSU	Form. Soviet Un.	–0.41	–0.52	USA	United States	–0.01	–0.01

Regional welfare effects, measured as percentage changes in consumption divided by the true-cost-of-living index driven by the two EU policies under scrutiny relative to the *benchmark* scenario, where *Dom* indicates policy scenario *Domestic* CO_2 *price* and *Bor* policy scenario *Border* CO_2 *price*. The welfare gains of the German low-income group depend on the (per-capita-based) distribution of the revenues from CO_2 pricing. In a new hypothetical scenario in which the low-income group receives only 13% of the revenues, the middle-income group receives 30% and the high-income group receives 57%, the welfare effect on the three groups will be similar and located around the welfare effect on the total German economy (–0.59% with *Dom)*.

According to Table 3, the first policy scenario *Domestic* CO_2 *price* has the following welfare effects on the countries and world regions in the model. It reduces the welfare of the EU ETS member countries implementing the policy by approximately 0.5%, with the strongest decline in Italy (ITA, –0.67%), followed by Germany (DEU, –0.59%).[20] Interestingly, the effect is similar across the remaining European countries outside the EU ETS (ROE) (–0.53%). The negative welfare effect on the Former Soviet Union (FSU) is slightly smaller (–0.41%). Surprisingly, Australia and Oceania (OCE) lose more than other countries or regions (–0.67%). Due to their sheer size, the United States of America (USA) and the Rest of Asia (ROA) are hardly affected (–0.01%). The welfare loss of the Rest of the World (ROW), comprising small and low-income economies, is more significant (–0.26%), while the loss for Canada is moderate (–0.08%). Notably, the South and East Asian economies, particularly China (CHN, 0.29%), followed by India (IND, 0.13%), Korea (KOR, 0.10%), and Japan (JPN, 0.08%), benefit from EU climate policy, presumably from trade redirection from EU exports to South and East Asian exports. Similarly, Mexico (MEX) also benefits (0.11%).

[20]The German total welfare effect is computed in a model run without the consumer split, not by aggregating the welfare effects of the consumer groups.

Figure 9
EU policy effects on Germany

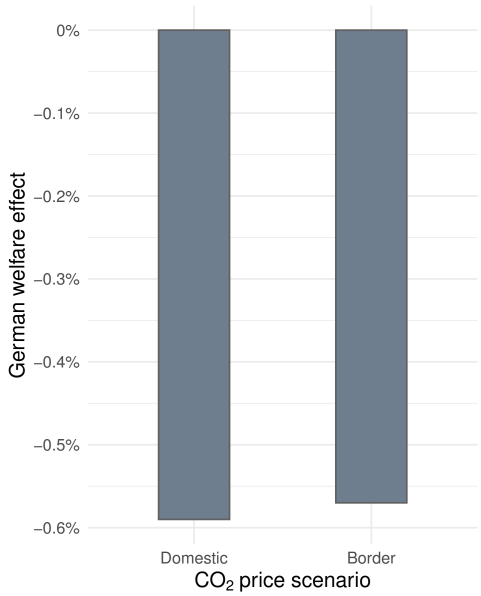
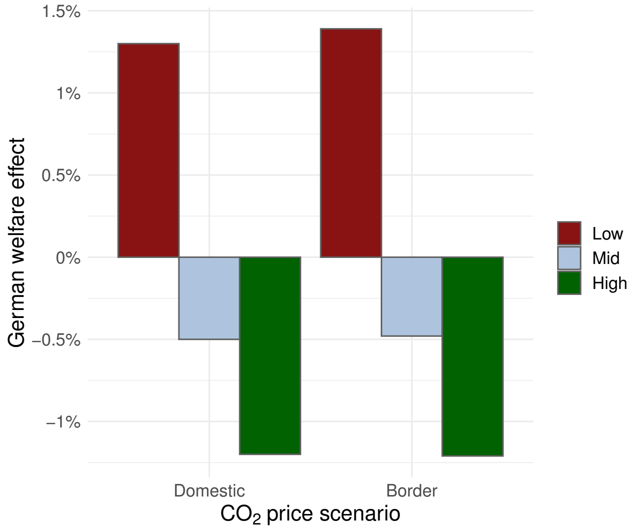


Figure 10
EU policy effects on German income groups



German welfare effects measured as percentage changes in consumption divided by the true-cost-of-living index of the two EU policies, *Dom = Domestic CO_2 price* and *Bor = Border CO_2 price*, relative to the *benchmark* scenario.

The second policy scenario *Border CO_2 price* generates the same pattern as the first one regarding the directions and magnitudes of welfare effects. However, some countries and regions are slightly better off, while others are slightly worse off than in the first scenario. Overall, the EU ETS member countries gain slightly from introducing *Border CO_2 price* (e.g., Germany, DEU, by 0.02 percentage points). In some cases, the gains are minor (the gains of the United Kingdom, GBR, and the USA are not visible in the table). Although the policy effects on the other countries and regions are small, most of them become worse off (ROE, FSU, ROA, ROW, CAN, CHN, IND, OCE and USA) due to the implicitly increased barrier to trade. As an exception, Japan (JPN), Korea (KOR) and Mexico (MEX) make slight gains, presumably due to trade redirection from other countries' exports to the EU towards exports to these countries. This outcome shows that CO_2 pricing at the border is particularly harmful for emerging (CHN and IND) and developing countries (implicitly included in the regions ROA and ROW).

The scenario *Domestic CO_2 price* has the following distributional welfare effects on the three German income groups. The low-income group makes considerable gains (1.30%), whereas the high-income group has losses of a similar magnitude (–1.20%). The middle-income group is located between these groups. Its loss (–0.50%) is close to the total welfare loss in Germany (–0.59%), indicating that the middle-income group roughly represents the average German consumer. *Border CO_2 price* is beneficial for all German income groups, with the largest gain (0.09 percentage points) in the low-income group, a smaller gain in the middle-income group (0.03 percentage points) and a minor loss (0.01 percentage points) in the high-income group.

4.3 Interpretation

This subsection explains and interprets the distributional effects of CO_2 pricing in Germany presented in the last subsection. To this end, Table 4 reports policy-induced price changes.

Table 4
EU policy effects on German goods and factor prices

Price	Description	*Dom*	*Bor*
P_{DEU}	German total consum. price	0.77	0.85
	Low-income	0.86	0.94
	Mid-income	0.81	0.89
	High-income	0.70	0.78
P^K_{DEU}	Capital price (rent)	–0.86	–0.80
P^L_{DEU}	Labor price (wage)	–0.79	–0.74
P^N_{DEU}	Land price (rent)	3.82	3.93
P^R_{DEU}	Natural resource price (rent)	–48.16	–47.94

German consumption (true-cost-of-living index, P_{DEU}) and German factor price effects (capital, K, labor, L, land, N and natural resources, R), measured as percentage changes in consumption divided by the true-cost-of-living index in the two EU policies, *Dom* = *Domestic CO_2 price* and *Bor* = *Border CO_2 price*, relative to the *benchmark* scenario. Each German income group has an own consumption price index, because it has distinct preferences and a distinct consumption structure. Factor prices are defined economy-wide (for all of Germany). The natural resource price P^R_{DEU} is an aggregate price that covers the fossil fuels and other natural resources.

Conceptually, our interpretation follows Goulder et al. (2019). Different from our study, they apply their theory and model to climate policy (carbon taxes) in the USA. Likewise, Dissou and Siddiqui (2014) apply their distributional policy modeling approach to Canada.

Our policy scenario analysis yields six key results:

1. The distributional pattern of the effects of *Domestic CO_2 price* and *Border CO_2 price* (see Table 3) reveals that the magnitude of (negative) policy effects increases households' income, which is in line with the literature (summarized by Wang et al. (2016) and Ohlendorf et al. (2021)). It is surprising, however, that the low-income group *gains* from climate policy. This outcome is in accordance with Goulder et al. (2019) and Böhringer et al. (2021). Lanbandeira et al. (2009) even find a positive effect for *all* income groups in Spain. In our study, this gain occurs because all income groups receive the same

per capita-based revenue from CO_2 pricing, which exceeds the negative expenditure and income effects (explained in the following) on the low-income group. Additionally, the low-income group significantly benefits from social redistribution transfers that are unaffected by climate policy and dampen any climate policy-induced effects.

2. As illustrated for EU countries by Böhringer et al. (2021), for the USA by Goulder et al. (2019) and for Canada by Dissou and Siddiqui (2014), consumption expenditure effects are regressive. Table 4 shows that the consumption price index increase from *Domestic CO_2 price* and *Border CO_2 price* for poor households is slightly stronger (0.86%) than that for middle-class households (0.81%), which is in turn larger than that for rich households (0.70%). This outcome, however, contradicts Feindt et al. (2021).

3. As demonstrated by Böhringer et al. (2021), Goulder et al. (2019) and Dissou and Siddiqui (2014), (factor) income effects are, on the contrary, progressive. In our study, *Domestic CO_2 price* and *Border CO_2 price* sharply reduce natural resource rents, including rents from fossil fuel ownership (by 48.16%). Labor income and, to a slightly larger extent, capital income decline moderately (by approximately 0.8% each). Land rents, on the other hand, increase significantly (by 3.82%): one can imagine that renewable energy expansion, such as the installation of wind parks or solar fields, requires land and hence raises land rents, although this is not directly observed in the model. Given that richer households own a larger part of the production factors than poorer ones, the former are more affected by factor price changes, particularly the dominating decline in resource rents, than the latter are.

4. To investigate the relative importance of the expenditure and income effect for the group-wise welfare effect, we run the model step by step: first, using the expenditure split only; second, including the income split; and third, with different redistributions of the revenues from CO_2 pricing among income groups (e.g., without any revenues transferred to the low-income group as a hypothetical scenario) and with different distributions of resource and land rents. It turns out that the income split is more important for the magnitudes of the welfare effects than the expenditure split, which is in agreement with Goulder et al. (2019). Furthermore, it turns out that in our study, the redistribution of revenues from CO_2 pricing (by default per capita) is more important than the distribution of resource rents.

Thus, in summary, richer households suffer higher losses from climate policy than poorer households, which can gain from climate policy, for the following reasons: first, the income effect dominates the expenditure effect, which affects especially high-income households; second, richer households do not receive net social transfers that dampen climate policy effects; third, richer households own more of the production factors that are affected by climate policy than poorer households do; and fourth, the land rent increase is dominated by the declining prices for the remaining factors, which again affects mostly rich households that own most of the land and the remaining factors.

5. The distributional patterns of *Border CO_2 price* with per capita-based distributions of revenues are similar to those of *Domestic CO_2 price* (see Tables 3 and 4). As expected, raising barriers to international trade via *Border CO_2 price* reduces imports to the EU countries and hence increases the scarcity of goods and their prices, as visible in Table 4. Such goods price increases are disadvantageous for consumers (and similarly for producers with respect to intermediate goods prices). However, the reduced imports are replaced by domestically produced goods that require more production inputs. As a result, factor prices increase more (or decrease to a smaller extent, respectively) with *Border CO_2 price* than with *Domestic CO_2 price*, as visible in Table 4. This generates a positive income effect for all income groups. Nonetheless, Table 3 shows that this income gain is most significant in the low-income group (a 0.08 percentage point gain between *Border CO_2 price* and *Domestic CO_2 price*). This distributional pattern concurs with CGE model-based findings for trade liberalization in Chile (O'Ryan et al., 2011). The downside of this pattern is that negative effects from erecting trade barriers also tend to hit poor people harder than richer people (Diao and Kennedy (2016)).

6. The estimated economy-wide welfare effect of *Domestic CO_2 price* on Germany amounts to –0.59% (see Table 3). Let us assume that German policymakers want to achieve an equal distribution of this effect across income groups. Model runs with different distributions of revenues from CO_2 pricing reveal that a redistribution of 13% for the low-income group, 30% for the middle-income group and 57% for the high-income group roughly achieves this egalitarian welfare distribution via climate policy without additional transfers from rich to poor groups.

4.4 Robustness

To evaluate the influence of uncertainty in crucial parameter values on the distributional policy results, we conduct a detailed sensitivity analysis following Pothen and Hübler (2018). To this end, we vary the relevant sets of parameter values within our CGE model. The results are presented in Section B.6 of the Appendix. The baseline (reference) values can be found in Table 3, particularly, the results for Germany (DEU).[21]

Specifically, we evaluate the welfare effects of the policies under scrutiny across the three income groups assuming upper or lower bounds of the sector-specific elasticities governing the substitution between imports from different countries/regions (σ_i^M), between domestic production versus imports (σ_i^{DM}) and between different production factor inputs (σ_i^Z). Then we carry out a computationally complex distributional sensitivity analysis (*Monte Carlo* analysis) of these parameter sets.

Furthermore, data on factor income from land and natural resource ownership and the distribution of revenues from CO_2 pricing are insufficiently available. Therefore, we evaluate the same distributional welfare effects given several alternative sets of the corresponding income/revenue shares.

Our sensitivity analysis provides the following insights:

1. In the analysis reported in Table B2, we uniformly vary the sector-specific Armington elasticities σ_i^M between imported goods by $\pm 10\%$ in all sectors i. In both policy scenarios, we find that deviations from the welfare effects in the baseline (see Table 3) are largest for the low-income group: Relative to the baseline, welfare gains increase (decrease) by 2.8% (2.6%) at the lower (upper) bound in the *Domestic* CO_2 *price* scenario. Similarly, we observe an increase (decrease) of 2.7% (2.5%) at the lower (upper) bound in the *Border* CO_2 *price* scenario. Compared with the low-income group, changes in welfare effects for the middle-income group are somewhat smaller in magnitude and less symmetric. We observe a decrease (increase) in the welfare loss of 1.6% (1.3%) at the lower (upper) bound in the *Domestic* CO_2 *price* scenario and a decrease (increase) in the welfare loss of 2.0% (1.6%) in the *Border* CO_2 *price* scenario. In contrast, only small changes are observed in the high-income group.

2. Turning to the distributional sensitivity analyses, we generate 1000 random draws from a $\pm 10\%$ interval around each of the sector-specific Armington elasticies σ_i^M (see column 1 of Table B1) resulting in 1000 sets of sectoral parameter values.[22] We then recalibrate and solve the model for each set of parameter values and evaluate the welfare effects for the two policy scenarios. Appendix Figures B4 and B5 plot the resulting distributions of welfare effects for *Domestic* CO_2 *price* and *Border* CO_2 *price*, respectively,

[21] The differences between the welfare effects in the scenarios with alternative parameter choices and the baseline (reported in Table 3) are computed based on exact values (with more decimal places than those reported in the Tables) and then rounded to two decimal places.

[22] This means, the elasticity values of the model sectors i are varied simultaneously and independently so that each sectoral parameter value in-/decreases randomly within the $\pm 10\%$ interval.

for each of the three income groups. Kernel density estimations are indicated by solid blue lines, and dashed vertical black lines represent 95% confidence intervals obtained via percentile bootstrapping (Wilcox, 2012) with 1000 drawings.

We find that the welfare effects approximately follow normal distributions with narrow 95% confidence intervals. Interestingly, the distributions are slightly left-skewed for the middle-income group for both policy scenarios, which is in line with the slightly asymmetric changes in welfare effects observed in Table B2. For the *Domestic CO_2 price* scenario, the low-income group's welfare gain varies between 1.2973% and 1.2984% with 95% confidence, while the corresponding intervals for the middle- and high-income groups are (–0.4945%, –0.4940%) and (–1.2065%, –1.2057%), respectively. The welfare effects under *Border CO_2 price* exhibit similarly small 95% confidence intervals with (1.3892, 1.3904), (–0.4698, –0.4693) and (–1.2084, –1.2076) for low-, middle- and high-income groups, respectively.

