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A Computable General Equilibrium Analysis for Germany

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We investigate the economic impacts of CO_2 emissions pricing for Germany in the context of the Paris Agreement where we highlight the role of international market responses for the incidence across heterogeneous households. We consider three settings for international spillover effects: (i) a small-open-economy framework where international commodity prices remain constant, (ii) a multi-region-trade framework with endogenous terms of trade where only Germany undertakes emission pricing, and (iii) a multi-region-trade framework where all other regions also price CO_2 emissions. In all three settings Germany complies to a given domestic CO_2 emissions reduction target through economy-wide uniform CO_2 emissions pricing. CO_2 revenues are recycled lump-sum to households on an equal-per-household basis. We find that the small-open-economy setting in the case of Germany not only overstates overall economic adjustment costs to CO_2 emissions pricing, but also understates the degree of progressiveness of CO_2 revenue recycling. The reason is that in the multi-region-trade frameworks Germany is able to pass through part of its economic adjustment costs to trading partners via higher export prices. As a consequence, the CO_2 prices required to achieve the domestic emissions reduction target are higher, yielding more CO_2 revenues that are recycled to households.

Keywords: computable general equilibrium; incidence; environmental taxes;
JEL-Classification: D58, H22, H23, Q58

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1. Introduction

The EU as a signatory to the Paris Agreement has committed itself to reducing greenhouse gas (GHG) emissions by at least 40% by 2030 compared to 1990.[1] In 2019, Germany as the EU's largest economy has passed its first federal climate law with a legally binding domestic GHG emissions reduction target of 55% by 2030.[2] Despite seemingly widespread support for climate change mitigation, policy makers in Germany (and elsewhere) are reluctant to make more stringent use of CO_2 emissions pricing, which is proposed by economists since Pigou (1920) as a cost-effective instrument for GHG emissions reduction. The caveats against CO_2 emissions pricing can be traced back to its potentially regressive impacts; given that lower-income households typically spend higher shares of their income on fossil fuels, which become more expensive under CO_2 emissions pricing. Concerns about the regressive impacts of more rigorous CO_2 emissions pricing have therefore been at the fore of the more recent climate policy debate in many countries.[3]

In the economic impact asssessment of climate policies it is often neglected that the incidence of GHG emission regulation may critically depend on international spillovers. Emission abatement in open economies not only causes adjustment of domestic production and consumption patterns but also affects international prices via trade (Böhringer and Rutherford, 2002). Changes in international prices – the so-called terms of trade – imply a secondary benefit or burden which can significantly alter the primary economic implications of domestic climate policies. Some countries may pass through part of their domestic abatement costs to trading partners ("beggar-thy-neighbor"), while other abating countries face additional welfare losses from a deterioration of their terms of trade. Hence, single-country impact analyses, which neglect policy-induced changes in international prices, may be quite misleading in quantifying the effective economic impacts of CO_2 emissions pricing.

Another "blind spot" in economic impact assessment is the traditional focus of economists on allocative efficiency, being agnostic on the incidence of policy regulation across heterogeneous households. The most prominent strand of literature in this regard deals with cost-effectiveness analysis in which policy choices are ranked in terms of their overall economic efficiency costs to achieve a given policy target.

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[1] See https://ec.europa.eu/clima/policies/strategies/2030_en. Note that in December 2020 the EU updated its Nationally Determined Contribution (NDC) to target a 55% reduction of greenhouse gas emissions compared to 1990. Emissions reductions targets in the EMF36 study – and likewise in our analysis here – are based on initial first-round NDCs, where the EU stated a 40% reduction in greenhouse gas emissions in 2030 compared to 1990.

[2] See BMU (2019).

[3] One prominent example are the 'yellow vest' protests that erupted across France in 2018, following the announcement of fuel price increases (Nossiter, 2018).

