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

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ABSTRACT

While climate policy studies are widespread, fully fledged computable general equilibrium (CGE) model analyses of distributional policy effects are challenging because the required data and approaches are not directly available. To ease such distributional analyses, 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. CO_2 pricing of imports at the (EU) border slightly strengthens these distributional effects and is mainly beneficial for the low-income group. The geographic extension of emissions trading within a "climate club" leads to substantial efficiency gains that are beneficial for Germany and the EU.

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). The distributional effects of carbon border adjustments and of "climate clubs" on household income groups are novel aspects analyzed in this article.

In this article, we make three contributions. First, we contribute to the literature by applying an elaborated method to new 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

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(household) approach in a macroeconomic model (e.g., Labandeira 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., 2019; Buddelmeyer et al., 2012; Durand-Lasserve et al., 2015).

The disaggregation of representative consumers in computable general equilibrium (CGE) models is a challenging endeavor. Böhringer et al. (2021), for example, 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 European Union (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 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] 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. As a consequence, the consumption of goods becomes more expensive. At the same time, the price decline of domestic production factors is mitigated because consumption shifts from imports to domestic production. By shedding light on these mechanisms, 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.

Additionally, we consider a so-called “climate club” that was announced by the German chancellor and launched at the COP[3] 28 in Dubai. Such a climate club with a common climate policy approach (e.g., a minimum CO_2 price) implemented within its political scope was, for example, recommended by Nordhaus (2015). It can constitute a stable form of international cooperation if there is a penalty in the form of a tariff imposed on non-participants (Nordhaus, 2021). Weitzel et al. (2012), for example, find in a CGE model analysis that the strategic (terms-of-trade) gain from carbon border adjustment dominates their environmental benefit (CO_2 reduction) and that high tariff rates are required to incentivize the formation of stable climate policy coalitions. We contribute to the broad literature on international cooperation (e.g., IPCC, 2014; Finus et al., 2013) and climate policy coalitions (e.g., Ghosh et al., 2012; Paroussos et al., 2019; Shaw and Fu, 2020; Perdana and Vielle, 2023) by analyzing the distributional effects of climate clubs on household income groups. Related to our work, Chepeliev et al. (2021) assess the effects of Nationally Determined Contributions (NDCs) on the household income distribution within international climate policy coalitions (without carbon border adjustments). They combine a CGE model with microsimulations and find that global cooperation significantly reduces the burden on the poor.

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 interesting 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) 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. Labandeira et al. (2009) even find a positive effect of energy taxation for *all* income groups, with larger effects for poorer households in Spain.

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

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

[3] Conference of the Parties.

Second, in accordance with the outcomes for the EU, Canada and the USA (Böhringer et al., 2021; Rausch and Mowers, 2014; 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%): intuitively, renewable energy expansion requires land and raises land rents.[4] The land rent increase, however, is dominated by declining prices for the remaining factors. Hence, overall, German climate policy effects are progressive (cf. Beck et al., 2015).

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 (very minor loss). The high-income group benefits most from mitigated price decreases of capital, labor and natural resources but it suffers about equally from increased consumption prices because it has not only the highest income but also the largest consumption of all income groups. Overall, CO_2 pricing of imports slightly 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 (0.6%) in all groups, then ceteris paribus, the low-income group will receive approximately 12% of the revenues, the middle-income group will receive 29% and the high-income group will receive 59%.

Sixth, when EU policymakers are able to encourage more economies in the world to join a climate club with a joint CO_2 price, the EU ETS countries will basically gain more when more countries join. For example, in a climate club of the EU (ETS) together with the remaining G7[5] countries, China and India, the EU ETS countries can recuperate approximately half their climate policy costs. Via lower climate policy costs, the distributional effects on German income groups become less pronounced as well. The low-income group, however, suffers most from the resulting increase in consumption prices.

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, 18 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 $Y_{C,s,i}^{DM}$ to maximize utility derived from consumption C_s. P_s indicates a corresponding price index for the consumption bundle of goods. The bundle $Y_{C,s,i}^{DM}$ 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.

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[4] Although renewable energies are not explicitly represented in the model, within the power sector, fossil fuels are substituted by land (and capital etc.).

[5] Canada, France, Germany, Italy, Japan, the United Kingdom and the United States.

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.

$$\max_{Y^{DM}_{C,i,s}} \; C_s,\; C_s = CES_i(Y^{DM}_{C,s,i}) \qquad (1)$$

$$\text{s. t.} \;\; P_s C_s = \xi_s I_s$$

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):

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

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):

$$I_s = \Theta_s + \Xi_s + \Delta_s \qquad (3)$$

Real consumption expenditures $C_S = \frac{\xi_s I_s}{P_s}$ reflect utility. Their relative change is 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). Due to the division by P_s, consumer price changes are eliminated such that welfare changes are measured in terms of constant benchmark prices. In this way, we obtain a welfare measure following the concept of the Hicks equivalent variation. In a model with more than one consumer, particularly, with several income groups, P_s is defined individually for each consumer (income group) based on the individual consumption basket.

2.2. Approach

To disaggregate a representative consumer into n consumption groups, we need to split all relevant parameters of Eqs. (1) to (3) into n parts. For this purpose, let us define the set of n consecutive integer numbers $\Phi_s = \{1,\dots,n\}$ 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 $(1-\xi_s)I_s$ with $\lambda^S_{s,\phi}\ \forall \phi \in \Phi_s$ such that $\sum_\phi \lambda^S_{s,\phi} = 1$. 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, Eq. (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

For the following exemplary disaggregation procedure based on household data, we refer to the 18 sectors (goods and services) displayed in Table 1 as defined by Pothen and Hübler (2018). Each sector produces one good or service that the representative consumer purchases. The investment good ($INVS$) is produced in a separate sector by using inputs like any other good. Savings equal investments in each model region. Hence, the demand for the investment good is determined by the savings of the representative consumer of each model region. Consumers (households), however, do not directly spend money on investments. Instead, they save part of their income, which is in reality converted into investments by financial intermediaries, such as banks. Consequently, savings appear in the household data where the investment sector does not appear.

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 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 version 10 of the Global Trade Analysis Project (GTAP) data (Aguiar et al.,

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. The detailed model-to-GTAP sector mapping can be found in Appendix Table A1.

2019) for the year 2014 covering most countries in the world.[6] 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 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 or a consistent method for mapping the consumption pattern to the available production sectors.