3. The sensitivity analyses of the sector-specific elasticities between domestically produced versus imported goods σ_i^{DM} and the input elasticities between production factors σ_i^{Z} are conducted in an analogous fashion. The results are presented in Appendix Tables B3 and B4 and Figures B6 to B9. In accordance with the sensitivity analysis of Armington elasticities, uniformly lowering σ_i^{DM} in all sectors leads to increases in welfare gains for the low-income group (vice versa for uniform increases of σ_i^{DM}). Likewise, lower values of σ_i^{DM} are associated with a small decrease in the welfare losses for the middle-income group. Overall, the results appear to be relatively robust to variations in σ_i^{DM} with changes in welfare effects ranging between –1.3% and 1.3% relative to the baseline across both policy scenarios. Regarding the distributional sensitivity analysis, Figures B6 and B7 indicate light-tailed distributions of welfare effects for the high-income group. This is confirmed by kurtosis values around 2.1, suggesting that extreme welfare effects occur less frequently than predicted based on a normal distribution.

As shown in Table B4, welfare effects are even less sensitive to variations in σ_i^{Z}: The choice of low values of σ_i^{Z} changes welfare effects of *Domestic CO_2 price* and *Border CO_2 price* by between –0.9% and 0.6% for all three income groups; likewise, welfare effects change by between –0.5% and 0.8% for high values of σ_i^{Z}. This insensitivity is also reflected in the narrow distributions shown in Figures B8 and B9.

4. By default, we distribute income from land and natural resource ownership in the same way we distribute total consumption expenditures. Appendix Table B5 reports the corresponding welfare effects assuming alternative distributions of the land and natural

resource income shares across the income groups. In column 1, we assume income shares of both land and natural resources to be 0%, 50% and 50% across the low-, middle- and high-income groups, respectively. We find that the welfare gains of the low-income group decrease by between 77 and 82%, while the respective welfare losses of the middle- and high-income groups decrease by 84 to 89% and 4% in both scenarios. Analogously, column 2 assumes income shares of 50%, 0% and 50%, and column 3 assumes income shares of 50%, 50% and 0%. As expected, in both cases the welfare loss of the respective income group with a share of 0% increases considerably. Column 4 sets the income shares of land and natural resources to the capital income shares of the three income groups (7.8%, 28.9% and 63.2% for the low-, middle- and high-income groups, respectively). In this case, the high-income group experiences a reduction of its welfare loss in both scenarios, whereas the middle-income group's welfare loss increases and the low-income group's welfare gain decreases significantly (52.7% and 49.2%). Column 5 sets the income shares to 1/3 for all three income groups, which leads to a considerable rise in the welfare gains of the low-income group (44.0% and 41.2%) and a small decrease in the losses of the middle-income group, while the welfare losses of the high-income group increase (ca. 16.2% in each case).

5. Finally, Table B6 presents the welfare effects assuming alternative CO_2 pricing revenue shares across the income groups compared to the default per-capita distribution. Columns 1 to 3 assume the same distribution of income shares as the corresponding columns in Table B5. In column 1, setting the revenue share of the low-income group to 0% leads to a very considerable welfare loss for this group (switching from +1.3% to –1.7%, i.e., a 234.5% reduction), while the middle-income group experiences a substantial welfare gain (switching from –0.5% to +0.2%, i.e., a 142.7% improvement) and the high-income group a moderate decrease in its welfare loss (37.8%). Accordingly, for the groups that do not receive revenues, column 2 exhibits a high increase of the welfare loss of the middle-income group (285.7%) and column 3 a moderate increase of the welfare loss of the high-income group (75.6%). The other two groups receiving 50% of the revenues experience a significant increase in their welfare gain (117% in the low-income group) or a substantial reduction in their welfare loss (143.0% in the middle-income group). Column 4 reports the results of an alternative scenario assuming that the CO_2 pricing revenue shares are equal to the expenditure shares of the three income groups in total consumption. In this case, the high-income group experiences a moderate reduction in its welfare loss compared to the default per-capita distribution (30.0%), while the middle-income group slightly loses (14.0%) and the low-income group becomes considerably worse off (81.6%).

5 Conclusion

Computable general equilibrium (CGE) models have become standard tools for exploring new policies, such as climate policies. For policymakers and public debates, distributional effects have become increasingly important, especially against the background of increasing inequality. The explicit representation of consumers at different income levels *within* CGE models, however, is rare. Therefore, it is important to analyze expenditure, income and tax revenue effects simultaneously in an interacting way based on a general equilibrium framework instead of computing those effects separately with statistical methods or in a cascade of modeling and econometric methods. Thus, we hope to provide some guidance for modelers who would like to implement a split of regionally representative consumers into n income groups independent of the particular model based on a standard consumption function.

Having implemented such a consumer split in our application in Germany, we find that the magnitudes and the *direction* of the investigated policy effects can be diverse across income groups and considerably different from the effects on a single representative consumer. In our case, surprisingly, low-income households *benefit* from climate policy with a magnitude of the relative welfare change that significantly exceeds the economy-wide negative welfare effect. Because this benefit depends on the use of revenues of taxation (in our case, CO_2 pricing), our approach also allows the identification of the distribution of revenues that would make all income groups equally well off and thus replicates the economy-wide welfare effect throughout all income groups. A strict focus on economy-wide welfare effects can be misleading for a socially sensitive policy investigation.

Our exemplary model is designed to be straightforward, compact and transparent. Therefore, it does not include a complex energy input or power generation system or complex future development scenarios with economic growth and an energy transition. Such extensions are left for a follow-up study of the model dynamics. A future holistic distributional analysis (of climate policy) could also examine sector-specific differences of policy effects (as studied by Hübler and Löschel (2013)) as well as technology-specific effects (across renewable, fossil and nuclear energy technologies in the power sector, as studied by Fischer et al. (2021)). In addition to different income groups, different social groups can be defined, e.g., based on professions, as far as the required data are available (see Siriwardana et al. (2013)). Further extensions of (publicly) available data sources may encompass private and public land and resource ownership, particularly the ownership of fossil fuels, because changes in the related revenues are significant drivers of distributional effects according to our policy analysis. Notwithstanding, our detailed distributional sensitivity analysis including upper and lower bound parameter values, alternative distributions of income/revenue shares across income groups and a complex *Monte Carlo* analysis confirms the qualitative validity of the policy results.

6 Acknowledgement

We gratefully acknowledge funding from the German Federal Ministry of Education and Research (BMBF) for the project "Mitigation Policies in a Globalized and Developing World: The Role of Structural Change and Distributional Effects" (ROCHADE, grant 01LA1828C). We are very grateful to Johannes Hampp and Eduard Bukin for data update and data computation support and to Ken Mauser for defining the data aggregation approach and contributing to the literature review. We thank Matthias Kalkuhl, Johannes Hampp, Jan Steckel, Gabriel Felbermayr and Frank Pothen for their helpful advice. We thank Matthias Höher (ZEU) and Martin Petrick for their managerial support and Marian Leimbach (PIK) for coordinating the ROCHADE project.

7 References

Aguiar, A., Chepeliev, M., Corong, E. L., McDougall, R. and van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. *Journal of Global Economic Analysis*, 4(1): 1–27.

Arkolakis, C., Costinot, A. and Rodríguez-Clare, A. (2012). New Trade Models, Same Old Gains? *American Economic Review*, 102(1): 94–130.

Armington, P. S. (1969). A Theory of Demand for Products Distinguished by Place of Production. *IMF Staff Papers*, 16(1): 159–178.

Böhringer, C., Balistreri, E. J. and Rutherford, T. F. (2012). The Role of Border Carbon Adjustment in Unilateral Climate Policy: Overview of an Energy Modeling Forum Study (EMF 29). *Energy Economics*, 34: S97–S110.

Böhringer, C., Peterson, S., Rutherford, T. F., Schneider, J. and Winkler, M. (2021). Climate policies after Paris: Pledge, Trade and Recycle: Insights from the 36th Energy Modeling Forum Study (EMF36). *Energy Economics*, 103: 105471.

Bourguignon, F. and Bussolo, M. (2013). Income Distribution in Computable General Equilibrium Modeling. *Handbook of Computable General Equilibrium Modeling*, 1, ch. 21: 1383–1437.

Buddelmeyer, H., Hérault, N., Kalb, G. and van Zijll de Jong, M. (2012). Linking a Microsimulation Model to a Dynamic CGE Model: Climate Change Mitigation Policies and Income Distribution in Australia. *International Journal of Microsimulations*, 5(2): 40–58.

Cunha Montenegro, R., Lekavicius, V., Brajković, J., Fahl, U. and Hufendiek, K. (2019). Long-Term Distributional Impacts of European Cap-and-Trade Climate Policies: A CGE Multi-Regional Analysis. *Sustainability*, 11(23): 6868.

Diao, X. and Kennedy, A. (2016). Economywide Impact of Maize Export Bans on Agricultural Growth and Household Welfare in Tanzania: A Dynamic Computable General Equilibrium Model Analysis. *Development Policy Review*, 34(1): 101–134.

Dissou, Y. and Siddiqui, M. S. (2014). Can Carbon Taxes be Progressive? *Energy Economics*, 42: 88–100.

Feindt, S., Kornek, U., Labeaga, J. M., Sterner, T., Ward, H. (2021). Understanding Regressivity: Challenges and Opportunities of European Carbon Pricing. *Energy Economics*, 103: 105550.

Fischer, C., Hübler, M. and Schenker, O. (2021). More Birds than Stones: A Framework for Second-best Energy and Climate Policy Adjustments. *Journal of Public Economics*, 203: 104515.

Forschungsdatenzentren (FDZ) der Statistischen Ämter des Bundes und der Länder (2019). Metadatenreport. Teil I: Allgemeine und methodische Informationen zur Einkommens- und Verbrauchsstichprobe (EVAS-Nummer: 63211, 63221, 63231), Berichtsjahre 2008, 2013 und 2018. Statistische Ämter des Bundes und der Länder, Wiesbaden, Germany. URL: https://www.forschungsdatenzentrum.de/de/10-21242-63221-2013-00-00-3-1-1.

Forschungsdatenzentren (FDZ) der Statistischen Ämter des Bundes und der Länder (2021). Einkommens- und Verbrauchsstichprobe 2013, Grundfile 5 (HB), Scientific-Use-File (SUF). URL: https://doi.org/10.21242/63221.2013.00.00.3.1.1.

Goulder, L. H., Hafstead, M. A. C., Kim, G. R. and Long, X. (2019). Impacts of a Carbon Tax Across US Household Income Groups: What are the Equity-efficiency Trade-offs? *Journal of Public Economics*, 175: 44–64.

Huang, H., Roland-Holst, D. , Springer, C., Lin, J., Cai, W. and Wang, C. (2019). Emissions Trading Systems and Social Equity: A CGE Assessment for China. *Applied Energy*, 235: 1254–1265.

Hübler, M. (2012). Carbon Tariffs on Chinese Exports: Emissions Reduction, Threat, or Farce? *Energy Policy*, 50: 315–327.

Hübler, M. and Löschel, A. (2013). The EU Decarbonisation Roadmap 2050: What Way to Walk? *Energy Policy*, 55: 190–207.

Jung, S., Lee, J.-D., Hwang, W.-S. and Yeo, Y. (2017). Growth versus Equity: A CGE Analysis for Effects of Factor-biased Technical Progress on Economic Growth and Employment. *Economic Modelling*, 60: 424–438.

Kim, E. and Kim, K. (2003). Impacts of the Development of Large Cities on Economic Growth and Income Distribution in Korea: A Multiregional CGE Model. *Papers in Regional Science*, 82: 101–122.

Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R. and Stern, N. (2018). Making Carbon Pricing Work for Citizens. *Nature Climate Change*, Perspective, 8: 669–677.

Kronenberg, T. (2010). Erstellung einer Input-Output-Tabelle für Mecklenburg- Vorpommern. *AStA Wirtschafts- und Sozialstatistisches Archiv*, 4(3): 223–248.

Labandeira, X., Labeaga, J. M. and Rodríguez, M. (2009). An Integrated Economic and Distributional Analysis of Energy Policies. *Energy Policy*, 37: 5776–5786.

Landis, F., Rausch, S., Kosch, M., and Böhringer, C. (2019). Efficient and Equitable Policy Design: Taxing Energy Use or Promoting Energy Savings? *The Energy Journal*, 40(1): 73–104.

Organisation for Economic Cooperation and Development (OECD) (2013). Framework for Integrated Analysis. In *OECD Framework for Statistics on the Distribution of Household Income, Consumption and Wealth*, 171–192. OECD Publishing, Paris. URL: https://doi.org/10.1787/9789264194830-11-en.

Ohlendorf, N., Jakob, M., Minx, J. C., Schröder, C. and Steckel, J. C. (2021). Distributional Impacts of Carbon Pricing: A Meta-Analysis. *Environmental and Resource Economics*, 78: 1–42.

O'Ryan, R., de Miguel, C. J., Miller, S. and Pereira, M. (2011). The Socioeconomic and Environmental Effects of Free Trade Agreements: A Dynamic CGE Analysis for Chile. *Environment and Development Economics*, 16(SE 3 Critical Environmental and Development Issues in Latin America): 305–327.

Peters, P. and Hertwich, E. G. (2008). CO_2 Embodied in International Trade with Implications for Global Climate Policy. *Environmental Science and Technology*, 42(5): 1401–1407.

Pothen, F. and Hübler, M. (2018). The Interaction of Climate and Trade Policy. *European Economic Review*, 107: 1–26. Working paper version, URL: http://diskussionspapiere.wiwi.uni-hannover.de/pdf_bib/dp-585.pdf.

Pothen, F. and Hübler, M. (2021). A Forward Calibration Method for Analyzing Energy Policy in New Quantitative Trade Models. *Energy Economics*, 100: 105352.

Rausch, S., Metcalf, G. E. and Reilly, J. M. (2011). Distributional Impacts of Carbon Pricing: A general Equilibrium Approach with Micro-data for Households. *Energy Economics*, 33: S20-S33.

Rueda-Cantuche, J. M., Revesz, T., Amores, A. F., Velázquez, A., Mraz, M., Ferrari, E., Mainar-Causapé, A. J., Montinari, L. and Saveyn, B. (2020). Improving the European input–output database for global trade analysis. *Economic Structures*, 9(1): 1–16.

Sajeewani, D., Siriwardana, M. and McNeill, J. (2015). Household Distributional and Revenue Recycling Effects of the Carbon Price in Australia. *Climate Change Economics*, 6(3): 1550012.

Siriwardana, M., Meng, S. and McNeill, J. (2013). A CGE Assessment of the Australian Carbon Tax Policy. *International Journal of Global Energy Issues*, 36(2/3/4): 242–261.

Statistisches Bundesamt (2013). Einnahmen und Ausgaben der privaten Haushalte. Systematisches Verzeichnis (Ausgabe 2013). URL: https://www.destatis.de/DE/Methoden/Klassifikationen/Private-Haushalte/sea-2013.pdf.

Statistisches Bundesamt (2018). Einkommens- und Verbrauchsstichprobe 2013. Einkommensverteilung in Deutschland 2013. *Destatis Fachserie*, 15(6): 1–42.

Statistisches Bundesamt (2020). Volkswirtschaftliche Gesamtrechnungen. Input-Output-Rechnung 2015 (Revision 2019; Stand: August 2019). *Destatis Fachserie*, 18(2): 1–42. URL: https://www.statistischebibliothek.de/mir/receive/DEHeft_mods_00130396

United Nations Economic Commission for Europe (UNECE) (2011). Standard Concepts and Definitions. In *Canberra Group Handbook on Household Income Statistics*, 9–20. UN, New York, Geneva. URL: https://unece.org/info/Statistics/pub/21866.

Wang, Q., Hubacek, K., Feng, K., Wei, Y.-M., Liang, Q.-M. (2016). Distributional Effects of Carbon Taxation. *Applied Energy*, 184: 1123–1131.