For the political feasibility of policy reforms, however, a central question is who gains and who loses. As a matter of fact, regulatory policies that impose a heavy burden on lower-income individuals can be very costly from a social perspective since they may undermine social cohesion. Taking into account distributional effects of policy interference across heterogeneous households is thus essential – the net gain or loss for an individual household as a fraction of its income may greatly exceed the aggregate economy-wide gain or loss as a fraction of total income.

Previous studies of emissions pricing have shown that the recycling of additional revenues can drastically affect the distributional consequences across households either enforcing or offsetting the direct incidence of emissions pricing (Rausch et al., 2010; Goulder et al., 2019). The challenge towards broader social acceptability is to find a policy design which on the one hand is environmentally effective and on the other hand appeals as fair (Klenert et al., 2018). In this vein, the economic literature has made the case for revenue-neutral recycling mechanisms, such as reductions in pre-existing distortionary taxes or lump-sum transfers per capita or per household. However, differential impacts across households are not only driven by the level of the CO_2 emissions price and the amount of recycled revenues, but also by indirect adjustments of commodity and factor prices that occur via international spillover and feedback effects.

Insights into the contribution of changes in terms of trade to economic outcomes are valuable from a research as well as policy perspective. In applied research, such a decomposition quantifies the role of trade exposure on the economic responses to policy interference and helps the analyst understand how structural assumptions on international trade affect model-based simulation results. In policy advice, such a decomposition fosters evidence-based analysis and puts decision makers on better informed grounds, in particular when drawing information from impact studies that neglect international spillover effects. In the context of climate policies, it has been shown that policy-induced changes in international prices for fossil fuels – the so-called fossil fuel channel – and for emission- and trade-intensive goods – the so-called competitiveness channel – play an important role for an accurate understanding and quantification of the economic impacts triggered by emission regulation (see e.g. Böhringer and Rutherford, 2002; Böhringer et al., 2012).

Against this background we investigate how international market responses affect the magnitude and distribution of economic impacts from CO_2 emissions pricing in Germany as an industrialized country which is heavily trade-exposed.

Based on computable general equilibrium (CGE) analysis we find that for a country like Germany which exports emission-intensive goods and imports fossil fuels, the omission of terms-of-trade effects will overstate the economic adjustment costs of CO_2 emissions pricing and understate the progressive impacts of lump-sum CO_2 revenue recycling to households.

In Section 2, we lay out the model and empirical data underlying our simulation analysis. In Section 3, we present the CO_2 emissions pricing scenarios for alternative trade closures and discuss our insights on overall economic impacts and distributional consequences. In Section 4, we conclude.

2. Model and Data

2.1. Computable general equilibrium model

For our quantitative analysis, we draw upon a standard static multi-sector, multi-region CGE model of the global economy developed in Lanz and Rutherford (2016). CGE models constitute a powerful method to perform economic impact assessment of policy reforms based on microeconomic theory and empirical data. A fundamental strength of the CGE approach is that it accommodates both an aggregate macroeconomic impact assessment as well as a more refined incidence analysis of policy interventions across heterogeneous household groups, while capturing spillovers between sectors and regions. CO_2 emissions pricing does not only affect the prices of consumer goods, but also sources of income, such as wages and capital returns. While partial equilibrium studies on the incidence of taxation are typically limited to the expenditure side, the general equilibrium framework captures also the economic consequences on the income side.

Below we provide a non-technical summary of key model characteristics.[4] The model adopts a canonical general equilibrium representation of economic activities combining assumptions on the optimizing behavior of economic agents with the analysis of equilibrium conditions. Decisions about the allocation of resources are decentralized, and the representation of behavior by producers and consumers in the model follows the standard microeconomic paradigm: producers employ primary factors and intermediate inputs at least cost subject to technological constraints; consumers with given preferences maximize their well-being subject to budget constraints.

Primary factors

Primary factors of production are labor, capital, and fossil resources. Labor and

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[4] An algebraic description of the generic model structure is provided in Appendix B.

capital are assumed to be mobile across sectors but not internationally mobile. Fossil resources (gas, crude oil, and coal) are specified as region- and sector-specific capital in fossil fuel production sectors. Supply of factors is fixed at business-as-usual levels and factor markets are perfectly competitive.