For example, Rausch et al. (2011) use a consumption interdependence table of the USA (called bridge matrix) that links consumption of the US consumer expenditure survey (CEX) to the North American Industry Classification System (NAICS).[7] Luu et al. (2020) show how EU household data classified according to COICOP can be mapped to GTAP sectors using concordance tables between different classifications.[8] Therefore, the procedure explained in the following can be used for other European countries, the USA and other countries that use COICOP statistics or for which a consistent mapping can be created. The following steps 1. and 2. can slightly differ while the step-wise procedure of creating a mapping table that converts consumption expenditures into (aggregate) GTAP sectors remains valid.

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.[9] 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

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

[7] The resulting NAICS sectors can then be linked to (aggregate) GTAP sectors in a second step.

[8] Particularly, the Central Product Classification (CPC) and International Standard Classification of All Economic Activities (ISIC). A similar procedure can be used to link the US CEX to GTAP with concordance tables linking NAICS to CPC/ISIC.

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

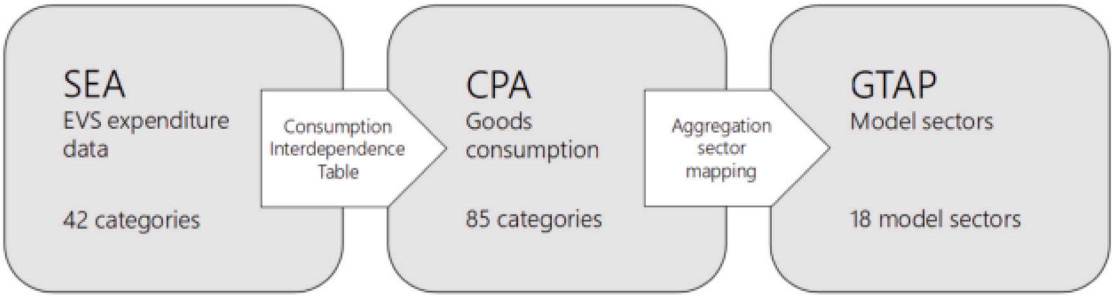

Fig. 1. Conversion and aggregation of sectors (goods).
Conversion and aggregation steps from the consumption (goods) expenditures data of the household survey to the required model sectors. EVS denotes "Einkommens- und Verbrauchsstichprobe", SEA denotes "Systematik der Einnahmen und Ausgaben der privaten Haushalte", CPA denotes "Statistical Classification of Products by Activity", and GTAP denotes "Global Trade Analysis Project".

same conversion coefficients.[10] 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:

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

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.[11] Fig. 1 illustrates steps 1 and 2.

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[12] 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. We follow UNECE (2011) by attributing income from self-employment to labor income. Net transfers include tax revenues generated by the government minus subsidy payments redistributed to the households.[13] 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 Bundesamt (2018) and draw on the Organization 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.[14] 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 source-specific income types $X_{s,f,\phi}$ from the available

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[10] 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.

[11] 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.

[12] Available income after deducting taxes.

[13] 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.

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

income sources indexed f, consumption expenditures $Y^{DM}_{C,s,i,\phi}$ on goods indexed i and savings $S_{s,\phi}$ 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:[15]

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

This sum can, in general, differ from the total values of the database (GTAP) underlying the model under scrutiny. This is not a problem, because 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, consumption expenditures and savings:

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

The household data (EVS), however, usually do not provide information on income from 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 Section 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 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 type, i.e., income from capital and labor (K, L) as well as net received transfers (Ξ) in the region (s) under scrutiny, and to savings ($(1-\xi_s)I_s$), which are all given by the model data (GTAP).[16] Likewise, we apply the share parameters $\lambda^C_{s,i,\phi}$ to the expenditures $Y^{DM}_{C,s,i}$ on each good (sector) i given by the model data. 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).[17]

In a similar vein, we calculate the share parameters $\iota^X_{s,f,\phi}$ and $\iota^C_{s,i,\phi}$ referring to Eqs. (1), (2) and (3) that represent the distribution of expenditures across various goods i and of 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 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 of consumption expenditures and the consumption fraction:

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

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 $I_{s,\phi}$ across income groups ϕ, the vertical and horizontal distribution of income sources $X_{s,f,\phi}$ that are available in the EVS, i.e., capital income, labor income and net received transfers ($f \in \{K, L, \Xi\}$ in the examined region s, here Germany, DEU), and the distribution of income across total consumption $C_{s,\phi}$ and savings $S_{s,\phi}$. Then, we present the vertical and horizontal distribution of consumption expenditures $Y^{DM}_{C,s,i,\phi}$ across the 17 consumption goods (sectors i without investment, $INVS$) 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) also for five and ten income groups ($n = 5$, $n = 10$); see Appendix A.8 regarding the resulting descriptive numbers and illustrations. 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.

Fig. 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. Fig. 3 shows the horizontal

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[15] 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.

[16] In our model application, net received transfers are implemented in absolute terms and adjusted to add up to zero across income groups ϕ in region s. As a result, the transfers are neutral with regard to the benchmark model equilibrium.

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

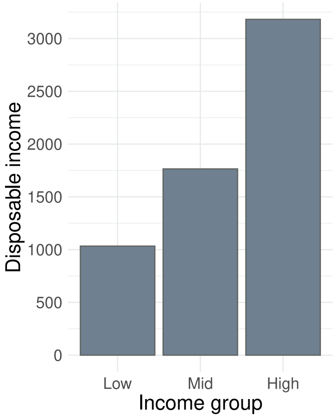

Fig. 2. Total German income by income group.
Distribution of the mean equivalent disposable income (total disposable income divided by the number of equivalent people based on the OECD scale) per month of the 52,421 German households in the survey across income groups in euros.
Data source: Authors' 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).

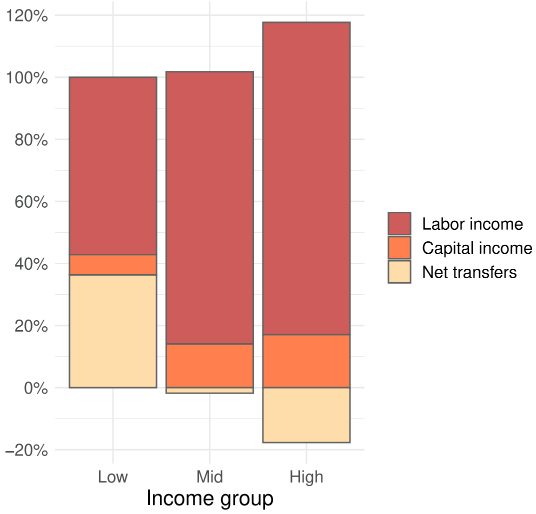

Fig. 3. German income sources by income group.
Horizontal distribution of income sources within each income group in Germany in percent (see Appendix Table A5 regarding the corresponding numbers).
Data source: Authors' own calculation; FDZ (2021).