Wilcox, R. R. (2012). *Introduction to Robust Estimation and Hypothesis Testing.* Elsevier, Amsterdam.

Supplementary online appendix for The distributional effects of CO_2 pricing at home and at the border on German income groups

Michael Hübler, Malin Wiese, Johannes Damster, Marius Braun

A Consumer disaggregation procedure

A.1 Data source

To disaggregate the representative consumer based on national accounts (Volkswirtschaftliche Gesamtrechnung, VGR), household expenditure data are required. Kronenberg (2010), for example, creates an input-output table with the household income and expenditure survey "Einkommens- und Verbrauchsstichprobe" (EVS) for the German federal state Mecklenburg-Vorpommern. Because the EVS is collected every five years only and was not collected in 2014, which is the base year of the Global Trade Analysis Project (GTAP) 10 data used in the model, we use the EVS of 2013 (FDZ, 2021), which is the closest year in which the survey was conducted. For this analysis, we only use the part of the survey that asks respondents explicitly about income and expenditures, the so-called "Haushaltsbuch" (HB) data file, a scientific use file with 98% coverage of all responses. More information on the data set (in German) can be found in FDZ (2019, 2020).

A.2 Conversion of consumption to goods categories

We use the consumption interdependence table provided by the German Federal Statistical Office (Statistisches Bundesamt, 2020) to transfer the consumption data from the EVS to the goods categories of the Classification of Products by Activity (CPA). The interdependence table is not available for the year of the EVS (2013) or the base year of the GTAP data; therefore, we use the available table from 2015, which is the year closest to the years of the EVS and GTAP 10 data (2013 and 2014, respectively). Because the consumption interdependence table is large, it is not displayed here but can be accessed online.[23]

The following adjustments are required. We disaggregate the CPA category "Crude oil and natural gas" into the two model sectors $CRUD$ and $NGAS$. Furthermore, we

[23] https://www.statistischebibliothek.de/mir/receive/DEHeft_mods_00130396.

omit the CPA sector "Crude petroleum and natural gas" from the consumption interdependence table. We then calculate new conversion coefficients of the CPA sector that include "Electricity, gas, other fuels and district heating" such that the new coefficients add up to one. The newly created categories of "Crude oil" and "Natural gas" are not transferred into the CPA classification; they directly form the model categories $CRUD$ and $NGAS$.

A.3 Aggregation of goods categories to model sectors

Table A1 displays how we aggregate the GTAP 10 sectors to our model sectors. Table A2 shows how the goods categories in the CPA classification are allocated to the GTAP 10 sectors or directly to the model sectors. The CPA sector "Crude petroleum and natural gas" (no. 06) is distributed across the two model sectors "Crude oil" ($CRUD$) and "Natural gas" ($NGAS$).

A.4 OECD equivalence scale

The EVS data are defined at the household level. When evaluating distributional effects, however, it is advisable to transfer income and consumption to the individual level because the available income per person in households with more members will be smaller than that in households with fewer members. In theory, however, we attempt to maximize consumption per capita. Notwithstanding, economies of scale emerge when households share goods or space such that the corresponding expenditures per person decline with a larger household size. Therefore, to obtain appropriate per capita-based data, we follow the German Federal Statistical Office (Statistisches Bundesamt, 2015) by applying the Organisation for Economic Co-operation and Development (OECD) equivalence scale (OECD, 2013). This scale attributes a weight of one to the household head (with the highest individual income), a weight of 0.5 to every other person in the household who is at least 14 years old, and a weight of 0.3 to every person who is less than 14.

Table A1
Aggregation of GTAP sectors to model sectors

Model		GTAP 10		
Sector	Description	No.	Code	Description
AGRI	Agriculture	1	pdr	Paddy rice
		2	wht	Wheat
		3	gro	Cereal grains nec.
		4	v_f	Vegetables, fruit, nuts
		5	osd	Oil seeds
		6	c_b	Sugar cane, sugar beet
		7	pfb	Plant-based fibres
		8	ocr	Crops nec.
		9	ctl	Bovine cattle, sheep and goats, horses
		10	oap	Animal products nec.
		11	rmk	Raw milk
		12	wol	Wool, silk-worm cocoons
		13	frs	Forestry
		14	fsh	Fishing
COAL	Coal	15	coa	Coal
CRUD	Crude oil	16	oil	Oil
NGAS	Natural gas	17	gas	Gas
		47	gdt	Gas manufacture, distribution
MINE	Mining	18	oxt	Other extraction
FOOD	Food production	19	cmt	Bovine meat products
		20	omt	Meat products nec.
		21	vol	Vegetable oils and fats
		22	mil	Dairy products
		23	pcr	Processed rice
		24	sgr	Sugar
		25	ofd	Food products nec.
		26	b_t	Beverages and tobacco products
MANU	Manufacturing	27	tex	Textiles
		28	wap	Wearing apparel
		29	lea	Leather products
		30	lum	Wood products
		39	fmp	Metal products
		40	ele	Computer, electronic and optical products
		41	eeq	Electrical equipment
		42	ome	Machinery and equipment nec.
		43	mvh	Motor vehicles and parts
		44	otn	Transport equipment nec.
		45	omf	Manufactures nec.
PAPR	Paper and pulp	31	ppp	Paper products, publishing
PETR	Refined petroleum	32	p_c	Petroleum, coal products
CHEM	Chemical, rubber, and plastic products	33	chm	Chemical products
		34	bph	Basic pharmaceutical products
		35	rpp	Rubber and plastic products
NMMS	Mineral products nec.	36	nmm	Mineral products nec.
IRST	Iron and steel	37	i_s	Ferrous metals
NFMS	Non-ferrous metals	38	nfm	Metals nec.
ELEC	Electricity	46	ely	Electricity
SERV	Services	48	wtr	Water
		50	trd	Trade (wholesale and retail)
		51	afs	Accommodation, food and service activities
		56	cmn	Communication
		57	ofi	Financial services nec.
		58	ins	Insurance
		59	rsa	Real estate activities
		60	obs	Business services nec.
		61	ros	Recreational and other services
		62	osg	Public administration and defense
		63	edu	Education
		64	hht	Human health and social work activities
		65	dwe	Dwellings
TRNS	Transport	52	otp	Transport nec.
		53	wtp	Water transport
		54	atp	Air transport
		55	whs	Warehousing and support activities
CONS	Construction	49	cns	Construction

Aggregation of the GTAP sectors to the model sectors defined by Pothen and Hübler (2018) adapted to the GTAP 10 database (Aguiar et al., 2019). The original GTAP sectors can be found at https://www.gtap.agecon.purdue.edu/databases/v10/v10_sectors.aspx.

Table A2
Conversion from CPA to GTAP and model sectors

	CPA Nr.	CPA Name	GTAP 10	Model
1	01	Products of agriculture, hunting and related services	*agric. sectors*	AGRI
2	02	Products of forestry, logging and related services	frs	AGRI
3	03	Fish and other fishing products; aquaculture products; support services for fishing	fsh	AGRI
4	5.1	Hard coal	coa	COAL
5	5.2	Lignite	coa	COAL
6	06	Crude petroleum and natural gas		
	06.1	Crude petroleum	oil	CRUD
	06.2	Natural gas	gas	NGAS
7	07	Metal ores	oxt	MINE
8	08-09	Other mining and quarrying products and mining support services	oxt	MINE
9	10	Food products	*food sectors*	FOOD
10	11	Beverages	b_t	FOOD
11	12	Tobacco products	b_t	FOOD
12	13	Textiles	tex	MANU
13	14	Wearing apparel	wap	MANU
14	15	Leather and related products	lea	MANU
15	16	Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials	lum	MANU
16	17.1	Pulp, paper and paperboard	ppp	PAPR
17	17.2	Articles of paper and paperboard	ppp	PAPR
18	18	Printing and recording services	ppp	PAPR
19	19.1	Coke oven products	p_c	PETR
20	19.2	Refined petroleum products	p_c	PETR
21	20	Chemicals and chemical products	chm	CHEM
22	21	Basic pharmaceutical products and pharmaceutical preparations	bph	CHEM
23	22.1	Rubber products	rpp	CHEM
24	22.2	Plastic products	rpp	CHEM
25	23.1	Glass and glass products	nmm	NMMS
26	23.2-23.9	Refractory products, clay building materials, Other porcelain and ceramic products, Cement, lime and plaster, articles of concrete, cement and plaster, Cut, shaped and finished stone, Other non-metallic mineral products	nmm	NMMS
27	24.1-24.3	Basic iron and steel and ferroalloys, tubes, pipes, hollow profiles and related fittings, of steel, Other products of the first processing of steel	i_s	IRST
28	24.4	Basic precious and other non-ferrous metals	nfm	NFMS
29	24.5	Casting services of metals	i_s	IRST
30	25	Fabricated metal products, except machinery and equipment	i_s	IRST
31	26	Computer, electronic and optical products	ele	MANU
32	27	Electrical equipment	eeq	MANU
33	28	Machinery and equipment n.e.c.	ome	MANU
34	29	Motor vehicles, trailers and semi-trailers	mvh	MANU
35	30	Other transport equipment	otn	MANU
36	31	Furniture	omf	MANU
37	32	Other manufactured goods	omf	MANU
38	33	Repair and installation services of machinery and equipment	omf	MANU
39	35.1, 35.3	Electricity, transmission and distribution services, Steam and air conditioning supply services	ely	ELEC
40	35.2	Manufactured gas; distribution services of gaseous fuels through mains	gdt	NGAS
41	36	Natural water; water treatment and supply services	wtr	SERV
42	37	Sewage services; sewage sludge	wtr	SERV

CPA categories no. 1 and no. 9 are transferred to sectors *AGRI* and *FOOD*. The specially treated CPA category "Crude oil and natural gas" is disaggregated into the two categories "Crude petroleum" (assigned no. 06.1) and "Natural gas" (assigned no. 06.2), which are not original CPA categories resulting from the consumption interdependence table but are calculated directly from the corresponding data in the EVS.

Table continues on the next page.

	CPA Nr.	CPA Name	GTAP 10	Model
43	38	Waste collection, treatment and disposal services; materials recovery services	wtr	SERV
44	39	Remediation services and other waste management services	wtr	SERV
45	41	Buildings and building construction works	cns	CONS
46	42	Constructions and construction work for civil engineering	cns	CONS
47	43	Specialized construction work	cns	CONS
48	45	Wholesale and retail trade and repair services of motor vehicles and motorcycles	trd	SERV
49	46	Wholesale trade services, except of motor vehicles and motorcycles	trd	SERV
50	47	Retail trade services, except of motor vehicles and motorcycles	trd	SERV
51	49	Land transport services and transport services via pipelines	otp	TRNS
52	50	Water transport services	wtp	TRNS
53	51	Air transport services	atp	TRNS
54	52	Warehousing and support services for transportation	whs	TRNS
55	53	Postal and courier services	cmn	SERV
56	55-56	Accommodation services and food and beverage serving services	afs	SERV
57	58	Publishing services	cmn	SERV
58	59-60	Motion picture, video and television program production services, sound recording and music publishing and programming and broadcasting services	cmn	SERV
59	61	Telecommunications services	cmn	SERV
60	62-63	Computer programming, consultancy and related services and information services	cmn	SERV
61	64	Financial services, except insurance and pension funding	ofi	SERV
62	65	Insurance, reinsurance and pension funding services, except compulsory social security	ins	SERV
63	66	Services auxiliary to financial services and insurance services	ins, ofi	SERV
64	68	Real estate services	rsa	SERV
65	69-70	Legal and accounting services and Services of head offices; management consulting services	obs	SERV
66	71	Architectural and engineering services; technical testing and analysis services	obs	SERV
67	72	Scientific research and development services	obs	SERV
68	73	Advertising and market research services	obs	SERV
69	74	Other professional, scientific and technical services	obs	SERV
70	75	Veterinary services	obs	SERV
71	77	Rental and leasing services	obs	SERV
72	78	Employment services	obs	SERV
73	79	Travel agency, tour operator and other reservation services and related services	obs	SERV
74	80-82	Security and investigation services, Services for buildings and landscape, Office administration, office support and other business support services	obs	SERV
75	84.1-84.2	Administration services of the state and the economic and social policy of the community and Provision of services to the community as a whole	osg	SERV
76	84.3	Compulsory social security services	osg	SERV
77	85	Education services	edu	SERV
78	86	Human health services	hht	SERV
79	87-88	Residential care services and social work services without accommodation	hht	SERV
80	90-92	Creative, arts and entertainment services and library, archive, museum and other cultural services and Gambling and betting services	ros	SERV
81	93	Sporting services and amusement and recreation services	ros	SERV
82	94	Services furnished by membership organizations	ros	SERV
83	95	Repair services of computers and personal and household goods	obs	SERV
84	96	Other personal services	ros	SERV
85	97-98	Services of households as employers of domestic personnel and undifferentiated goods and services produced by private households for own use	ros	SERV

Model sectors defined by Pothen and Hübler (2018) adapted to GTAP 10. The goods categories following the Classification of Products by Activity (CPA) are derived from the German consumption interdependence table, which can be accessed at https://www.statistischebibliothek.de/mir/receive/DEHeft_mods_00130396.

A.5 Income calculation

Table A3
EVS data items used to generate the required income types

Data item	Number in the EVS
Income from employment	EF109-EF119
+ Non-cash benefits belonging to the salary	EF120-EF133
+ Income from self-employment	EF134-EF136, EF176, EF137
= *Labor income*	
Income from assets	EF178-EF182
= *Capital income*	
Pensions from state pension insurance	EF138-EF140
+ Other pensions	EF142-EF144
+ Transfers from public health insurance funds	EF145, EF146
+ Transfers from programs for the promotion of employment	EF147-EF149, EF151-EF152
+ Transfers of regional authorities	EF153-EF161, EF183-EF184, EF162-EF168
+ Public pensions	EF169-EF170
+ Income from non-public transfer payments	EF171-EF173, EF185-EF192, EF174
+ Additional payments from the employer / pension insurance provider	EF116, EF117, EF141
+ Revenue from sale of goods and other revenue	EF68
+ Income from subletting	EF193
− Income and church taxes (including solidarity surcharge)	EF94
− Compulsory social insurance contributions, contributions to voluntary public and private health insurance	EF95
− Other taxes	EF96
− Insurance contributions	EF98
− Other transfers made	EF100
− Other expenses	EF103
− Contributions to supplementary public service pension scheme (e.g. VBL employee's share)	EF230
− Voluntary contributions to public pension insurance	EF232
= *Net transfers*	

Data items from the "Einkommens- und Verbrauchsstichprobe" (EVS) 2013 (FDZ, 2021) used to generate the required income types of labor income, capital income and net transfers.

A.6 Savings calculation

Table A4
EVS data items used to generate savings

Data item	Number in the EVS
Expenditure on asset formation	EF101
+ Repayment of loans (principal and interest)	EF102
− Income from the liquidation of tangible assets	EF69
− Income from the liquidation of financial assets	EF70
− Income from loans	EF71
= *Savings*	

Data items of the "Einkommens- und Verbrauchsstichprobe" (EVS) 2013 (FDZ, 2021) used to generate the required savings data.

A.7 Resulting data on three income groups

The following tables contain the numbers presented in the figures in Section 2.6.