Production

The production of goods other than fossil resources is represented by a nested constant-elasticity-of-substitution (CES) function. At the top level, a composite of value-added and energy trades off with a composite of material inputs. At the second level, substitution possibilities among material inputs are described as well as substitution possibilities between value-added and energy. At the third level, labor and capital trade off in the value-added aggregate, while electricity trades off with fossil fuels in the energy composite. In fossil fuel production, the specific capital (resource) trades off with a Leontief composite of all other inputs at a constant elasticity of substitution. Output in each production sector is allocated either to the domestic market or the export market according to a constant-elasticity-of-transformation function.

International trade

Following the proposition of Armington (1969), domestic and foreign goods are distinguished by origin. This accommodates both imports and exports of the same commodity to reflect empirical evidence on the crosshauling of trade flows. The Armington composite for a traded good is a CES function of domestic production and an imported composite. The import composite, in turn, is a CES function of production from all other countries. For each region, a balance-of-payment constraint warrants that the total value of exports equals the total value of imports accounting for an initial deficit or surplus. In order to investigate the implications of alternative international market responses for the economic outcomes of policy shocks, the model framework permits two alternative trade closures: a small-open-economy setting with fixed terms of trade and a multi-region-trade setting with endogenous terms of trade.

In the small-open-economy setting a single region – in our case: Germany – is treated as small relative to the world market. We thus assume that changes in the region's import and export volumes have no effect on international prices; in other words, export and import prices in foreign currency – and hence the terms of trade – are exogenous.

The multi-region-trade setting features bilateral trade flows which implies that production and consumption decisions in a given region will affect international prices depending on initial trade shares and trade elasticities.

CO_2 emissions

The analysis is focused on CO_2 emissions from fossil fuel combustion. The use of fossil fuels is associated with fixed region- and sector-specific CO_2 coefficients. CO_2 emission abatement can take place by fuel switching (i.e., interfuel substitution), energy efficiency improvements (i.e., substituting capital for energy in more energy-efficient appliances), or energy savings (i.e., a scale reduction of production and final demand activities).

Final consumption

In order to accommodate incidence analysis across heterogeneous households, private final consumption in a specific region - here: Germany - is disaggregated into ten household income deciles who receive income from primary factors and transfers. Each household maximizes consumption utility according to its preferences subject to its budget constraint.[5] Final private consumption in other model regions in the multi-region-trade setting is represented by a representative household. Household utility is represented by a nested CES function which captures price-responsive trade-offs across consumption goods.

Government and investment demand are fixed in real terms at business-as-usual levels.

2.2. Data

For model parameterization we use data from the Global Trade Analysis Project (GTAP version 9.2) which includes detailed balanced accounts of production, consumption, bilateral trade flows as well as data on physical energy consumption and CO_2 emissions for the base-year 2011 in 141 regions and 57 sectors (Aguiar et al., 2016). As is customary in applied general equilibrium analysis, base-year data together with exogenous elasticities determine the free parameters of the functional forms. Elasticities in international trade (Armington elasticities) as well as factor substitution elasticities are directly provided by the GTAP database. The elasticities of substitution in fossil fuel sectors are calibrated to match exogenous estimates

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[5] In addition, we introduce a residual 'capitalist' household which only earns capital rents and saves all its income. This approach has been used before, e.g. in Rausch et al. (2011) and Böhringer and Müller (2014), and facilitates a more accurate representation of income and expenditure patterns of household income deciles, see also Appendix A.

of fossil-fuel supply elasticities. The GTAP dataset can be flexibly aggregated across sectors and regions to reflect specific requirements of the policy issue under investigation. We adopt the regional and sectoral aggregation as defined in the EMF36 core scenarios (Böhringer et al., 2021), with the adjustments that we partition the EU into Germany (DEU) and the Rest of the EU (REU).[6]

In order to decompose the representative household in Germany into income deciles, we employ data from the German income and expenditure survey 2013 (Statistisches Bundesamt, 2015). We use a bridge matrix for Germany, provided by Cai and Vandyck (2020), to map our production goods as classified in the GTAP dataset to seven final consumption categories, namely *food*, *housing*, *energy* (electricity and heating), *transport*, *education*, *durables*, and *other goods*.