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%).[18]

Fig. 4 illustrates the corresponding use of income for savings versus consumption in each income group (see Appendix Table A5).[19] The low-income group's consumption share (103%) exceeds its income. Hence, the remaining part is financed via a debt

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

[19] 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.

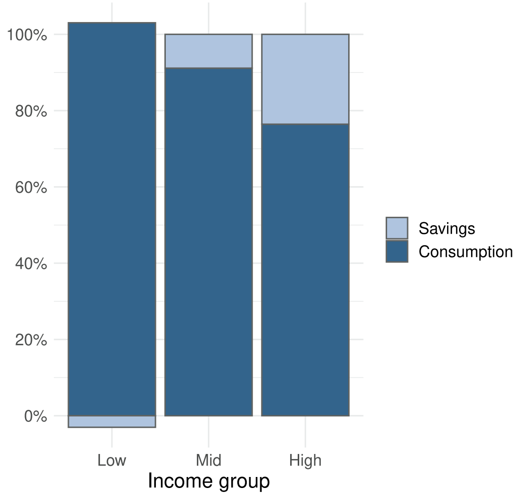

Fig. 4. German savings and consumption by income group.
Horizontal distribution of the use of income in savings versus consumption expenditures within each income group in Germany in percent (see Appendix Table A5 regarding the corresponding numbers).
Data source: Authors' own calculation; FDZ (2021).

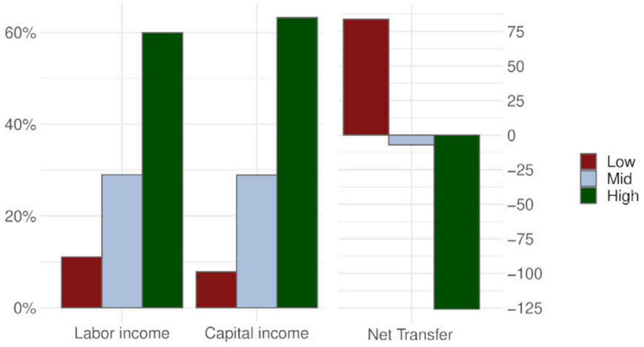

Fig. 5. German income by income source.
Vertical distribution of income sources across income groups (low, middle, high) in Germany; net transfers in billions of euros, other sources in percent (see Appendix Table A6 regarding the corresponding numbers).
Data source: Authors' own calculation; FDZ (2021).

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%).

Fig. 5 depicts the vertical distribution of each income source across income groups (Appendix Table A6 provides the corresponding numbers). The vertical shares of labor 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 Fig. 2. Whereas the relative capital and labor income shares are similar in the middle- and high-income groups (Fig. 3), capital and labor income in absolute values is more than twice as high in the high-income than in the middle-income group reflected in the vertical shares in Fig. 5. Note that income from self-employment, management or other well-paid jobs contributes to labor income. Nonetheless, the capital (labor) income share of the high-income group can be an underestimation (overestimation), because households with a monthly net income exceeding €18,000 are not represented in the survey. To address this data limitation, we carry out a robustness check that varies the high-income group's capital share as summarized in Section 4.4. Net transfers are shown in absolute numbers as they enter the model calibration.[20]

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[20] 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.

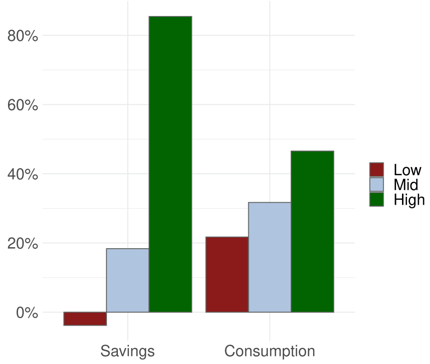

Fig. 6. German income by savings and consumption.
Vertical distribution of income in savings versus consumption expenditures across income groups (low, middle, high) in Germany in percent (see Appendix Table A6 regarding the corresponding numbers).
Data source: Authors' own calculation; FDZ (2021).

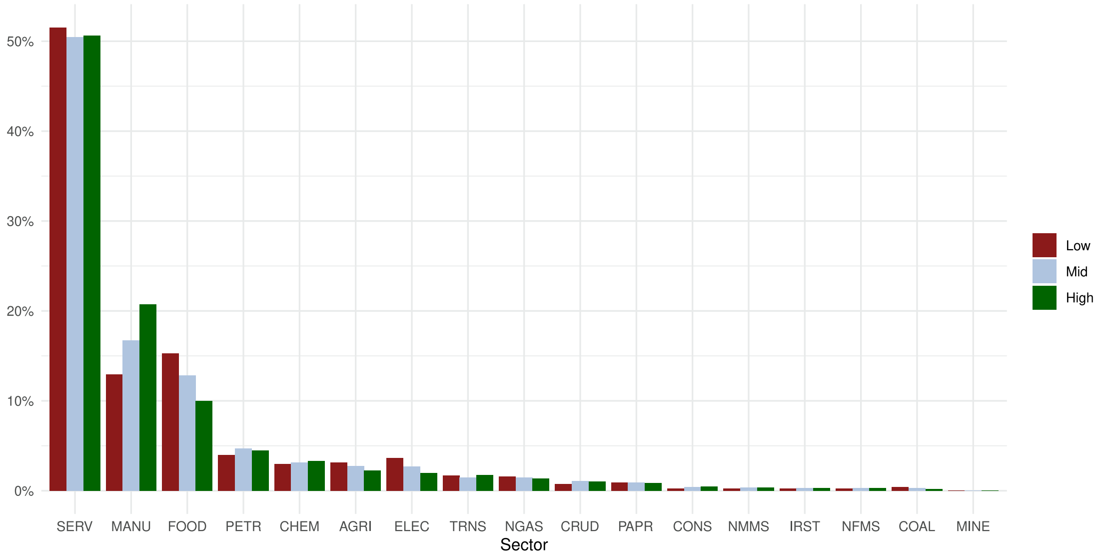

Fig. 7. Horizontal distribution of German consumption expenditures by goods.
Horizontal distribution of each income group's consumption expenditures across types of goods (sectors) in Germany (see Appendix Table A7 regarding the corresponding numbers).
Data source: Authors' own calculation; FDZ (2021).

Fig. 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.

Fig. 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.