Table A5
Horizontal source distribution of German income and its use for consumpt. and savings

Income group	Labor income	Capital income	Net transfers	Disposable income	Consump- tion	Savings
Low	132.10	15.07	83.96	231.13	246.05	–7.25
	(57.15%)	(6.52%)	(36.33%)	(100%)	(103.04%)	(-3.04%)
Mid	346.13	55.59	–7.04	394.68	359.11	34.91
	(87.70%)	(14.09%)	(–1.78%)	(100%)	(91.14%)	(8.86%)
High	716.01	121.51	–125.89	711.63	527.29	162.49
	(100.62%)	(17.08%)	(–17.69%)	(100%)	(76.44%)	(23.56%)

Absolute values refer to Germany in the year 2013 and are reported in billions of euros. The percentage shares displayed in parentheses show the distribution of disposable income across income sources and consumption expenditures versus savings within each income group. Data source: authors' own calculation drawing on data from the Research Data Centre (RDC) of the German Federal Statistical Office and Statistical Offices of the Federal States, "Einkommens- und Verbrauchsstichprobe" 2013, base file 5 (FDZ, 2021).

Table A6
Vertical group distribution of German income and its use for consumption and savings

Income group	Labor income	Capital income	Net transfers	Disposable income	Consump- tion	Savings
Low	132.10	15.07	83.96	231.13	246.05	–7.25
	(11.06%)	(7.84%)	(–171.45%)	(17.28%)	(21.73%)	(–3.81%)
Mid	346.13	55.59	–7.04	394.68	359.11	34.91
	(28.98%)	(28.93%)	(14.37%)	(29.51%)	(31.71%)	(18.36%)
High	716.01	121.51	–125.89	711.63	527.29	162.49
	(59.96%)	(63.23%)	(257.08%)	(53.21%)	(46.56%)	(85.45%)
Total	1,194.24	192.18	–48.97	1,337.45	1,132.45	190.15
	(100%)	(100%)	(100%)	(100%)	(100%)	(100%)

Absolute values refer to Germany in the year 2013 and are reported in billions of euros. The percentage shares displayed in parentheses show the distribution of each income type, disposable income, consumption expenditures and savings across the income groups. Data source: authors' own calculation; FDZ (2021), see above.

Table A7
Distribution of German consumption across goods in billions of euros

Income group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
Low	7.80	7.38	1.01	0.61	1.89	9.03	37.57	0.65	0.65	31.84	0.01	3.85	0.62	2.25	9.85	126.82	4.22	246.05
Middle	9.98	11.38	1.07	1.46	3.86	9.66	46.07	1.14	1.14	60.04	0.02	5.28	1.20	3.24	16.92	181.26	5.38	359.11
High	11.80	17.54	1.15	2.38	5.31	10.36	52.64	1.73	1.73	109.28	0.04	7.06	1.95	4.49	23.59	266.90	9.34	527.29
Total	29.58	36.29	3.23	4.45	11.05	29.06	136.29	3.52	3.52	201.16	0.08	16.19	3.77	9.98	50.36	574.98	18.94	1132.45

Horizontal goods distribution of German consumption in percent

Income group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
Low	3.17	3.00	0.41	0.25	0.77	3.67	15.27	0.26	0.26	12.94	0.01	1.56	0.25	0.92	4.00	51.54	1.71	100
Mid	2.78	3.17	0.30	0.41	1.07	2.69	12.83	0.32	0.32	16.72	0.01	1.47	0.33	0.90	4.71	50.47	1.50	100
High	2.24	3.33	0.22	0.45	1.01	1.97	9.98	0.33	0.33	20.72	0.01	1.34	0.37	0.85	4.47	50.62	1.77	100

Vertical group distribution of German consumption in percent

Income group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
Low	26.38	20.33	31.14	13.66	17.07	31.08	27.57	18.41	18.41	15.83	18.87	23.77	16.36	22.56	19.56	22.06	22.28	21.73
Mid	33.75	31.35	33.25	32.76	34.92	33.26	33.80	32.35	32.35	29.85	31.39	32.63	31.92	32.49	33.60	31.52	28.39	31.71
High	39.87	48.32	35.60	53.57	48.02	35.66	38.63	49.24	49.24	54.32	49.74	43.60	51.72	44.95	46.83	46.42	49.33	46.56
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

The absolute values at the top refer to Germany in the year 2013 and are reported in billions of euros. The corresponding percentage shares in the middle display the distribution of consumption expenditures across goods (sectors) within each income group. The percentage shares at the bottom display the distribution of consumption expenditures for each good across income groups. Data source: authors' own calculation; FDZ (2021), see above.

A.8 Resulting data on more income groups

A.8.1 Five income groups

Figure A1
Distribution of total German income

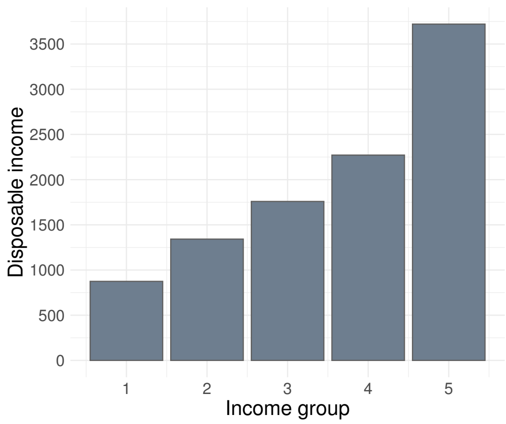


Figure A2
German income sources by income group

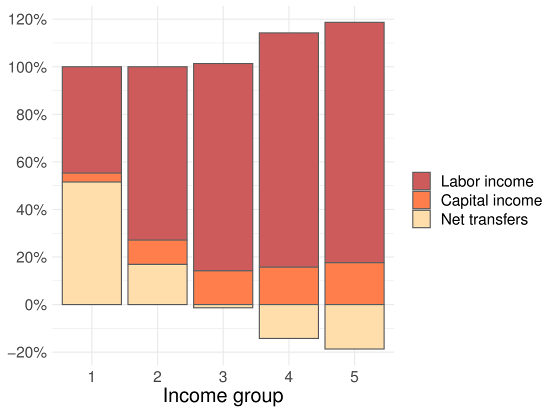


Figure A3
German savings/cons. by income group

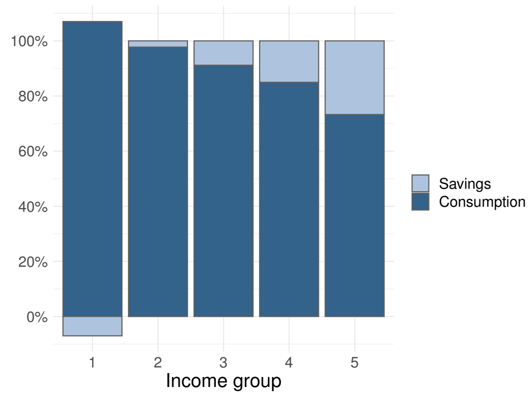


Figure A4
German income sources by source type

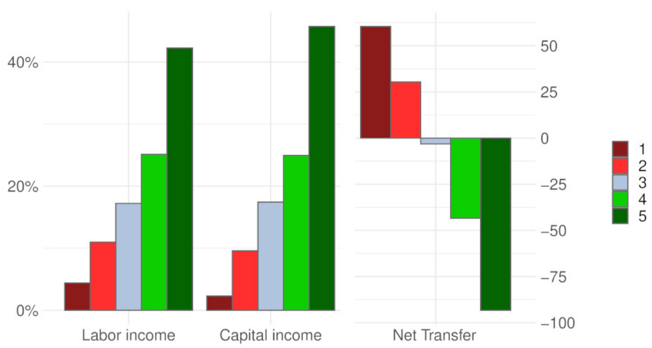
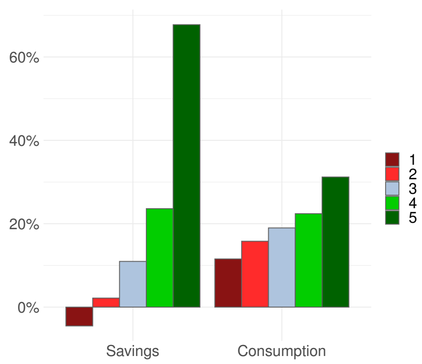


Figure A5
German savings vs. consumption



Income group 1 has the lowest income, and group 5 the highest income. Top row: distribution of the mean equivalent disposable income (total disposable income divided by the number of equivalent people based on the OECD scale) per month of the 52,421 German households in the survey across the income groups in euros. Middle row: Horizontal distribution of income sources (left) and their use for savings versus consumption expenditures (right) within each income group in percent. Bottom row: Vertical distribution of income sources (left) and their use for savings versus consumption expenditures (right) across income groups; net transfers are in billions of euros, and other sources are in percent. Data source: authors' own calculation drawing on data from the Research Data Centre (RDC) of the German Federal Statistical Office and Statistical Offices of the Federal States, "Einkommens- und Verbrauchsstichprobe" 2013, base file 5 (FDZ, 2021). See the following tables for the numbers.

Table A8
Horizontal source distribution of German income and its use for consumpt. and savings

Income group	Labor income	Capital income	Net transfers	Disposable income	Consump-tion	Savings
1	52.45	4.42	60.46	117.33	130.92	–8.58
	(44.71%)	(3.77%)	(51.53%)	(100%)	(107.01%)	(–7.01%)
2	131.23	18.43	30.42	180.08	179.00	4.12
	(72.88%)	(10.23%)	(16.89%)	(100%)	(97.75%)	(2.25%)
3	205.65	33.50	–3.19	235.97	215.19	20.86
	(87.15%)	(14.20%)	(–1.35%)	(100%)	(91.16%)	(8.84%)
4	300.25	47.94	–43.39	304.80	253.83	44.91
	(98.51%)	(15.73%)	(–14.24%)	(100%)	(84.97%)	(15.03%)
5	504.64	87.88	–93.26	499.25	353.50	128.83
	(101.08%)	(17.60%)	(–18.68%)	(100%)	(73.29%)	(26.71%)

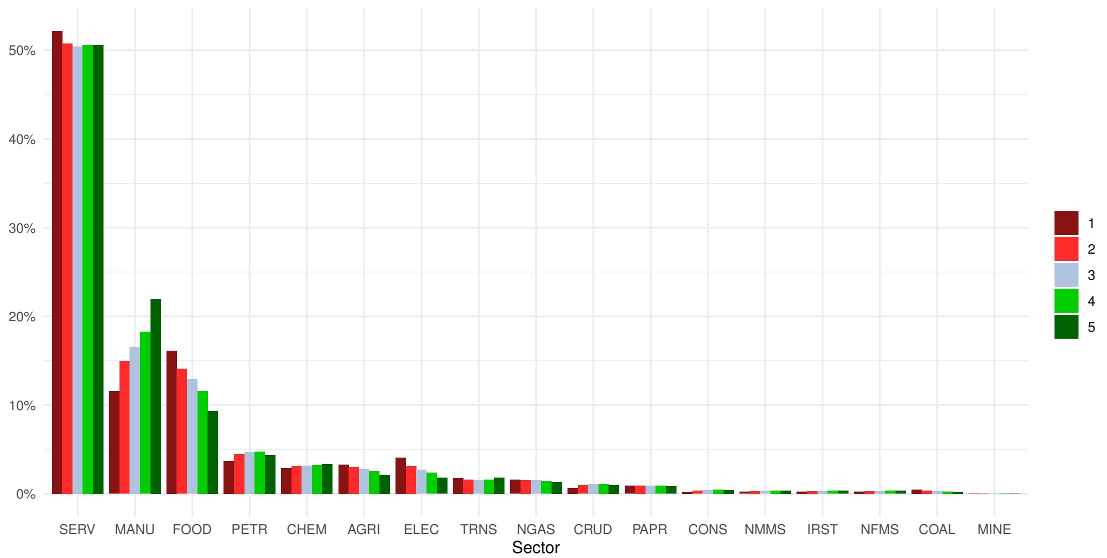
Absolute values refer to Germany in the year 2013 and are reported in billions of euros. The percentage shares displayed in parentheses show the distribution of the disposable income across income sources and expenditures within each income group (1 lowest, 5 highest). Data source: authors' own calculation; FDZ (2021), see above.

Table A9
Vertical group distribution of German income and its use for consumption and savings

Income group	Labor income	Capital income	Net transfers	Disposable income	Consump-tion	Savings
1	52.45	4.42	60.46	117.33	130.92	–8.58
	(4.39%)	(2.30%)	(–123.48%)	(8.77%)	(11.56%)	(–4.51%)
2	131.23	18.43	30.42	180.08	179.00	4.12
	(10.99%)	(9.59%)	(–62.12%)	(13.46%)	(15.81%)	(2.17%)
3	205.65	33.50	–3.19	235.97	215.19	20.86
	(17.22%)	(17.43%)	(6.52%)	(17.64%)	(19.00%)	(10.97%)
4	300.25	47.94	–43.39	304.80	253.83	44.91
	(25.14%)	(24.95%)	(88.62%)	(22.79%)	(22.41%)	(23.62%)
5	504.64	87.88	–93.26	499.25	353.50	128.83
	(42.26%)	(45.73%)	(190.47%)	(37.33%)	(31.22%)	(67.75%)
Total	1,194.22	192.17	–48.96	1,337.43	1,132.44	190.15
	(100%)	(100%)	(100%)	(100%)	(100%)	(100%)

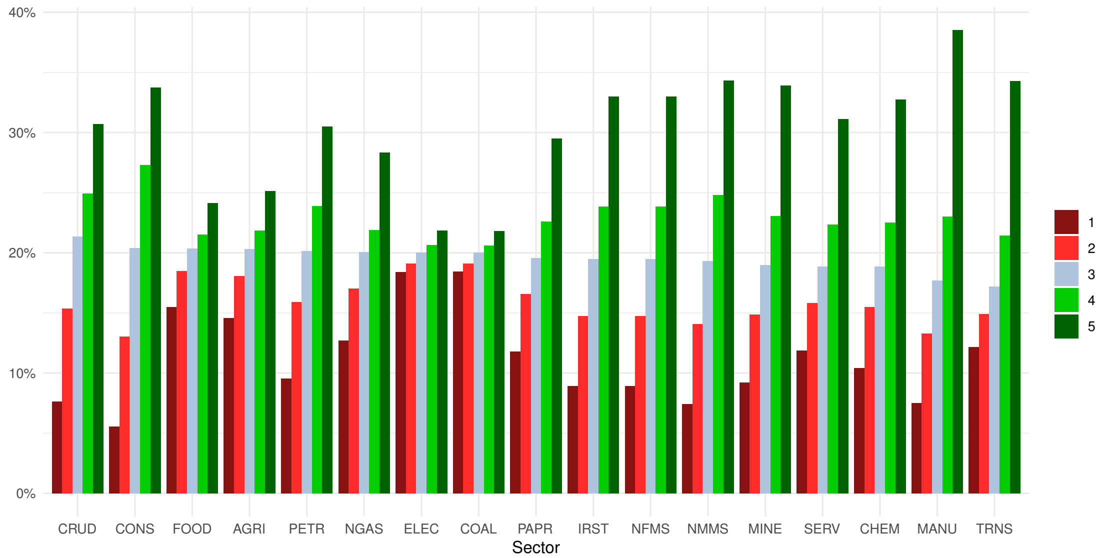
Absolute values refer to Germany in the year 2013 and are reported in billions of euros. The percentage shares displayed in parentheses show the distribution of each income type, disposable income, consumption expenditures and savings across the income groups (1 lowest, 5 highest). Data source: authors' own calculation; FDZ (2021), see above.

Figure A6
Horizontal distribution of German consumption expenditures of each group across goods



Horizontal distribution of each income group's (1 lowest, 5 highest) consumption expenditures across goods (sectors) in Germany. Data source: authors' own calculation; FDZ (2021), see above. See the following table for the numbers.

Figure A7
Vertical distribution of German consumption expenditures on each good across groups



Vertical distribution of consumption expenditures on each good (sector) across the income groups (1 lowest, 5 highest) in Germany. Data source: authors' own calculation; FDZ (2021), see above. See the following table for the numbers.