Scaling of household data assures that income (per income factor) and expenditures (per consumption category) across household deciles match national accounts for the representative consumer in the GTAP dataset. We provide more detail on the treatment of household-level data in Appendix A.

Table 1 provides an overview of countries (regions) as well as production goods (sectors) and final consumption goods represented in our model.

In line with the EMF36 study design, we quantify the economic impacts of CO_2 emissions pricing against a hypothetical business-as-usual in 2030. Details on the business-as-usual data are provided in Böhringer et al. (2021) while we adopt the canonical forward-projection routine as laid out in Böhringer et al. (2009).

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[6] Furthermore, we split out an explicit production sector ”Food, beverages and tobacco” from the composite of ”Other manufacturing” (see Table 1) in order to obtain a more accurate representation of how consumption categories are composed of heterogenous production goods.

Table 1: Regions and goods in the model

Countries and regions	**Sectors and goods**
Countries	*Production goods*
Germany	*Energy goods*
United States of America	Coal
Canada	Petroleum and coal products
Japan	Crude oil
South Korea	Natural gas
Russia	Electricity
China	*Non-energy goods*
India	Emission-intensive and trade exposed goods
Brazil	Transport
Aggregated regions	Agriculture
Australia and New Zealand	Food, beverages, and tobacco
Rest of the EU*	Other manufacturing
Middle East	Services
Africa	*Consumption goods*
Other Americas	Food
Other Asia	Housing
	Energy
	Transport
	Education
	Durables
	Other goods

* Includes EU27 + UK + EFTA members (excl. Germany).

3. Scenarios and Results

3.1. Scenarios

Our primary research interest is in assessing how the economic impacts of CO_2 emissions pricing for a domestic economy – here: the German economy – depend on international spillover effects. More specifically, we want to quantify how changes in international prices affect the magnitude of overall economic adjustment costs to domestic emission constraints and how these costs get distributed across heterogeneous households with different income and expenditure patterns.

Due to the multilateral nature of climate policies, terms-of-trade effects can be triggered both through domestic emission reduction measures in Germany as well as through emission reduction efforts in other countries. Following the design of the EMF36 study on Post-Paris climate policies we translate the Nationally Determined Contributions (NDCs) of Paris Parties into reduction requirements of CO_2 from fossil fuel combustion relative to a business-as-usual development in 2030 that is based on GDP and CO_2 projections for individual countries/regions issued by the International Energy Outlook (EIA, 2017). For the case of Germany, we obtain a

CO_2 emissions reduction target of 28.5% from the business-as-usual in 2030.

Emissions reduction targets are reached via domestic CO_2 emissions pricing which applies uniformly to all CO_2 emissions from fossil fuel combustion in production and consumption activities. This is a stylized assumption abstracting from complementary instruments that Germany and other countries employ to reduce emissions – for example, renewable energy subsidies or energy efficiency mandates. Given that these complementary instruments imply diverging marginal costs of abatement across CO_2 emissions sources, our specification of uniform CO_2 emissions pricing portrays domestic policies as more efficient as they are in the real world.

To investigate how the magnitude and incidence of Germany's adjustment costs depends on international price changes we devise three scenarios.

The first scenario – denoted *SOE* – treats Germany as a small open economy thereby neglecting changes in international prices. The two subsequent scenarios – denoted *MRT-U* and *MRT-M* – treat Germany as a large open economy embedded in a multi-region-trade setting with bilateral trade flows where the terms of trade are endogenous. In the multi-region-trade setting we distinguish the variant *MRT-U* where Germany acts unilaterally whereas other regions stick to the business-as-usual and the variant *MRT-M* with multilateral action where all model regions achieve their reduction targets via domestic emissions pricing.