Fig. 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

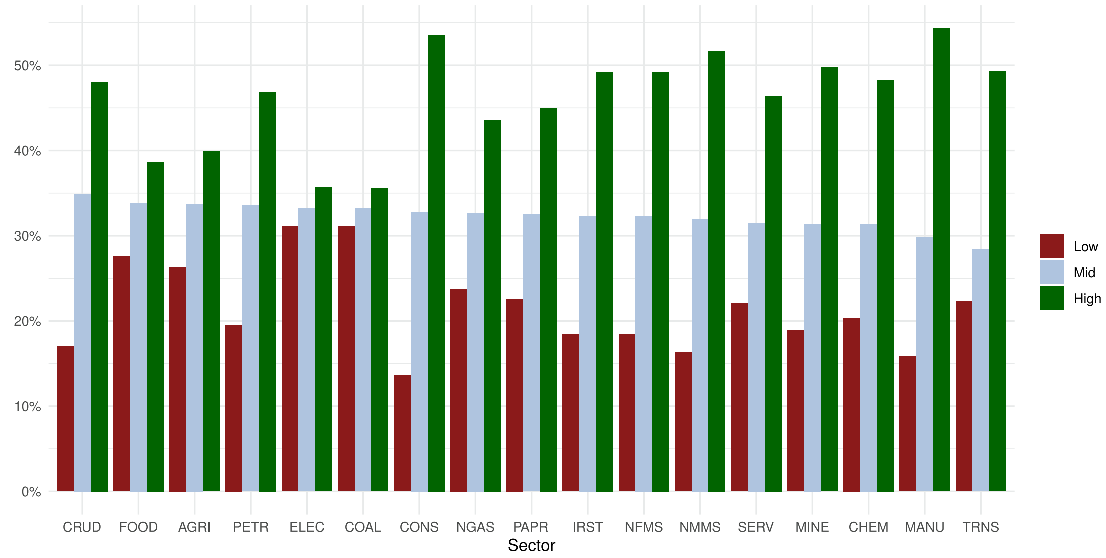

Fig. 8. Vertical distribution of German consumption expenditures by goods.
Vertical distribution of consumption expenditures on each type of good (sector) across income groups (low, middle, high) in Germany (see Appendix Table A7 regarding the corresponding numbers).
Data source: Authors' own calculation; FDZ (2021).

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

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 basic model builds on Thomas Rutherford's approach,[21] and has been extended according to the requirements of this study. The model represents the world economy in the benchmark year 2014 according to the GTAP 10 data. This section provides a nontechnical model summary. Appendix B contains further model details.

Each of the 18 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 (social/public or other kinds of) transfers or a regional (current account) deficit. Each regional deficit (or surplus) stays constant throughout the analysis. It is valued at the numeraire price defined by the price of the consumption bundle (consumer price index) in the USA. 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). Tariffs (and subsidies) can be imposed on imports (and exports).

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 and production factors (capital, labor, land and natural resources including endowments with fossil fuel resources) as inputs (see Appendix Figure B3). Capital and labor are mobile across sectors within each region but immobile across regions, i.e., foreign direct investments, international portfolio investments and international migration are not represented explicitly. There is perfect competition ruling out positive profits in all sectors.

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[21] 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	BRA	Brazil	No	No
FRA	France	No	Yes	CAN	Canada	No	No
GBR	United Kingdom	No	Yes	CHN	China	No	No
ITA	Italy	No	Yes	IND	India	No	No
EUR	Rest of EU-27	No	Yes	JPN	Japan	No	No
ROE	Rest of ETS (non-EU)	No	Yes	KOR	South Korea	No	No
FSU	Former Soviet Union	No	No	MEX	Mexico	No	No
ROA	Rest of Asia	No	No	OCE	Austral. & Ocean.	No	No
ROW	Rest of the World	No	No	USA	United States	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. The detailed model-to-GTAP region mapping can be found in Appendix Table B1.

Each region has a government that purchases goods like a private consumer. Governments' total expenditures (and surpluses or deficits) are taken from GTAP and then held constant, while governments' demand for different domestically produced and imported goods adjusts endogenously in counterfactual scenarios. Endogenous tax revenues and subsidy payments are attributed to the representative consumer as a net transfer. Each production input or output (producer side) and any consumption good (consumer side) can be subject to taxation or subsidization. The benchmark year values of taxes (tariffs) and subsidies are also taken from GTAP.

The benchmark data on savings and investments are taken from GTAP as well. For Germany, the saved part of income of each income group is derived from the household data.

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 production 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. Given that 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 three policy scenarios:

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 disaggregation and to emulate emissions 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 to obtain the initial allocation of CO_2 allowances and an EU ETS-wide 10% CO_2 reduction in all policy scenarios.[22] Emissions allowances can be traded across countries/regions

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[22] 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 sectors within the EU ETS. The revenues of CO_2 pricing are redistributed across income groups in 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.[23] 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.[24] 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. This means, the policy intends to reduce the negative effects of CO_2 pricing on 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).

3. Climate club (Clu): includes *Domestic CO_2 price* or *Border CO_2 price* and extends the geographic scope of these policies successively beyond the borders of the original EU ETS and CBAM.[25] In the first strand of coalition scenarios, we add the major greenhouse gas emitters of the world, the United States (USA), China (CHN) (Chepeliev et al., 2021; Tagliapietra and Wolff, 2021; Perdana and Vielle, 2023) and India (IND) successively to the EU ETS to obtain "the big four" (Convery and Sterner, 2021).[26]

In the second strand of coalition scenarios, we follow the announcement at the COP 28 that the G7 countries and the EU form a climate club and further countries will join (Climate Club, 2023). We denote the combination of the G7 countries with the EU ETS countries (that partly overlap) by $G7EU$.[27] As before, we successively add the major emitters China and India. The hypothetical global coalition $WORLD$ includes all countries/regions and renders border carbon adjustments obsolete. It defines a global first-best reference point.

As in the scenarios *Domestic* and *Border CO_2 price*, each climate policy coalition implements an international emissions trading system with a common CO_2 price and a 10% CO_2 reduction in each member country/region that determines the initial allocation of CO_2 allowances and a 10% reduction target of the entire emissions trading system.

To express policy effects, such as welfare effects measured as Hicks equivalent variations, 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 the three German consumer income groups. Table 3 reports the regional results of the EU policy scenarios. Figs. 9 and 10 summarize and illustrate the policy effects on Germany. Table 4 presents selected regional results of the climate club scenarios, Appendix Table B3 provides the results of all climate club scenarios.

According to Table 3, the first policy scenario *Domestic CO_2 price* entails a CO_2 price of €45.72 in the EU ETS and 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 with the strongest decline in the non-EU countries that are part of the EU ETS (ROE, –0.97%) followed by Italy (ITA, –0.67%) and Germany (DEU, –0.60%).[28] Interestingly, the climate policy effect is similar across the remaining EU-27 countries participating in the EU ETS, reaching approximately –0.5% (EUR, –0.49%; GBR, –0.46%; FRA, –0.51%). The negative welfare effect on the Former Soviet Union (FSU) countries is slightly smaller (–0.45%). Surprisingly, Australia and Oceania (OCE) lose more than other countries or regions (–0.69%). Due to their sheer size, the United States of America (USA) and the Rest of Asia

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and 2020, they decreased by 18.5% (Umweltbundesamt, UBA, accessed 01-2022, https://www.umweltbundesamt.de/en/data/environmental-indicators/indicator-greenhouse-gas-emissions). 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.