Table A10

Distribution of German consumption across goods in billions of euros

Group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
1	4.31	3.77	0.60	0.25	0.85	5.35	21.13	0.31	0.31	15.11	0.01	2.06	0.28	1.18	4.81	68.30	2.30	130.92
2	5.35	5.61	0.62	0.58	1.70	5.55	25.20	0.52	0.52	26.69	0.01	2.76	0.53	1.65	8.01	90.86	2.83	179.00
3	6.01	6.85	0.65	0.91	2.36	5.82	27.75	0.69	0.69	35.59	0.01	3.25	0.73	1.95	10.15	108.54	3.25	215.19
4	6.47	8.17	0.67	1.21	2.75	5.99	29.32	0.84	0.84	46.31	0.02	3.54	0.94	2.26	12.03	128.42	4.06	253.83
5	7.44	11.88	0.70	1.50	3.39	6.35	32.89	1.16	1.16	77.46	0.03	4.59	1.29	2.94	15.36	178.86	6.49	353.50
Total	29.58	36.29	3.23	4.45	11.05	29.06	136.29	3.52	3.52	201.16	0.08	16.19	3.77	9.98	50.36	574.97	18.94	1,132.44

Horizontal goods distribution of German consumption in percent

Group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
1	3.30	2.88	0.46	0.19	0.65	4.09	16.14	0.24	0.24	11.54	0.01	1.57	0.21	0.90	3.68	52.17	1.76	100
2	2.99	3.14	0.35	0.32	0.95	3.10	14.08	0.29	0.29	14.91	0.01	1.54	0.30	0.92	4.48	50.76	1.58	100
3	2.79	3.18	0.30	0.42	1.10	2.70	12.90	0.32	0.32	16.54	0.01	1.51	0.34	0.91	4.72	50.44	1.51	100
4	2.55	3.22	0.26	0.48	1.08	2.36	11.55	0.33	0.33	18.24	0.01	1.40	0.37	0.89	4.74	50.59	1.60	100
5	2.10	3.36	0.20	0.42	0.96	1.80	9.30	0.33	0.33	21.91	0.01	1.30	0.37	0.83	4.35	50.60	1.84	100

Vertical group distribution of German consumption in percent

Group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
1	14.58	10.40	18.45	5.54	7.65	18.40	15.51	8.93	8.93	7.51	9.21	12.71	7.43	11.79	9.55	11.88	12.15	11.56
2	18.08	15.47	19.12	13.05	15.37	19.11	18.49	14.75	14.75	13.27	14.88	17.04	14.08	16.57	15.91	15.80	14.92	15.81
3	20.33	18.87	20.01	20.40	21.37	20.01	20.36	19.49	19.49	17.69	18.96	20.04	19.33	19.55	20.15	18.88	17.19	19.00
4	21.87	22.52	20.61	27.29	24.92	20.63	21.51	23.83	23.83	23.02	23.04	21.89	24.82	22.60	23.88	22.33	21.44	22.41
5	25.14	32.74	21.81	33.73	30.70	21.85	24.13	33.01	33.01	38.51	33.90	28.33	34.33	29.49	30.50	31.11	34.30	31.22
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

The absolute values at the top refer to Germany in the year 2013 and are reported in billions of euros. The corresponding percentage shares in the middle display the distribution of consumption expenditures across goods (sectors) within each income group (1 lowest, 5 highest). The percentage shares at the bottom display the distribution of consumption expenditures for each sector good across the income groups. Data source: authors' own calculation; FDZ (2021), see above.

A.8.2 Ten income groups

Figure A8
Distribution of total German income

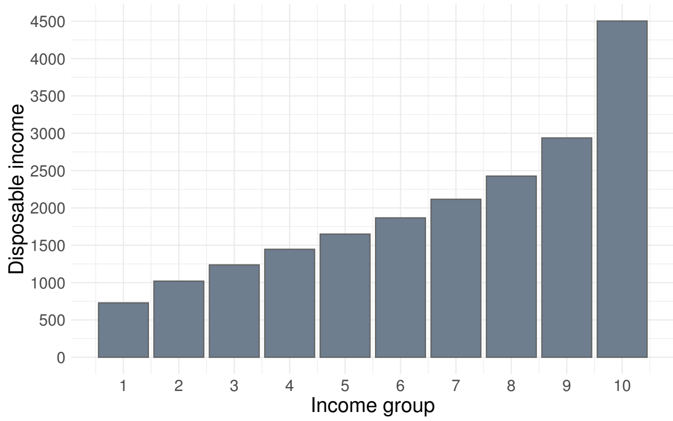


Figure A9
German income sources by income group

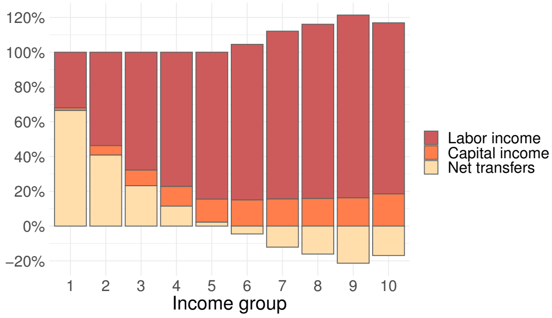


Figure A10
German savings/cons. by income group

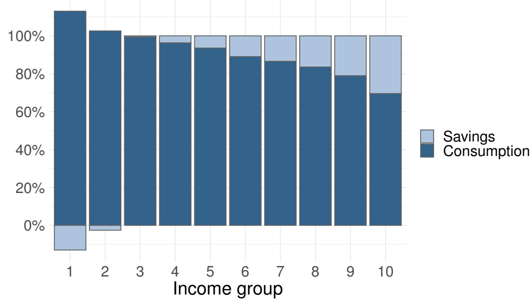


Figure A11
German income sources by source type

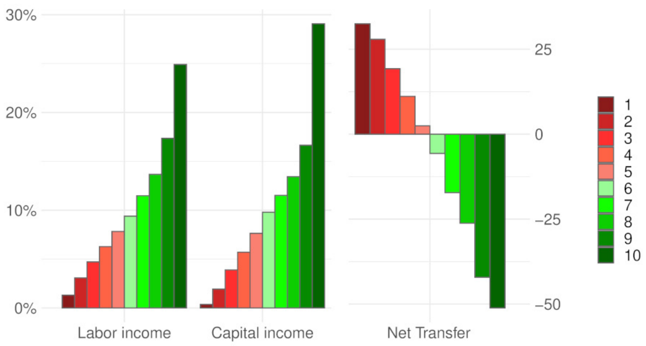
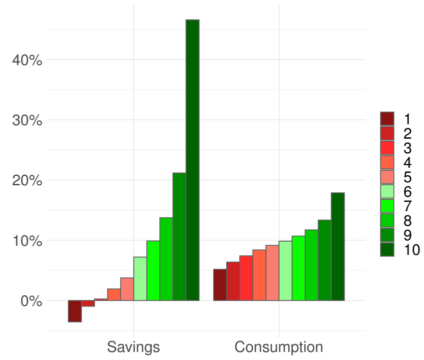


Figure A12
German savings vs. consumption



Income group 1 has the lowest income, and group 10 has the highest income. Top row: distribution of the mean equivalent disposable income (total disposable income divided by the number of equivalent people based on the OECD scale) per month of the 52,421 German households in the survey across the income groups in euros. Middle row: Horizontal distribution of income sources (left) and their use for savings versus consumption expenditures (right) within each income group in percent. Bottom row: Vertical distribution of income sources (left) and their use for savings versus consumption expenditures (right) across the income groups; net transfers in billions of euros, other sources in percent. Data source: authors' own calculation drawing on data from the Research Data Centre (RDC) of the German Federal Statistical Office and Statistical Offices of the Federal States, "Einkommens- und Verbrauchsstichprobe" 2013, base file 5 (FDZ, 2021). See the following tables for the numbers.

Table A11
Horizontal source distribution of German income and its use for consumpt. and savings

Income Group	Labor Income	Capital Income	Net Transfers	Disposable Income	Consumption	Savings
1	15.68	0.71	32.52	48.91	58.68	–6.75
	(32.07%)	(1.44%)	(66.49%)	(100%)	(113.01%)	(–13.01%)
2	36.78	3.71	27.94	68.43	72.25	-1.82
	(53.74%)	(5.43%)	(40.83%)	(100%)	(102.59%)	(-2.59%)
3	56.28	7.47	19.27	83.03	83.95	0.48
	(67.79%)	(9.00%)	(23.21%)	(100%)	(99.43%)	(0.57%)
4	74.96	10.96	11.14	97.06	95.05	3.65
	(77.23%)	(11.29%)	(11.48%)	(100%)	(96.31%)	(3.69%)
5	93.53	14.68	2.48	110.69	103.69	7.14
	(84.50%)	(13.26%)	(2.24%)	(100%)	(93.55%)	(6.45%)
6	112.12	18.82	–5.67	125.28	111.50	13.71
	(89.50%)	(15.03%)	(–4.53%)	(100%)	(89.05%)	(10.95%)
7	137.04	22.13	–17.19	141.98	121.06	18.80
	(96.52%)	(15.59%)	(–12.11%)	(100%)	(86.56%)	(13.44%)
8	163.21	25.82	–26.20	162.82	132.77	26.12
	(100.24%)	(15.86%)	(–16.09%)	(100%)	(83.56%)	(16.44%)
9	207.23	32.00	–42.12	197.10	151.12	40.25
	(105.14%)	(16.23%)	(–21.37%)	(100%)	(78.97%)	(21.03%)
10	297.42	55.89	–51.14	302.17	202.38	88.58
	(98.43%)	(18.50%)	(–16.92%)	(100%)	(69.55%)	(30.45%)

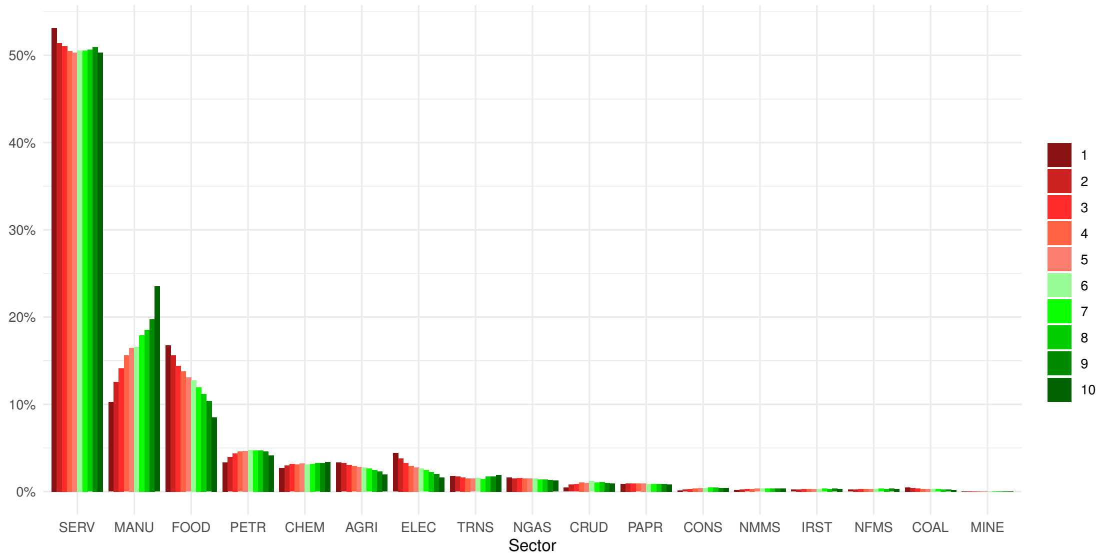
Absolute values refer to Germany in the year 2013 and are reported in billions of euros. The percentage shares displayed in parentheses show the distribution of the disposable income across income sources and consumption expenditures versus savings within each income group (1 lowest, 10 highest). Data source: authors' own calculation; FDZ (2021), see above.

Table A12
Vertical group distribution of German income and its use for consumption and savings

Income Group	Labor Income	Capital Income	Net Transfers	Disposable Income	Consumption	Savings
1	15.68 (1.31%)	0.71 (0.37%)	32.52 (–66.40%)	48.91 (3.66%)	58.68 (5.18%)	–6.75 (–3.55%)
2	36.78 (3.08%)	3.71 (1.93%)	27.94 (–57.06%)	68.43 (5.12%)	72.25 (6.38%)	–1.82 (–0.96%)
3	56.28 (4.71%)	7.47 (3.89%)	19.27 (–39.35%)	83.03 (6.21%)	83.95 (7.41%)	0.48 (0.25%)
4	74.96 (6.28%)	10.96 (5.70%)	11.14 (–22.75%)	97.06 (7.26%)	95.05 (8.39%)	3.65 (1.92%)
5	93.53 (7.83%)	14.68 (7.64%)	2.48 (-5.06%)	110.69 (8.28%)	103.69 (9.16%)	7.14 (3.76%)
6	112.12 (9.39%)	18.82 (9.79%)	–5.67 (11.58%)	125.28 (9.37%)	111.50 (9.85%)	13.71 (7.21%)
7	137.04 (11.48%)	22.13 (11.51%)	–17.19 (35.10%)	141.98 (10.62%)	121.06 (10.69%)	18.80 (9.88%)
8	163.21 (13.67%)	25.82 (13.43%)	–26.20 (53.50%)	162.82 (12.17%)	132.77 (11.72%)	26.12 (13.74%)
9	207.23 (17.35%)	32.00 (16.65%)	–42.12 (86.01%)	197.10 (14.74%)	151.12 (13.34%)	40.25 (21.17%)
10	297.42 (24.90%)	55.89 (29.08%)	–51.14 (104.43%)	302.17 (22.59%)	202.38 (17.87%)	88.58 (46.58%)
Total	1,194.25 (100%)	192.18 (100%)	–48.97 (100%)	1,337.46 (100%)	1,132.45 (100%)	190.16 (100%)

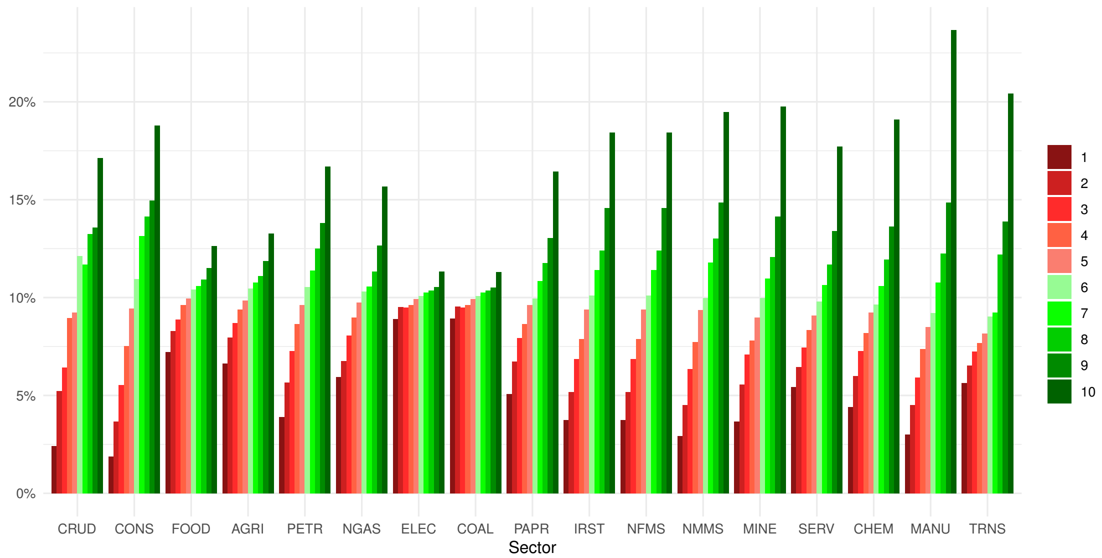
Absolute values refer to Germany in the year 2013 and are reported in billions of euros. The percentage shares displayed in parentheses show the distribution of each income type, disposable income, consumption expenditures and savings across the income groups (1 lowest, 10 highest). Data source: authors' own calculation; FDZ (2021), see above.