Scenario *SOE* provides a useful benchmark for the domestic climate policy debate since many national studies on economy-wide impacts of emissions reductions neglect international price changes. Scenarios *MRT-U* and *MRT-M* then complement the *SOE* analysis in quantifying the importance of international price changes when Germany acts alone (*MRT-U*) or in combination with other regions (*MRT-M*). Among the three scenarios *MRT-M* provides the most comprehensive impact assessment including international spillover and feedback effects from multilateral policy action.[7]

Table 2 summarizes the key differences in trade closure and regional emission policies across our three scenarios.

Across all scenarios, revenues from CO_2 emissions pricing are recycled lump-sum to the households. Since we have disaggregated the representative household in Germany into ten income deciles, we can not only investigate how international price changes affect the magnitude of overall adjustment costs for the German economy but also how these price changes affect the incidence across heterogenous households. More specifically we can quantify how international price changes affect the

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[7] Note that scenario *MRT-M* corresponds to the central case scenario *ref/NDC* investigated in the EMF36 study such that our analysis provides a constructive refinement in understanding the key drivers of economic impacts for Germany.

Table 2: Overview of central case scenarios

Label	**Trade closure**	**Climate policy**
SOE	small-open-economy closure with exogenous terms of trade	Germany achieves its reduction target through domestic emissions pricing
MRT-U	Multi-region-trade setting with bilateral trade flows and endogenous terms of trade	Unilateral climate policy where only Germany achieves its reduction target through domestic emissions pricing
MRT-M	Multi-region-trade setting with bilateral trade flows and endogenous terms of trade	Multilateral climate policy where all regions achieve their reduction targets through domestic emissions pricing

degree of regressiveness/progressiveness of a revenue-neutral green tax reform in Germany where revenues from CO_2 pricing are recycled back to households (ten income deciles) on an equal-per-household basis.[8]

3.2. Results

3.2.1. Macroeconomic impacts

We discuss the simulation results for the three aforementioned scenarios in two sections. First, we focus on economy-wide impacts for Germany from the perspective of a representative household. Second, we provide a more refined incidence analysis by breaking down aggregate impacts to household deciles. If not stated otherwisem results are reported as percentage changes from the business-as-usual (BaU) situation in 2030. Monetary units are provided in USD for the GTAP base-year of 2011.

Table 3 summarizes macroeconomic results for CO_2 emissions and prices as well as aggregate welfare impacts. Welfare changes (ignoring the benefits from reduced environmental damages) are measured in terms of Hicksian equivalent variation (HEV) in income denoting the amount of money that is necessary to add to or deduct from the BaU income of the representative consumer so that she enjoys a utility level equal to the one in the counterfactual policy scenario on the basis of ex-ante (BaU) relative prices. At the macroeconomic level, we thus capture adjustment costs to climate policy as changes in money-metric utility from a utilitarian welfare perspective, i.e., being agnostic on the cost distribution across households. We also report

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[8] In our equal-yield setting for Germany, government public good provision is kept constant in real terms at benchmark levels via an endogenous adjustment of value-added taxes.

changes in production and exports of energy-intensive and trade-exposed (EITE) sectors in Table 3 since impacts for these vulnerable sectors are of particular policy interest.