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

[24] 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.

[25] The EU ETS with CBAM already represents a climate club (Szulecki et al., 2022).

[26] China, the USA and the EU together emitted more than 50% of global CO_2 emissions, together with India approximately 60% in 2022 and in the benchmark year 2014 (based on Global Carbon Budget 2023 data, Friedlingstein et al., 2023).

[27] The G7 and EU countries jointly emitted approximately 25% of global emissions in 2022 and 30% in the benchmark year 2014 (Global Carbon Budget 2023, Friedlingstein et al., 2023).

[28] 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.

Table 3
EU climate policy effects on countries and world regions.

Region	*Dom*	*Bor*	Region	*Dom*	*Bor*
DEU tot.	−0.60	−0.58			
Low	**1.33**	**1.41**	BRA	−0.03	−0.04
Mid	**−0.50**	**−0.48**	CAN	−0.08	−0.10
High	**−1.21**	**−1.22**	CHN	0.25	0.22
FRA	−0.51	−0.50	IND	0.14	0.12
GBR	−0.46	−0.46	JPN	0.08	0.09
ITA	−0.67	−0.66	KOR	0.10	0.12
EUR	−0.49	−0.45	MEX	−0.11	−0.12
ROE	−0.97	−0.90	OCE	−0.69	−0.74
FSU	−0.45	−0.56	USA	−0.01	−0.01
ROA	−0.01	−0.02	ROW	−0.27	−0.31

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* (CO_2 price = €45.72) and *Bor* policy scenario *Border CO_2 price* (CO_2 price = €46.14). 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 12% of the revenues, the middle-income group receives 29% and the high-income group receives 59%, the welfare effect on the three groups will be similar and located close to the welfare effect on the total German economy (−0.60%/−0.58% with *Dom*/*Bor*).

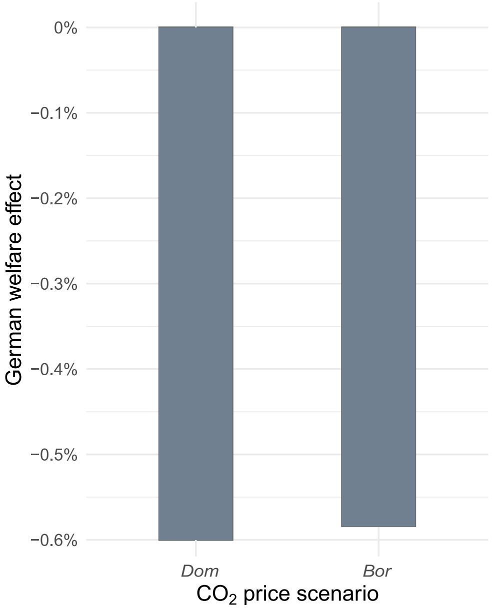

Fig. 9. EU policy effects on Germany.
German welfare effects measured as percentage changes in consumption divided by the true-cost-of-living index of the two EU policies, *Dom* = *Domestic CO_2 price* and *Bor* = *Border CO_2 price*, relative to the *Benchmark* scenario.

(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 (–0.27%), while the losses for Canada (CAN, –0.08%) and Mexico (MEX, –0.11%) are moderate. Notably, the South and East Asian economies, particularly China (CHN, 0.25%), followed by India (IND, 0.14%), South 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.

As shown in Table 3, the second policy scenario (*Border CO_2 price*) generates the same pattern as the first one (*Domestic CO_2 price*) regarding the directions and magnitudes of welfare effects. The CO_2 price of €46.14 in the EU ETS is slightly higher than in the *Domestic CO_2 price* scenario. Overall, due to strategic gains on international goods markets, the EU ETS member countries gain slightly from introducing the *Border CO_2 price* compared with the *Domestic CO_2 price* (e.g., Germany, DEU, by 0.02 percentage points). In some cases, the gains are minor (the gain of the United Kingdom, GBR, is not visible in the table). Although the policy effects on the other countries and regions are small, most of them become worse off compared with *Domestic CO_2 price* (FSU, ROA, ROW, BRA, CAN, CHN, IND, MEX, OCE and effect not visible in the table: USA) due to the implicitly increased barrier to trade. As an exception, Japan (JPN) and Korea (KOR) make slight gains, presumably due to trade redirection from other countries'

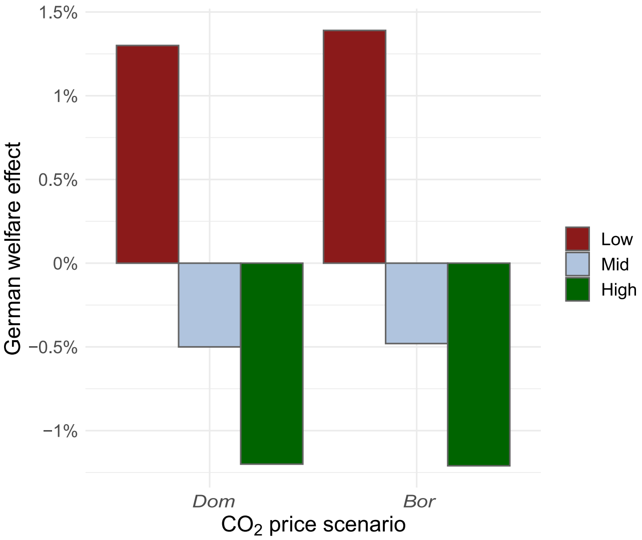

Fig. 10. EU policy effects on German income groups.
German welfare effects measured as percentage changes in consumption divided by the true-cost-of-living index of the two EU policies, *Dom* = *Domestic* CO_2 *price* and *Bor* = *Border* CO_2 *price*, relative to the *Benchmark* scenario.

Table 4
International climate policy coalition effects on countries and world regions.