Figure A13
Horizontal distribution of German consumption expenditures of each group across goods



Horizontal distribution of each income group's (1 lowest, 10 highest) consumption expenditures across goods (sectors) in Germany. Data source: authors' own calculation; FDZ (2021), see above. See the following table for the numbers.

Figure A14
Vertical distribution of German consumption expenditures on each good across groups



Vertical distribution of consumption expenditures on each good (sector) across income groups (1 lowest, 10 highest) in Germany. Data source: authors' own calculation; FDZ (2021), see above. See the following table for the numbers.

Table A13

Distribution of German consumption across goods in billions of euros

Group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
1	1.96	1.60	0.29	0.08	0.27	2.58	9.84	0.13	0.13	6.02	0.00	0.96	0.11	0.51	1.96	31.17	1.06	58.68
2	2.36	2.18	0.31	0.16	0.58	2.76	11.29	0.18	0.18	9.09	0.00	1.10	0.17	0.67	2.85	37.13	1.24	72.25
3	2.57	2.64	0.31	0.25	0.71	2.76	12.10	0.24	0.24	11.88	0.01	1.31	0.24	0.79	3.66	42.89	1.37	83.95
4	2.78	2.97	0.31	0.34	0.99	2.80	13.10	0.28	0.28	14.82	0.01	1.45	0.29	0.86	4.35	47.98	1.45	95.05
5	2.92	3.35	0.32	0.42	1.02	2.88	13.55	0.33	0.33	17.07	0.01	1.58	0.35	0.96	4.85	52.20	1.54	103.69
6	3.10	3.50	0.33	0.49	1.34	2.93	14.20	0.36	0.36	18.52	0.01	1.67	0.38	0.99	5.30	56.34	1.71	111.50
7	3.19	3.84	0.33	0.59	1.29	2.98	14.45	0.40	0.40	21.68	0.01	1.71	0.44	1.08	5.73	61.20	1.75	121.06
8	3.28	4.33	0.33	0.63	1.46	3.01	14.87	0.44	0.44	24.63	0.01	1.84	0.49	1.17	6.30	67.22	2.31	132.77
9	3.51	4.95	0.34	0.67	1.50	3.06	15.68	0.51	0.51	29.87	0.01	2.05	0.56	1.30	6.95	77.01	2.63	151.12
10	3.93	6.93	0.36	0.84	1.89	3.29	17.21	0.65	0.65	47.59	0.01	2.54	0.73	1.64	8.41	101.85	3.87	202.38
Total	29.58	36.29	3.23	4.45	11.05	29.06	136.29	3.52	3.52	201.16	0.08	16.19	3.77	9.98	50.36	574.98	18.94	1132.45

Horizontal goods distribution of German consumption

Group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
1	3.34	2.72	0.49	0.14	0.46	4.40	16.78	0.22	0.22	10.26	0.00	1.64	0.19	0.86	3.34	53.11	1.81	100
2	3.26	3.01	0.43	0.23	0.80	3.83	15.62	0.25	0.25	12.58	0.01	1.52	0.23	0.93	3.95	51.39	1.71	100
3	3.07	3.14	0.37	0.29	0.85	3.28	14.41	0.29	0.29	14.15	0.01	1.56	0.28	0.94	4.36	51.08	1.64	100
4	2.92	3.13	0.33	0.35	1.04	2.94	13.78	0.29	0.29	15.59	0.01	1.53	0.31	0.91	4.58	50.47	1.53	100
5	2.81	3.23	0.31	0.41	0.99	2.78	13.07	0.32	0.32	16.47	0.01	1.52	0.34	0.92	4.67	50.34	1.49	100
6	2.78	3.14	0.29	0.44	1.20	2.63	12.73	0.32	0.32	16.61	0.01	1.50	0.34	0.89	4.75	50.53	1.53	100
7	2.63	3.17	0.27	0.48	1.07	2.46	11.93	0.33	0.33	17.90	0.01	1.41	0.37	0.89	4.73	50.55	1.44	100
8	2.47	3.26	0.25	0.47	1.10	2.27	11.20	0.33	0.33	18.55	0.01	1.38	0.37	0.88	4.74	50.63	1.74	100
9	2.32	3.28	0.22	0.44	0.99	2.03	10.37	0.34	0.34	19.77	0.01	1.36	0.37	0.86	4.60	50.96	1.74	100
10	1.94	3.42	0.18	0.41	0.94	1.63	8.50	0.32	0.32	23.51	0.01	1.25	0.36	0.81	4.15	50.33	1.91	100

Vertical group distribution of German consumption

Group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
1	6.62	4.40	8.92	1.87	2.42	8.89	7.22	3.75	3.75	2.99	3.66	5.94	2.93	5.06	3.89	5.42	5.62	5.18
2	7.97	6.00	9.53	3.67	5.23	9.51	8.28	5.18	5.18	4.52	5.55	6.77	4.50	6.72	5.67	6.46	6.53	6.38
3	8.70	7.27	9.50	5.52	6.43	9.48	8.88	6.86	6.86	5.90	7.09	8.07	6.35	7.93	7.28	7.46	7.25	7.41
4	9.38	8.20	9.63	7.53	8.95	9.62	9.61	7.89	7.89	7.37	7.79	8.97	7.73	8.64	8.64	8.34	7.67	8.39
5	9.86	9.24	9.93	9.44	9.24	9.93	9.94	9.38	9.38	8.49	8.99	9.74	9.36	9.60	9.62	9.08	8.16	9.16
6	10.47	9.63	10.08	10.96	12.12	10.09	10.42	10.11	10.11	9.20	9.97	10.30	9.98	9.95	10.53	9.80	9.03	9.85
7	10.77	10.58	10.26	13.15	11.68	10.26	10.60	11.42	11.42	10.78	10.98	10.55	11.80	10.83	11.38	10.64	9.24	10.69
8	11.10	11.94	10.35	14.13	13.24	10.36	10.91	12.41	12.41	12.24	12.07	11.33	13.02	11.76	12.50	11.69	12.20	11.72
9	11.87	13.64	10.52	14.96	13.57	10.53	11.50	14.57	14.57	14.85	14.15	12.66	14.85	13.04	13.81	13.39	13.88	13.34
10	13.27	19.10	11.29	18.78	17.13	11.32	12.63	18.43	18.43	23.66	19.75	15.66	19.49	16.45	16.69	17.71	20.41	17.87
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

The absolute values at the top refer to Germany in the year 2013 and are reported in billions of euros. The corresponding percentage shares in the middle display the distribution of consumption expenditures across goods (sectors) within each income group (1 lowest, 10 highest). The percentage shares at the bottom display the distribution of consumption expenditures for each good across income groups. Data source: authors' own calculation; FDZ (2021), see above.

B Computable general equilibrium model

Appendix B describes the exemplary basic model with regard to the trade, consumption and production structure followed by the corresponding parameter values, i.e., elasticities of substitution. It begins by characterizing the model solution that represents a global general equilibrium of all goods and factor markets.

B.1 Model implementation and solution

The model solution defines a holistic global market solution derived from consumer and producer optimization, excluding any external effects, such as climate change impacts.

The model follows the standard approach to setting up a general equilibrium (CGE) model by defining a balanced (consumer) budget, zero (producer) profit and (goods and factor) market clearance conditions. Production factor endowments (with capital K, labor L, land N, and natural resources R including fossil fuels) are given in each model region (r or, equivalently, s) and attached to the representative consumer (or each income group). The regional representative consumers and the regional sectoral producers (of each good or service i or, equivalently, j) maximize their utility or profits, respectively, which leads to optimality conditions. They form a system of n equations with n unknowns, for which a unique solution representing a Walrasian (Arrow–Debreu) equilibrium of all markets exists.

The computable general equilibrium (CGE) model is programmed as a mixed complementarity problem (MCP) in general algebraic modeling system (GAMS; Bussieck and Meeraus (2004)).[24] It features the mathematical programming system for general equilibrium analysis (MPSGE) introduced by Thomas Rutherford.[25] It is solved by using the PATH algorithm (Dirkse and Ferris (1995)) with the MPSGE solver. The model is calibrated to the newest GTAP[26] 10 data for the benchmark year 2014 (cf. Pothen and Hübler (2018)). The *Monte Carlo* (sensitivity) analysis with 1000 random draws of parameter sets and corresponding model solutions in each experiment is carried out by using the Snakemake workflow management system.[27]

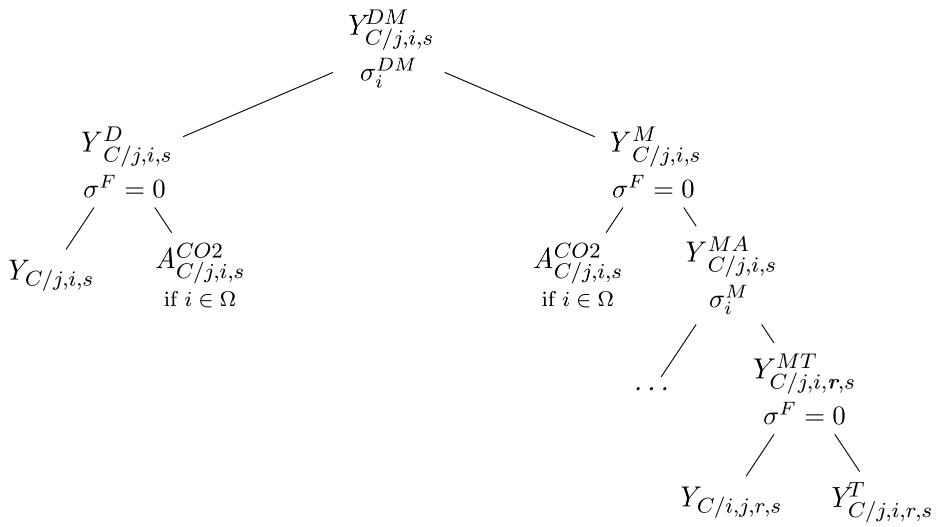
For each model region r (equivalently s), the model solution contains the quantities of private consumption C (of each income group if available) and the corresponding utility based on consumption expenditures, public consumption G, sectoral production Y, sec-

[24] https://www.gams.com/.
[25] https://www.gams.com/latest/docs/UG_MPSGE.html, https://www.gams.com/latest/docs/mpsge.pdf.
[26] Global Trade Analysis Project, https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx.
[27] https://snakemake.readthedocs.io/en/stable/.

toral imports M, associated sectoral transportation services Y^T, and the corresponding market equilibrium prices p of goods and factors, including a CO_2 price p^E, while the total CO_2 emissions $\bar{E}_r$ are given for each region as an emissions cap. Relative (percentage) changes in consumption (utility) between a policy and the reference scenario represent regional (or income-group-specific) welfare changes that are used as the main policy outcome.

B.2 Representation of international trade

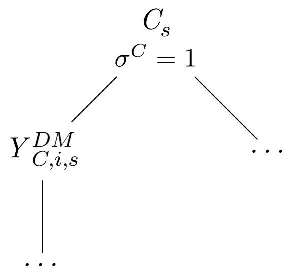
Figure B1
Nesting structure of international trade



This nesting structure represents a constant elasticity of substitution (CES) function describing international trade in goods (and services) i (or, equivalently, j). Goods i are produced in regions r, internationally traded and consumed in region s (see Figure B2) or used as intermediate inputs in production in s (see Figure B3) (where $s = r$ implies domestic consumption within a region). Therefore, this function is defined for consumption, C, and for each sector j in s, symbolized by C/j. Y denotes production. Similar to consumption, C, it is measured in pecuniary terms. D indicates domestically produced goods, and M indicates imported goods. Y^{MT} combines production Y with transport services Y^T. Y^{MA} aggregates a good i over all available regions r of origin to an Armington aggregate. $\Omega = \{COAL, CRUD, NGAS, PETR\}$ is a subset of all sectors containing fossil fuels that release fossil fuel-specific amounts A of CO_2 when used in production. Therefore, a CO_2 price is attached to them, resulting in bundles Y^D and Y^M. For each i, Y^{DM} combines the domestically produced good Y^D with the aggregate of imports Y^M. σ denotes an elasticity of substitution between inputs. A higher σ value implies better substitutability. $\sigma^F = 0$ characterizes a Leontief relation without room for substitution. The sector-specific elasticity values σ_i^{DM} and σ_i^M are displayed in Table B1.

B.3 Consumption structure

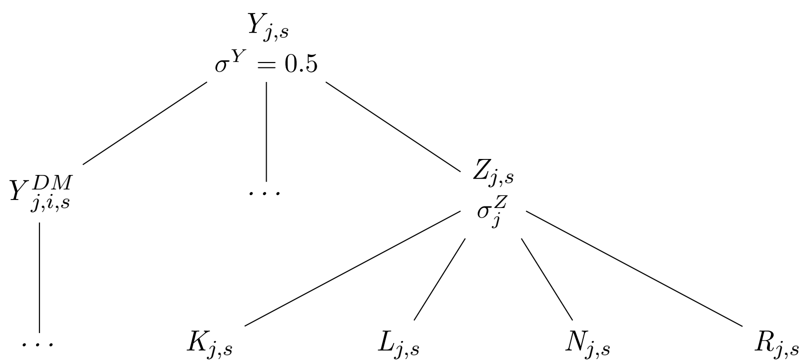
Figure B2
Nesting structure of consumption



This nesting structure represents a constant elasticity of substitution (CES) function describing private (utility) or public consumption. (Unlike private consumption, public consumption does not include CO_2 inputs.) The consumption bundle Y^{DM} of each good i used in consumption C in region s is detailed in Figure B1. $\sigma^C = 1$ implies a Cobb-Douglas aggregate over all available goods i (including fossil fuels).

B.4 Production structure

Figure B3
Nesting structure of sectoral production



For each good (sector) j in a region s, this nesting structure represents a constant elasticity of substitution (CES) production function. The intermediate goods bundle Y^{DM} of each good i used in production, Y, in region s is detailed in Figure B1. Y denotes production, Z the combined production factors (both are quantities measured in pecuniary terms): capital K, labor L, land N, and natural resources R including fossil fuels. $\sigma^Y = 0.5$ implies an aggregate over all available intermediate goods inputs i (including fossil fuels) and the combined production factor inputs with a low substutability.

B.5 Elasticities of substitution

Table B1
Sector-specific elasticities of substitution in the CES functions of the model

Sector i	Description	Armgt. elast. btw. region-spec. imp. σ_i^M	Trade elast. btw. dom. & imp. σ_i^{DM}	Input elast. btw. prod. factors σ_i^Z
$AGRI$	Agriculture	2.69	2.35	0.25
$COAL$	Coal	10.02	3.05	0.20
$CRUD$	Crude oil	7.89	5.20	0.20
$NGAS$	Natural gas	7.94	12.96	0.49
$PETR$	Refined petroleum	9.67	2.10	1.26
$FOOD$	Food production	3.80	2.48	1.12
$MINE$	Mining	2.43	0.90	0.20
$PAPR$	Paper and pulp	5.18	2.95	1.26
$CHEM$	Chemicals, rubber and plastic	4.45	3.30	1.26
$NMMS$	Mineral products nec.	6.39	2.90	1.26
$IRST$	Iron and steel	4.21	2.95	1.26
$NFMS$	Non-ferrous metals	4.43	4.20	1.26
$MANU$	Manufacturing	5.05	3.83	1.26
$ELEC$	Electricity	18.66	2.80	1.26
$TRNS$	Transport	6.21	1.90	1.70
$CONS$	Construction	15.07	1.90	1.40
$SERV$	Services	6.43	1.92	1.36

Model sectors (goods and services as defined by Pothen and Hübler (2018)) and related elasticities of substitution (rounded to two digits). Armington elasticities are derived from the structural estimation of the Eaton and Kortum trade model by Pothen and Hübler (2018) according to the trade model unification theory of Arkolakis et al. (2012). The remaining trade and input elasticities are taken from the GTAP 10 database (Aguiar et al., 2019).