Across all scenarios, we request that Germany achieves an identical reduction of domestic CO_2 emissions (i.e., 28.5% from BaU). Because of international spillover effects, the endogenous CO_2 emissions price to achieve this emissions reduction will vary across scenarios. For the small-open-economy setting (*SOE*) with exogenous terms of trade the required CO_2 emissions price amounts to 81 USD per ton of CO_2. As we move to the multi-region-trade setting where Germany acts unilaterally (*MRT-U*) the same domestic emission reduction requires a higher CO_2 emissions price of 109 USD/tCO_2. The primary reason for the higher price is that German exporters of EITE goods are able to pass through part of their regulatory costs to international trading partners via higher export prices. As a consequence, output losses in these sectors are attenuated compared to *SOE*. While exports of EITE goods in Germany drop by 19.4% for *SOE* they drop only by 6.7% for *MRT-U*. Hence, the CO_2 emissions price for *MRT-U* must be higher than for *SOE* to achieve the same domestic emissions reduction target. If multilateral abatement policies of all other regions are taken into account as well (*MRT-M*), CO_2 emissions prices must be even higher (123 USD/tCO_2). Here the main reason is the so-called fossil-fuel price channel. Multilateral abatement efforts additionally depress international fuel prices which in turn stimulates fossil fuel consumption. For example, coal import prices in Germany remain constant under *SOE* (by assumption), decline by 0.21% in *MRT-U*, and go down by 3.15% in *MRT-M*. For the case of multilateral emission abatement, German EITE exports decline only by 5.6%. Compared to unilateral abatement by Germany in the multi-region-trade setting, with multilateral abatement three (intertwined) effects kick in. First, higher CO_2 emissions prices increase EITE production costs; second, lower fuel prices decrease EITE production costs; and third, emissions pricing abroad improves the competitiveness of the German EITE industry. In aggregate, the combination of these effects play out positively for the German EITE industry.

Economy-wide adjustment costs – measured in terms of HEV for the representative household – are highest in the *SOE* variant followed by variants *MRT-U* and *MRT-M*. The ranking of inframarginal adjustment costs (welfare) is just opposite to the ranking of marginal abatement costs (CO_2 emissions prices) which points to the critical importance of international market responses for the appraisal of (uni- and multilateral) climate policies. When accounting for changes in international prices triggered by unilateral action of Germany (*MRT-U*), Germany as a large exporter

Table 3: Impacts on CO_2 emissions prices/CO_2 emissions, EITE output/exports and economy-wide welfare

	SOE	*MRT-U*	*MRT-M*
CO_2 emissions price*	81	109	123
CO_2 emissions**	-28.5	-28.5	-28.5
EITE output**	-14.4	-6.3	-5.0
EITE exports**	-19.4	-6.7	-5.6
Welfare**	-1.54	-0.87	-0.80

* In USD per ton of CO_2.
** In percentage change from *BaU*.

of emission-intensive goods can pass part of its domestic abatement burden through to trading partners via higher export prices thereby extracting terms-of-trade gains. Hence, welfare losses assessed in *SOE* overstate Germany's economic burden.[9] When we consider multilateral abatement by all other regions as well (*MRT-M*), welfare losses from a German perspective even decline further compared to unilateral German action (*MRT-U*) for two reasons. First, emission constraints abroad improve the competitiveness of German EITE goods on international markets such that burden shifting via exports is exacerbated. Second, the stronger decline in international fuel prices further benefits Germany as a fuel importer.

We can decompose the aggregate welfare effect for the German economy into monetary changes on the income side and the expenditure side. Figure 1 shows this decomposition on the income side for the income sources labor, capital, resource rents, transfers, and CO_2 revenues; and on the expenditure side for expenditure categories consumption and savings.[10] We see that emissions pricing in Germany depresses factor productivity and hence the factors' real returns. While the downward pressure of CO_2 pricing on factor remuneration is prevailing across the different scenarios, the implications of terms-of-trade effects for labor and capital earnings take opposite directions. Labor returns slightly decrease under *MRT-U* compared to *SOE* whereas capital returns slightly increase. The reason is that capital-intensive exporting sectors benefit from changes in international prices while labor-intensive sectors such as service sectors are slightly worse off. CO_2 revenues yield a positive income effect. CO_2 revenues amount to 48.4 billion USD under *SOE*, 65 billion USD under *MRT-U*, and 73.4 billion USD under *MRT-M* reflecting the different levels of CO_2 emissions