Coalition	$G7EU$ CHN/IND		$WORLD$		$G7EU$ CHN/IND		$WORLD$
Region	*Dom*	*Bor*	*Dom/Bor*	Region	*Dom*	*Bor*	*Dom/Bor*
DEU tot.	−0.28	−0.27	−0.11				
Low	**0.62**	**0.65**	**0.90**	BRA	−0.03	−0.04	−0.41
Mid	**−0.24**	**−0.23**	**−0.10**	CAN	−0.05	−0.04	−0.23
High	**−0.58**	**−0.57**	**−0.43**	CHN	−0.46	−0.44	−0.23
FRA	−0.16	−0.15	0.03	IND	−0.26	−0.24	0.19
GBR	−0.22	−0.22	−0.20	JPN	−0.20	−0.18	0.12
ITA	−0.28	−0.27	−0.08	KOR	0.22	0.23	0.72
EUR	−0.22	−0.20	0.00	MEX	−0.31	−0.34	−1.04
ROE	−0.61	−0.59	−0.87	OCE	−0.70	−0.74	−1.81
FSU	−0.33	−0.40	−0.53	USA	−0.17	−0.17	−0.15
ROA	−0.05	−0.08	−0.10	ROW	−0.54	−0.57	−1.52

Regional welfare effects, measured as percentage changes in consumption divided by the true-cost-of-living index driven by the international *Climate club* (Clu) under scrutiny relative to the *Benchmark* scenario. EU refers to the entire EU ETS, which is enlarged to an international climate policy club including the remaining G7 countries (Canada, Japan and the United States) indicated by $G7EU$ plus the major emitters China and India. They share a common CO_2 price under the policy scenario *Dom* (CO_2 price = €23.15) and add border carbon adjustments towards countries/regions outside the coalition under the policy scenario *Bor* (CO_2 price = €23.19). The hypothetical global coalition $WORLD$ (CO_2 price = €26.90) includes all countries and renders border carbon adjustments obsolete.

exports to the EU towards exports to these countries. Compared with domestic CO_2 pricing, CO_2 pricing at the border is harmful for emerging (CHN and IND) and developing countries (included in the regions ROA and ROW).

Table B3 in Appendix B.7 provides all international *Climate Club* scenario results. As displayed in Table 4, the third *Climate Club* scenario with the members EU ETS/G7, China and India halves the joint CO_2 price of the scenarios *Domestic* CO_2 *price* and *Border* CO_2 *price* to approximately €23.20 due to efficient global emissions reduction options (low marginal abatement costs), especially in developing and emerging economies. Similarly, it approximately halves the relative welfare losses of Germany (DEU, –0.28% in Dom, –0.27% in Bor) and the other EU ETS members (FRA, –0.16%; GBR, –0.22%; ITA, –0.28%; EUR, –0.22%) compared with *Domestic* CO_2 *price* and *Border* CO_2 *price* in Table 3. The welfare loss of ROE declines by approximately one third to a relatively high loss of –0.61%. As expected, *Border* CO_2 *price* creates positive effects on climate policy coalition members and negative effects on outsiders. However, as in the EU policy simulations, the effects of *Border* CO_2 *price* compared with *Domestic* CO_2 *price* are overall small (similar to Weitzel et al., 2012; in their study, oil exporters and Russia experience stronger welfare losses). The effects on China (CHN) as a coalition outsider are mixed and small: China becomes worse (better) off when the United States (the G7) join the coalition but better (worse) off when they join with carbon border adjustments compared with the *Benchmark*. Canada (CAN) gains significantly when the United States (USA) join the EU ETS. As expected, countries/regions basically become worse off when they join a climate policy coalition with the strongest welfare losses in Australia & Oceania (OCE, –1.81%), the Rest of the World (ROW,

Table 5
EU climate policy effects on German goods and factor prices.

Price	Description	*Dom*	*Bor*
P_{DEU}	German consum. price	0.78	0.86
	Low	0.87	0.96
	Mid	0.82	0.90
	High	0.71	0.79
P^K_{DEU}	Capital price (rent)	−0.87	−0.81
P^L_{DEU}	Labor price (wage)	−0.80	−0.75
P^N_{DEU}	Land price (rent)	3.89	4.00
P^R_{DEU}	Natural resource price (rent)	−48.83	−48.62

German consumption price (true-cost-of-living index, P_{DEU}) and factor price effects (capital, K, labor, L, land, N and natural resources, R) 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.

–1.52%) and Mexico (MEX, –1.04%) in the *WORLD* coalition. As a notable exception, Korea (KOR) gains from all climate policy coalitions (0.08%–0.23%) where it is an outsider, and it gains even more in the *WORLD* coalition (0.72%) where it is an insider. India (IND) also gains (approximately 0.15%) when it is an outsider and in the *WORLD* coalition compared with the *Benchmark* scenario except in the "big four" coalition ($EUETS/USA/CHN/IND$, –0.29%) and the extended G7 ($EUG7/CHN/IND$, –0.26%). Interestingly, the remaining EU-27 countries (EUR) end up with a climate policy effect of nearly zero in the *WORLD* coalition. These results indicate that worldwide significant options to reduce CO_2 emissions efficiently (at lower marginal abatement costs than in the EU ETS) exist which are beneficial for the EU ETS members.

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 (1.33%) compared with the *Benchmark* case, whereas the high-income group has losses of a similar magnitude (–1.21%). The middle-income group is located between these groups. Its loss (–0.50%) is close to the total welfare loss in Germany (almost –0.60%), indicating that the middle-income group roughly represents the average German consumer. Compared with *Domestic* CO_2 *price*, the *Border* CO_2 *price* policy is beneficial for the lower German income groups, with the largest gain (0.08 percentage points) in the low-income group, a smaller gain in the middle-income group (0.02 percentage points) and a minor loss (less than 0.01 percentage points) in the high-income group. *Climate club (Clu)* basically has the following distributional effects in Germany. When more countries join the climate club, the negative welfare effects on the middle- and high-income groups are reduced; however, the positive welfare effects on the low-income group are reduced as well.

4.3. Interpretation

Referring to the results presented in the last subsection, this subsection explains and interprets the distributional effects of CO_2 pricing on German income groups. To this end, Table 5 reports price changes induced by the EU ETS scenarios and Table 6 the corresponding changes induced by the international climate club scenarios. 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.

In summary, our policy scenario analysis yields eight 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 negative effect of climate policy increases in households' income, which is in line with the literature (summarized by Wang et al., 2016 and Ohlendorf et al., 2021). Notably, the low-income group *gains* from climate policy. This outcome is in accordance with Goulder et al. (2019) and Böhringer et al. (2021). Labandeira 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 5 shows that the climate policy-induced consumption price index increase from *Domestic* CO_2 *price* and *Border* CO_2 *price* for poor households is slightly stronger (0.87%) than that for middle-class households (0.82%), which is in turn larger than that for rich households (0.71%). 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 48.83%). Labor income (0.80%) and, to a slightly larger extent, capital income (0.87%) decline moderately. Land rents, on the other hand, increase significantly (by 3.89%): 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

Table 6
International climate policy coalition effects on German goods and factor prices.