B.6 Sensitivity analysis

Table B2
Robustness check: varying Armington elasticities σ_i^M

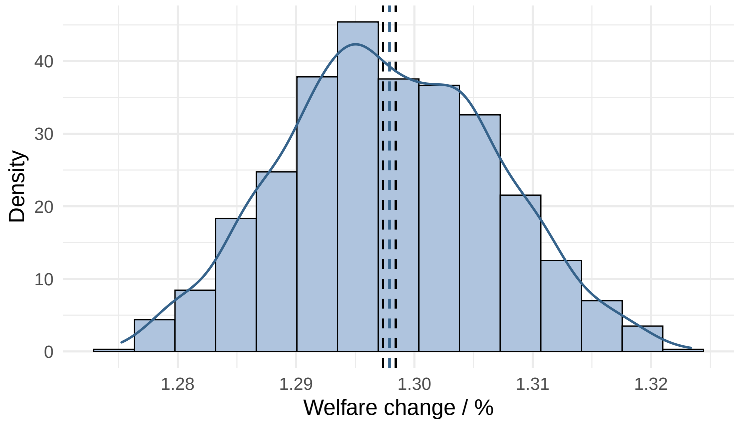
	Domestic CO_2 price				*Border CO_2 price*			
Income group	LO		UP		LO		UP	
1	1.33	(2.79)	1.26	(–2.56)	1.43	(2.70)	1.36	(–2.48)
2	–0.49	(–1.62)	–0.50	(1.25)	–0.46	(–2.03)	–0.48	(1.61)
3	–1.21	(0.01)	–1.20	(–0.16)	–1.21	(–0.15)	–1.21	(–0.02)

Welfare effects are reported as percentage changes for variation of Armington elasticities σ_i^M by ±10%. Additionally, deviations of these numbers relative to the standard results are reported in per cent in parentheses, i.e. (robustness check change – baseline change)/(baseline change). LO = lower bound with all $\sigma_i^M \cdot 0.9$; UP = upper bound with all $\sigma_i^M \cdot 1.1$.

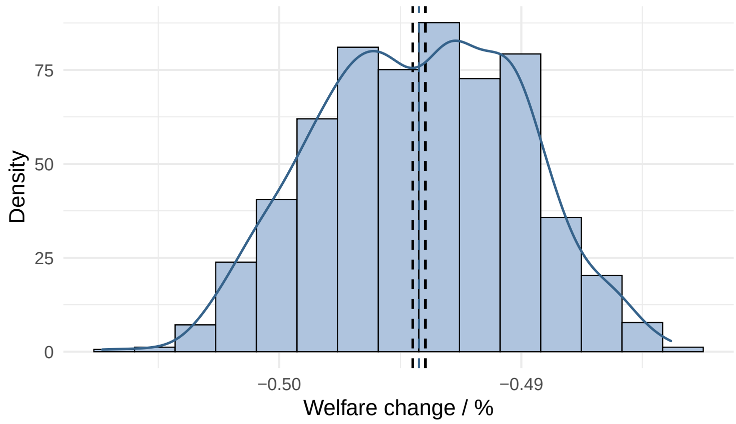
Figure B4

Distributional sensitivity analysis of Armington elasticities σ_i^M:

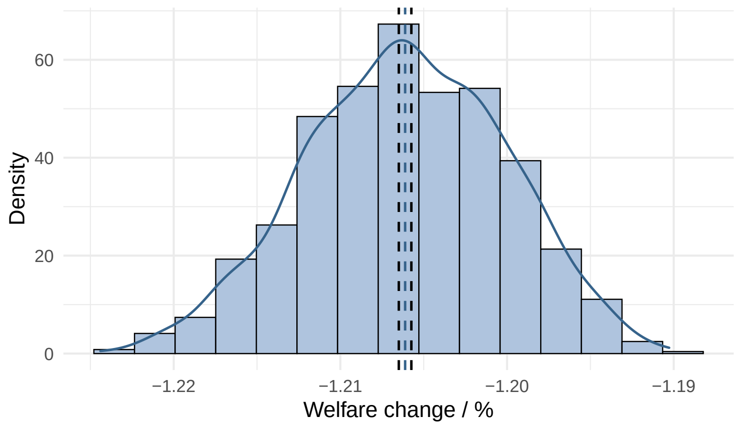
Domestic CO_2 price



(a) Low-income group



(b) Middle-income group



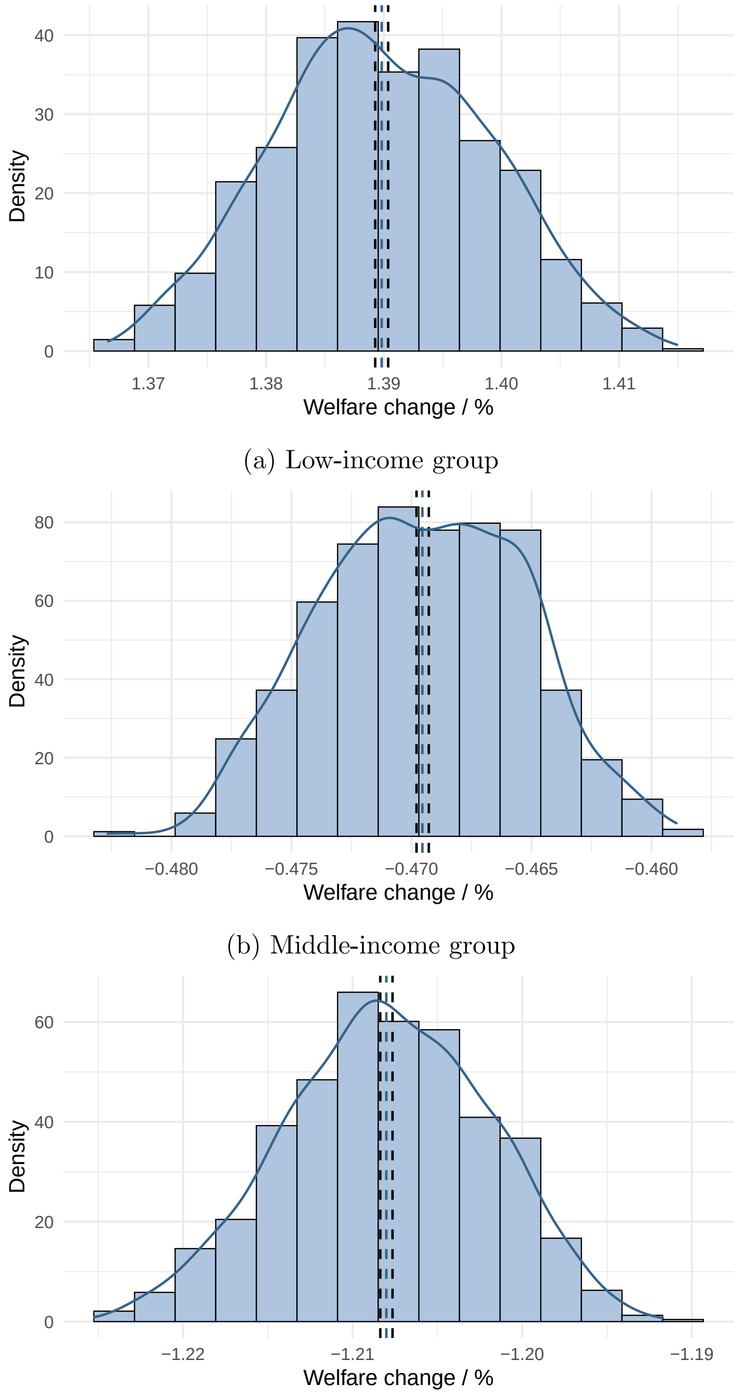
(c) High-income group

Distribution of welfare effects of *Domestic CO_2 price* for the low-, middle- and high-income groups. The distributions are generated from 1000 random draws from a ±10% interval around each sector-specific Armington elasticity σ_i^M. Dashed vertical blue lines indicate mean welfare effects, while dashed vertical black lines indicate bootstrap 95% confidence intervals. Solid blue lines represent Kernel density estimations.

Figure B5

Distributional sensitivity analysis of Armington elasticities σ_i^M:

Border CO_2 price



(c) High-income group

Distribution of welfare effects of *Border CO_2 price* for the low-, middle- and high-income groups. The distributions are generated from 1000 random draws from a ±10% interval around each sector-specific Armington elasticity σ_i^M. Dashed vertical blue lines indicate mean welfare effects, while dashed vertical black lines indicate bootstrap 95% confidence intervals. Solid blue lines represent Kernel density estimations.

Table B3

Robustness check: varying domestic import elasticities σ_i^{DM}

Income group	*Domestic CO_2 price* LO		UP		*Border CO_2 price* LO		UP	
1	1.31	(1.28)	1.28	(–1.23)	1.41	(1.26)	1.37	(–1.22)
2	–0.49	(–0.16)	–0.49	(0.10)	–0.47	(–0.24)	–0.47	(0.18)
3	–1.21	(0.36)	–1.20	(–0.38)	–1.21	(0.35)	–1.20	(–0.38)

Welfare effects are reported as percentage changes for variation of domestic import elasticities σ_i^{DM} by ±10%. Additionally, deviations of these numbers relative to the standard results are reported in per cent in parentheses, i.e. (robustness check change – baseline change)/(baseline change). LO = lower bound with all $\sigma_i^{DM} \cdot 0.9$; UP = upper bound with all $\sigma_i^{DM} \cdot 1.1$.

Table B4

Robustness check: varying input elasticities between production factors σ_i^Z

Income group	*Domestic CO_2 price* LO		UP		*Border CO_2 price* LO		UP	
1	1.30	(0.57)	1.29	(–0.50)	1.40	(0.54)	1.38	(–0.48)
2	–0.49	(–0.80)	–0.50	(0.72)	–0.47	(–0.87)	–0.47	(0.79)
3	–1.20	(–0.27)	–1.21	(0.25)	–1.20	(–0.28)	–1.21	(0.26)

Welfare effects are reported as percentage changes for variation of input elasticities between production factors σ_i^Z by ±10%. Additionally, deviations of these numbers relative to the standard results are reported in per cent in parentheses, i.e. (robustness check change – baseline change)/(baseline change). LO = lower bound with all $\sigma_i^Z \cdot 0.9$; UP = upper bound with all $\sigma_i^Z \cdot 1.1$.

Table B5

Robustness check: alternative land and natural resources income shares

Domestic CO_2 price	(1)		(2)		(3)		(4)		(5)	
Income group										
1	0.23	(–82.39)	2.69	(107.26)	2.69	(107.39)	0.61	(–52.66)	1.87	(44.03)
2	–0.08	(–84.46)	–1.22	(146.57)	–0.08	(–84.76)	–0.56	(12.89)	–0.46	(–7.54)
3	–1.16	(–4.18)	–1.15	(–4.26)	–1.90	(57.11)	–0.96	(–20.40)	–1.40	(16.20)
Border CO_2 price	(1)		(2)		(3)		(4)		(5)	
Income group										
1	0.32	(–77.00)	2.78	(100.24)	2.78	(100.36)	0.71	(–49.22)	1.96	(41.15)
2	–0.05	(–88.97)	–1.19	(154.39)	–0.05	(–89.28)	–0.53	(13.58)	–0.43	(–7.95)
3	–1.16	(–4.18)	–1.16	(–4.26)	–1.90	(57.06)	–0.96	(–20.39)	–1.40	(16.19)

Welfare effects of *Domestic CO_2 price* and *Border CO_2 price* for alternative values of land and natural resources income shares. In column 1, income shares of both land and natural resources are 0%, 50% and 50% for low-, middle- and high-income groups, respectively. Analogously, column 2 assumes income shares of 50%, 0% and 50%, and column 3 assumes income shares of 50%, 50% and 0%. In column 4, income shares are set to capital income shares of the three income groups. In column 5, income shares are set to 1/3 for all three income groups. Additionally, deviations of these numbers relative to the standard results are reported in per cent in parentheses, i.e. (robustness check change – baseline change)/(baseline change).

Table B6

Robustness check: alternative CO_2 pricing revenue shares

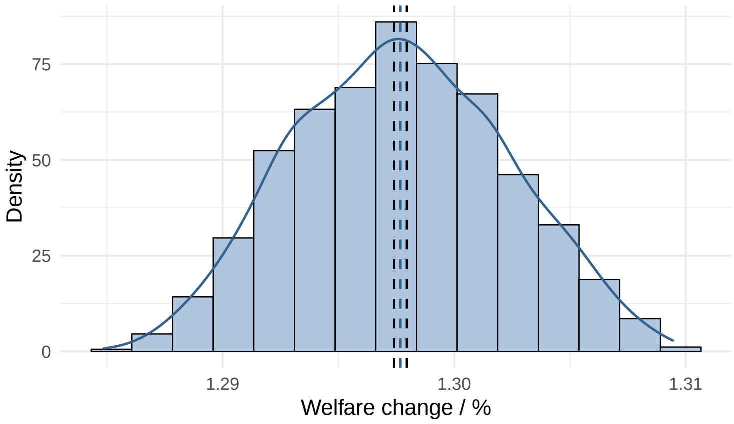
Domestic CO_2 price	(1)		(2)		(3)		(4)	
Income group								
1	–1.75	(–234.48)	2.82	(117.23)	2.82	(117.30)	0.24	(–81.63)
2	0.21	(–142.71)	–1.91	(285.72)	0.21	(–143.04)	–0.56	(13.98)
3	–0.75	(–37.80)	–0.75	(–37.93)	–2.12	(75.75)	–0.84	(–30.04)

Welfare effects of *Domestic CO_2 price* for alternative values of CO_2 pricing revenue shares. In column 1, CO_2 pricing revenue shares are 0%, 50% and 50% for low-, middle- and high-income groups, respectively. Analogously, column 2 assumes revenue shares of 50%, 0% and 50%, and column 3 assumes revenue shares of 50%, 50% and 0%. In column 4, revenue shares are set to the consumption shares of the three income groups. Additionally, deviations of these numbers relative to the standard results are reported in per cent in parentheses, i.e. (robustness check change – baseline change)/(baseline change).