Coalition		$G7EU$ CHN/IND		$WORLD$
Price	Description	*Dom*	*Bor*	*Dom/Bor*
P_{DEU}	German consum. price	1.24	1.25	1.41
	Low	1.28	1.28	1.46
	Mid	1.26	1.26	1.42
	High	1.21	1.21	1.37
P^K_{DEU}	Capital price (rent)	0.48	0.48	0.70
P^L_{DEU}	Labor price (wage)	0.51	0.51	0.71
P^N_{DEU}	Land price (rent)	2.42	2.36	1.89
P^R_{DEU}	Nat. resource price (rent)	−31.59	−31.38	−38.15

German consumption price (true-cost-of-living index, P_{DEU}) and factor price effects (capital, K, labor, L, land, N and natural resources, R) driven by the international *Climate club* (Clu) under scrutiny relative to the *Benchmark* scenario. For further explanations, see Table 5.

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 5). 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 raises their prices, as visible in Table 5. 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 (or decrease to a smaller extent, respectively) with *Border CO$_2$ price* compared with *Domestic CO$_2$ price*, as visible in Table 5. This generates a positive income effect for all income groups. Nonetheless, Table 3 shows that the resulting welfare gain is most dominant in the low-income group (a 0.08 percentage point gain with *Border CO$_2$ price* relative to *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). The middle-income group can also benefit from taxing imports (a 0.02 percentage point gain with *Border CO$_2$ price* relative to *Domestic CO$_2$ price*). In contrast, in the high-income group with the highest income and expenditures among the three groups, the losses from increased consumer prices and the gains from increased factor prices roughly counterbalance each other resulting in a minor loss (of less than 0.01 percentage points with *Border CO$_2$ price* relative to *Domestic CO$_2$ price*).

6. The estimated economy-wide welfare effect of *Domestic CO$_2$ price* on Germany amounts to –0.60% (see Table 3). Let us assume that German policymakers want to achieve an equal distribution of this effect across all income groups. Model runs with different distributions of revenues from CO$_2$ pricing reveal that a redistribution of approximately 12% for the low-income group, 29% for the middle-income group and 59% for the high-income group roughly achieves this egalitarian welfare distribution via climate policy without additional transfers from rich to poor groups.

7. Germany and the EU ETS countries gain when more countries in the world join a climate coalition with a joint CO$_2$ price, presumably, due to relatively low marginal abatement costs abroad. This reduces the climate policy-induced welfare losses of the German middle- (0.24% in $EUG7/CHN/IND$, *Dom*) and high-income groups (0.58% in $EUG7/CHN/IND$, *Dom*) compared with the analyzed EU policy (*Domestic CO$_2$ price*). Given the relatively low CO_2 prices in the scenario simulations, carbon border adjustments (*Bor*) are, however, blunt instruments for incentivizing countries to join a climate club.

8. Opposite effects are observed regarding the German low-income group. Because this group gains from CO_2 pricing, its welfare gain shrinks when more countries enter the climate policy coalition. This effect turns, however, when China and India join the G7 ($EUG7/CHN/IND$, *Dom*, 0.62%) and in the global coalition ($WORLD$, 0.90%). Table 6 provides interesting insights into the underlying mechanisms: When more countries in the world introduce CO$_2$ pricing, consumption prices will increase, especially the consumption price index of the low-income group which is hit hard by this price increase given its relatively low income. When the climate coalition is extended, however, factor prices change as well. The wage rate and the capital rent increase relative to the

Benchmark (instead of a decline in the EU ETS scenarios). Likewise, the drastic devaluation of natural resources (including fossil fuels) in Germany is significantly dampened (–31.59% resource price change in $EUG7/CHN/IND$, *Dom* compared with –48.83% under EU policy in Table 5) because the CO_2 price in the EU ETS declines when more countries join the climate policy coalition and consequently the demand for fossil fuels increases in Germany. This effect is reversed under the assumption of a worldwide climate policy coalition (–38.15% resource price change in $WORLD$) because it exhibits a higher CO_2 price (€ 26.90) than, for example, the $EUG7/CHN/IND$ club (€ 23.19 with *Bor*). Moreover, the increase in the land rent induced by the EU ETS policies is mitigated when the coalition expands, because the lower CO_2 price puts less pressure on the economy, especially the energy sector, to decarbonize by using more land (which is in reality particularly used for renewable energy installations that are not explicitly represented in the model).

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 relevant (sets of) parameter values within our CGE model around the default values used in the analysis so far in three alternative ways: First, we assume upper and lower bounds of relevant parameter values. Second, we vary selected parameter values within an interval. Third, we carry out a computationally complex *Monte Carlo* analysis by repeatedly drawing random combinations of crucial parameter values. The results are presented in Sections B.6 to B.13 of the Appendix. The baseline (reference) values can be found in Table 3, particularly, the results for Germany (DEU).[29]

Our sensitivity analysis is structured in eight steps:

1. In the robustness check reported in Table B4 of Appendix B.8, we uniformly vary the sector-specific *Armington* elasticities σ_i^M between *imported* goods by ±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 2.7% (2.5%) at the lower (upper) bound in the *Domestic* CO_2 *price* scenario. Similarly, we observe an increase (decrease) of 2.6% (2.4%) 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 1.7% (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.

In the corresponding Monte Carlo analysis, we generate 1000 random draws from a ±10% interval around each of the sector-specific Armington elasticities σ_i^M (column 1 of Appendix Table B2) resulting in 1000 sets of sectoral parameter values.[30] 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, 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, i.e., using the 2.5th and 97.5th percentiles of the respective bootstrap distribution as the confidence interval.

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 in both policy scenarios, which is in line with the slightly asymmetric changes in welfare effects observed in Table B4. 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.

2. 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 (Appendix Table B2) are conducted in an analogous fashion. The results are presented in Tables B5 and B6 and Figures B6 to B9 of Appendix B.9 and B.10. In accordance with the sensitivity analysis of the 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 −1.2% 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.

3. Next, we vary the elasticity between different production *factor inputs* σ_i^Z. As shown in Table B6 of Appendix B.10, the welfare effects are hardly sensitive to variations in σ_i^Z by ±10%: 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.

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[29] 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.

[30] 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 ±10% interval.

4. We vary the elasticity of substitution σ^C in the consumption function of the consumer (in each region, in Germany also of each income group, see Appendix Figure B2) within a ±50% interval around the default value $\sigma^C = 1$ (Cobb–Douglas preferences for different goods) and solve the model under each policy scenario. As displayed in Table B7 of Appendix B.11, reducing σ^C by 50% results in an increase in the low-income group's welfare gain (by 35.2% or 34.6% depending on the scenario) and a decrease in the middle-income group's welfare loss (by 22.8% or 24.9%), while the high-income group experiences a small increase in its welfare loss (of more than 4.7% in both scenarios). Conversely, due to a 50% increase in σ^C, the low- and middle-income groups become worse off (at least 24.0% and 17.0%) while the high-income group's welfare loss decreases only slightly (2.8%) in both scenarios. These findings are also reflected in Figures B10 and B11 plotting the welfare effects of each policy scenario as a function of σ^C. The graphs show that the welfare gain of the low-income group decreases and the welfare loss of the middle-income group increases in higher values of σ^C, while the welfare loss of the high-income group decreases.