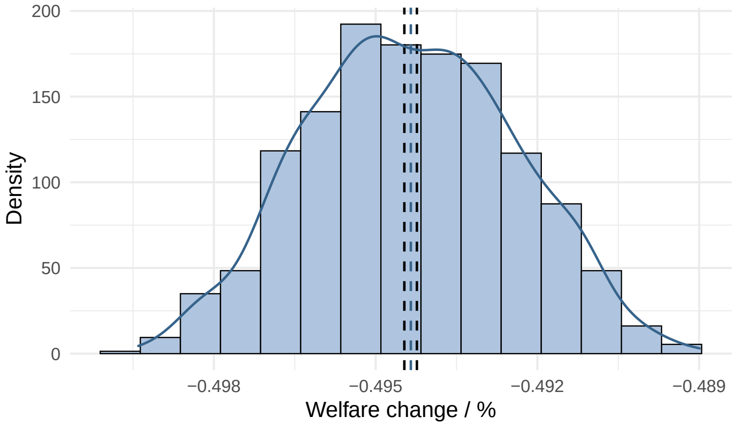
Figure B6

Distributional sensitivity analysis of domestic import elasticities σ_i^{DM}:

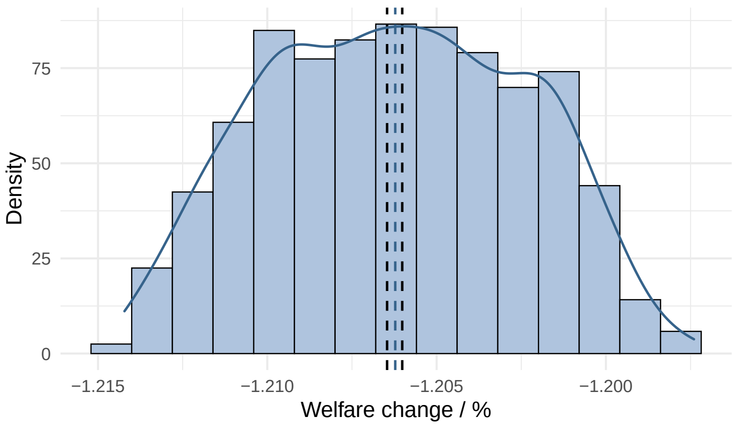
Domestic CO_2 price



(a) Low-income group



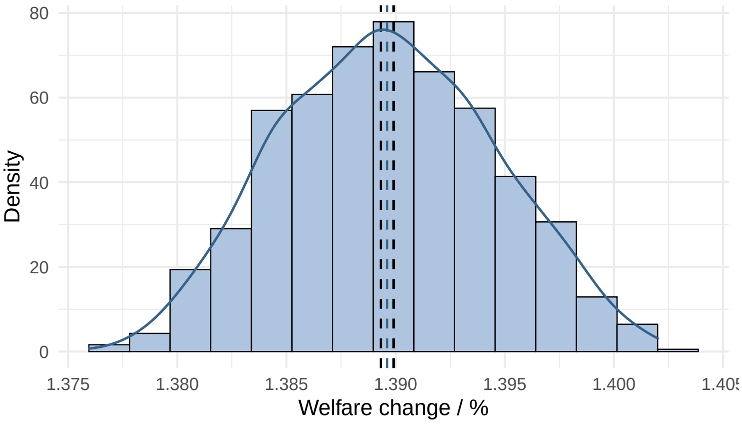
(b) Middle-income group



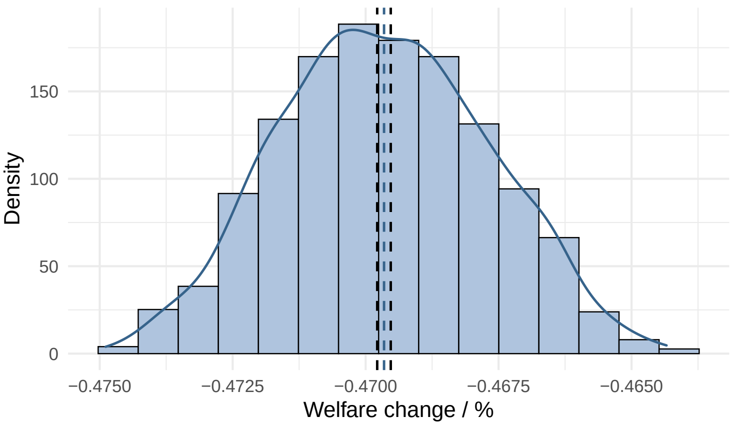
(c) High-income group

Distribution of welfare effects of *Domestic CO_2 price* for the low-, middle- and high-income groups. The distributions are generated from 1000 random draws from a ±10% interval around each sector-specific domestic import elasticity σ_i^{DM}. Dashed vertical blue lines indicate mean welfare effects, while dashed vertical black lines indicate bootstrap 95% confidence intervals. Solid blue lines represent Kernel density estimations.

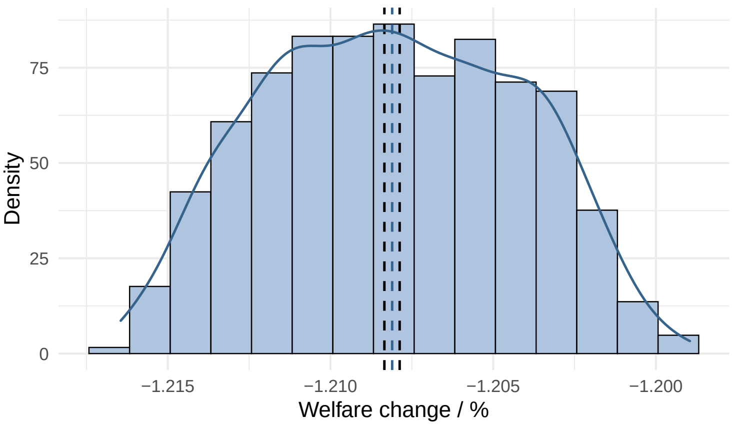
Figure B7
Distributional sensitivity analysis of domestic import elasticities σ_i^{DM}:
Border CO_2 price



(a) Low-income group



(b) Middle-income group



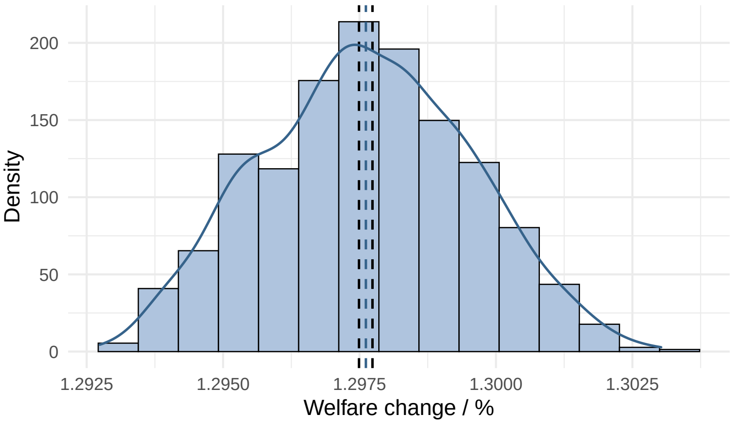
(c) High-income group

Distribution of welfare effects of *Border CO_2 price* for the low-, middle- and high-income groups. The distributions are generated from 1000 random draws from a ±10% interval around each sector-specific domestic import elasticity σ_i^{DM}. Dashed vertical blue lines indicate mean welfare effects, while dashed vertical black lines indicate bootstrap 95% confidence intervals. Solid blue lines represent Kernel density estimations.

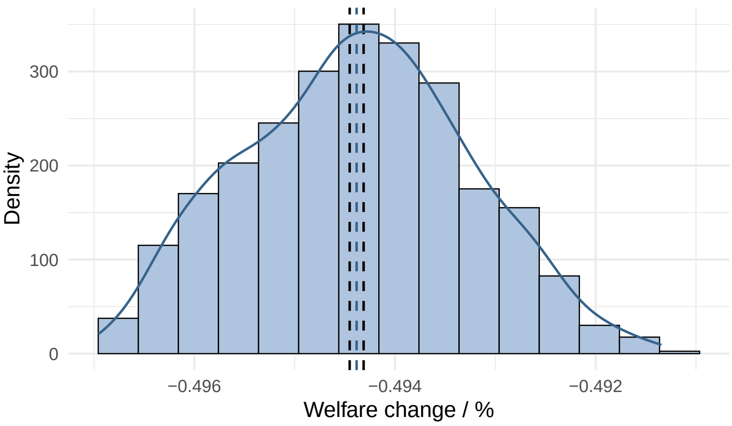
Figure B8

Distributional sensitivity analysis of input elasticities between production factors σ_i^Z:

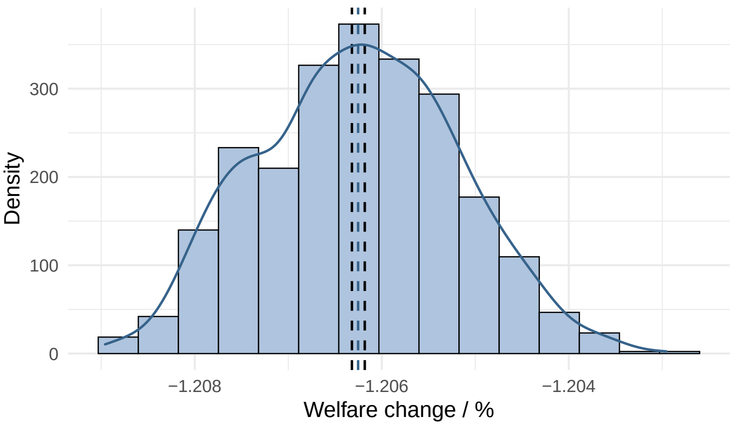
Domestic CO_2 price



(a) Low-income group



(b) Middle-income group



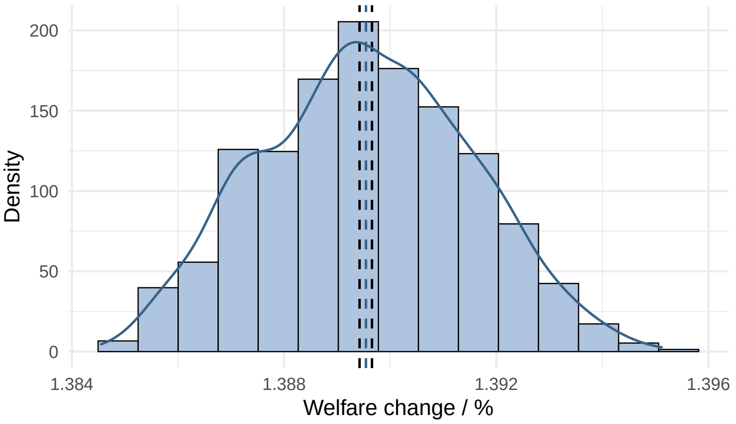
(c) High-income group

Distribution of welfare effects of *Domestic CO_2 price* for the low-, middle- and high-income groups. The distributions are generated from 1000 random draws from a ±10% interval around each sector-specific input elasticity between production factors σ_i^Z. Dashed vertical blue lines indicate mean welfare effects, while dashed vertical black lines indicate bootstrap 95% confidence intervals. Solid blue lines represent Kernel density estimations.

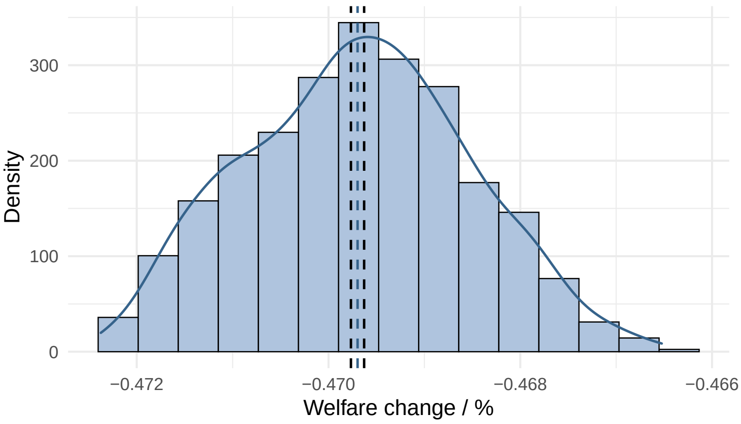
Figure B9

Distributional sensitivity analysis of input elasticities between production factors σ_i^Z:

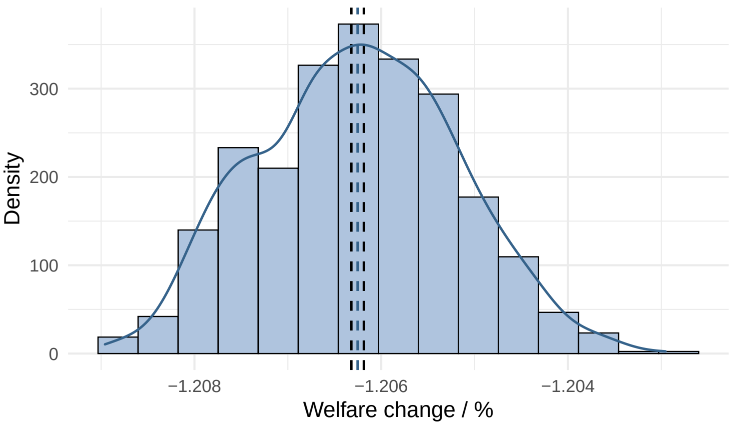
Border CO_2 price



(a) Low-income group



(b) Middle-income group



(c) High-income group

Distribution of welfare effects of *Border CO_2 price* for the low-, middle- and high-income groups. The distributions are generated from 1000 random draws from a ±10% interval around each sector-specific input elasticity between production factors σ_i^Z. Dashed vertical blue lines indicate mean welfare effects, while dashed vertical black lines indicate bootstrap 95% confidence intervals. Solid blue lines represent Kernel density estimations.

References of the appendix

Aguiar, A., Chepeliev, M., Corong, E. L., McDougall, R. and van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. *Journal of Global Economic Analysis*, 4(1): 1–27.

Arkolakis, C., Costinot, A. and Rodríguez-Clare, A. (2012). New Trade Models, Same Old Gains? *American Economic Review*, 102(1): 94–130.

Bussieck, M. R. and Meeraus, A. (2004). General Algebraic Modeling System (GAMS). In Kallrath, J., editor, *Modeling Languages in Mathematical Optimization*, 137–157. Springer US, Boston, MA.

Dirkse, S. P. and Ferris, M. C. (1995). The PATH Solver: A Non-Monotone Stabilization Scheme for Mixed Complementarity Problems. *Optimization Methods and Software*, 5(2): 123–156.

Forschungsdatenzentren (FDZ) der Statistischen Ämter des Bundes und der Länder (2019). Metadatenreport. Teil I: Allgemeine und methodische Informationen zur Einkommens- und Verbrauchsstichprobe (EVAS-Nummer: 63211, 63221, 63231), Berichtsjahre 2008, 2013 und 2018. Statistischen Ämter des Bundes und der Länder, Wiesbaden, Germany. URL: https://www.forschungsdatenzentrum.de/de/10-21242-63221-2013-00-00-3-1-1.

Forschungsdatenzentren (FDZ) der Statistischen Ämter des Bundes und der Länder (2020). Metadatenreport. Teil II: Produktspezifische Informationen zur Nutzung der Einkommens- und Verbrauchsstichprobe 2013, Grundfile 5 (EVAS-Nummer: 63221) als Scientific-Use-File. Version 2. Statistische Ämter des Bundes und der Länder, Wiesbaden, Germany. URL: https://www.forschungsdatenzentrum.de/de/10-21242-63221-2013-00-00-3-1-1.

Forschungsdatenzentren (FDZ) der Statistischen Ämter des Bundes und der Länder (2021). Einkommens- und Verbrauchsstichprobe 2013, Grundfile 5 (HB), Scientific-Use-File (SUF). URL: https://doi.org/10.21242/63221.2013.00.00.3.1.1.

Kronenberg, T. (2010). Erstellung einer Input-Output-Tabelle für Mecklenburg-Vorpommern. *AStA Wirtschafts- und Sozialstatistisches Archiv*, 4(3):223–248.

Pothen, F. and Hübler, M. (2018). The Interaction of Climate and Trade Policy. *European Economic Review*, 107: 1–26. Working paper version, URL: http://diskussionspapiere.wiwi.uni-hannover.de/pdf_bib/dp-585.pdf.

Statistisches Bundesamt (2015). Wirtschaftsrechnungen. Einkommens- und Verbrauchsstichprobe 2013. Einkommensverteilung in Deutschland 2013. *Destatis Fachserie*, 15(6):1–42.

Statistisches Bundesamt (2020). Volkswirtschaftliche Gesamtrechnungen. Input-Output-Rechnung 2015 (Revision 2019; Stand: August 2019). *Destatis Fachserie*, 18(2): 1–42. URL: https://www.statistischebibliothek.de/mir/receive/DEHeft_mods_00130396