5. Data on factor income from land, natural resource and capital ownership and the distribution of revenues from CO_2 pricing are insufficiently available. Especially, natural resource ownership is crucial for climate policy effects, because the natural resources include fossil fuels. Therefore, we evaluate the distributional welfare effects given several alternative sets of the corresponding German income/revenue shares $\lambda^X_{DEU,f,\phi}$. By default, we distribute German income from land and natural resource ownership in the same way we distribute total consumption expenditures. Table B8 in Appendix B.12 reports the corresponding welfare effects assuming alternative distributions of the land and natural resources income shares across the income groups in the two policy scenarios. 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 gain of the low-income group decreases (by 76% or 80% depending on the scenario), the respective welfare loss of the middle-income group decreases (by 84% or 88%) and the loss of the high-income group decreases (by approximately 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%. 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 (51.5% and 48.5%). 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 (43.0% and 40.6%) and a small decrease in the losses of the middle-income group, while the welfare losses of the high-income group increase (ca. 16.0% in each case).

6. This robustness check addresses the lack of data from households with a monthly net income exceeding €18,000 by assuming alternative capital income shares $\lambda^X_{DEU,K,\phi}$ of the German income groups ϕ. To define a lower bound, we assume that the capital share of the German high-income group is as high as the average macro-economic German capital share, i.e., $\lambda^X_{DEU,K,high} = 16.46\%$, according to the German national accounts (disposable income in "Volkswirtschaftliche Gesamtrechnung", VGR in 2013; Statistisches Bundesamt, 2023). To obtain an upper bound, we assume that only the high-income group receives more capital than recorded by the EVS data, such that the weighted average capital share across all German income groups matches the average share of 16.46%. In either case, the capital shares of the low- and middle-income groups are recalculated by keeping their absolute capital income values constant. Table B9 in Appendix B.12 displays the results. The middle-income group is affected most (between −16.53% and −31.60%) whereas the high-income group is affected least (between 1.39% and 2.38%). While the low- and middle-income groups become better off, the high-income group becomes worse off, because the decline in the capital price hits the high-income group harder when assuming a larger high-income capital share.

7. Table B10 in Appendix B.12 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 B8. 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 −1.8%, i.e., a 233.4% reduction), while the middle-income group experiences a substantial welfare gain (switching from −0.5% to +0.2%, i.e., a 144.6% improvement) and the high-income group a moderate decrease in its welfare loss (38.0%). Accordingly, for the groups that do not receive revenues, column 2 exhibits a high increase in the welfare loss of the middle-income group (289.5%) and column 3 a moderate increase in the welfare loss of the high-income group (76.2%). The other two groups receiving 50% of the revenues experience a significant increase in their welfare gain (116.7% in the low-income group) or a substantial reduction in their welfare loss (145.0% 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 (30.7%), while the middle-income group slightly loses (16.4%) and the low-income group becomes considerably worse off (81.0%).

8. The default emissions target in the scenarios *Domestic CO_2 price* and *Border CO_2 price* is a 10% CO_2 reduction. This target is derived from the actual emissions reduction in the EU ETS in the benchmark year 2014. In the sensitivity analysis, we vary the emissions target in the range of 99% to 87% around the default target and repeatedly solve the model.[31] The results of the policies *Domestic CO_2 price* and *Border CO_2 price* are presented in Figures B12 and B13 of Appendix B.13. In both policy scenarios, the welfare effects are qualitatively the same as under the default emissions target and quantitatively similar. While the welfare gains

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[31] More ambitious emissions reductions do not lead to feasible model solutions, because the model does not feature renewable energies, energy efficiency improvements or other decarbonization options explicitly; particularly, it does not feature a dynamic transition of the energy system.

of the low-income group increase in the emissions reductions, the middle- and high-income groups experience greater welfare losses due to more ambitious emissions reductions. These results suggest that the distributional patterns of the policies under scrutiny are qualitatively robust to moderate variations in the emissions target, and more ambitious emissions reductions cause stronger distributional effects across household income groups.

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 challenging. 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, notably, 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. CO_2 pricing at the border, such as the EU CBAM, alters the distributional effects of domestic CO_2 only slightly. Hence, such a policy does not seem to introduce new distributional patterns but strengthens existing climate policy effects. Given the relatively low CO_2 prices and hence low CO_2-based tariff rates in the policy simulations, carbon border adjustments, are, however, blunt instruments for incentivizing countries to join a climate club. Notwithstanding, the EU ETS countries can substantially gain when they are able to encourage more countries in the world to join a climate club with a joint CO_2 price. The resulting increase in consumption prices is, however, especially harmful for low-income households, which can be compensated through a social transfer.

Our exemplary model is designed to be straightforward, compact and transparent. Therefore, it does not include a complex energy input and power generation system or complex future development scenarios with economic growth and an explicit energy transition. In future research, the model can be extended to a dynamic model that represents the transition of the energy system and enables the analysis of ambitious climate policy targets, possibly with forward-looking (strategic) behavior.

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). In reality, however, not all households or social groups are affected by sector-specific shocks in the same way. Households often receive most of their income from one or a few sectors, which makes them vulnerable to shocks affecting these sectors. This mechanism is currently not represented in the model. The implementation of this mechanism requires household data that include the sectoral source of labor, capital and other types of income. Furthermore, data containing different income groups' expenditures on different *imported* goods would enable a more precise analysis of the *distributional* effects of import tariffs. New data could also provide better information on expenditures on durable goods across income groups. In studies like ours, insufficient expenditure information on durable goods can create a bias if these expenditures differ across income groups (in relative terms).

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. To address the limitations of income and expenditure surveys, one can also link them to complementary surveys. In Germany (EVS data), the Socio-Economic Panel ("Sozio-oekonomisches Panel", SOEP), the wage and income tax statistics ("Faktisch anonymisierte Lohn- und Einkommenssteuerstatistik", FAST) and the Linked-Employer–Employee Dataset (LIAB) provide useful data sources (see, e.g., Bach et al., 2009, 2017; Buhlmann et al., 2022).

CRediT authorship contribution statement

Michael Hübler: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Malin Wiese:** Data curation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Marius Braun:** Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Johannes Damster:** Data curation, Software, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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