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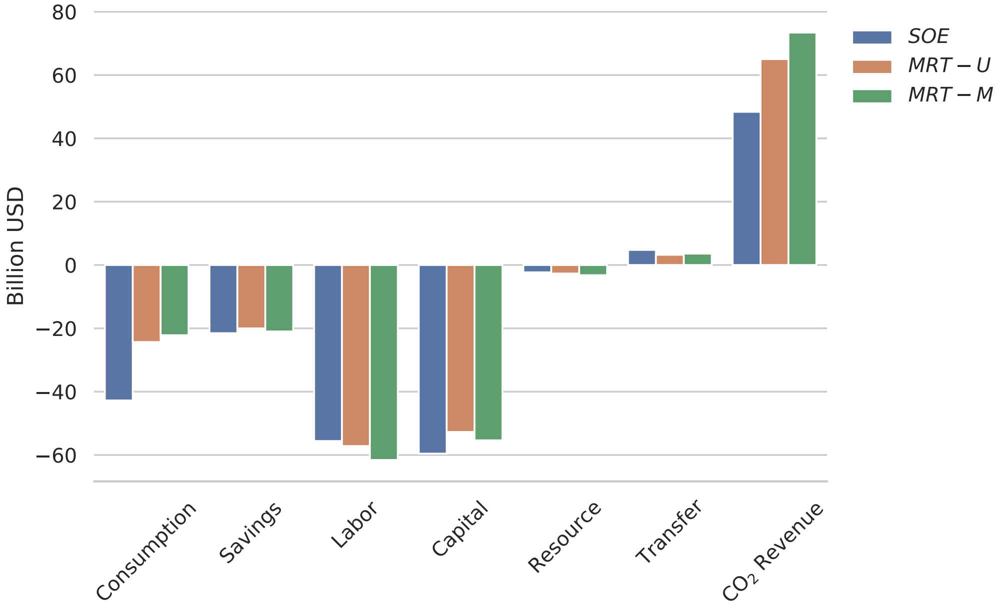
[9] This finding relates to the beggar-thy-neighbor potential of unilateral climate policies where domestic emissions pricing is implicitly working as a substitute for optimal tariffs to exploit terms of trade (Böhringer et al., 2014).

[10] Note that Figure 1 comprises the ten income deciles of private households as well as the residual "capitalist" household (which earns capital income and saves/invests all income), see Appendix.

Figure 1: Aggregate income and expenditure effects for private households under *SOE*, *MRT-U*, and *MRT-M*



prices in the different scenarios. Savings (investment) are fixed in real terms at the *BaU* level but decline when denominated with the aggregate German consumption price index (in other words the price of savings/investment declines in real terms). Overall, the disposable income for real consumption decreases – reflecting the welfare costs of emission abatement as reported in Table 3.[11]

Table 4 reports how CO_2 emission constraints affect prices on the expenditure side (consumption goods) and on the income side (factors). We see that energy-intensive consumption goods such as energy and transport become relatively more expensive. Their price increase is less pronounced for *SOE* as compared to the *MRT* variants due to the lower CO_2 emissions price. For *MRT-M*, where all regions abate, the energy consumption price is slightly higher than for unilateral action (*MRT-U*) which indicates that for the case of Germany the higher CO_2 emissions price dominates the lower international fuel prices as the driver of the overall price impact on the energy consumption composite. As to factor prices, the numerical results in Table 4 quantify our graphical exposition of factor returns in Figure 1. We will revert to price changes in consumption goods and factor earnings in our discussion of the household incidence below as the differential impacts across households are

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[11] We endogenously adjust transfers from the government to private households such that the residual "capitalist" meets its income balance which requires that the earnings from its capital endowment pay for the fixed amount of savings/investment. A positive transfer is necessary as the rental price for capital declines more than the price of the investment good.

driven by their heterogeneity in expenditure patterns (consumption preferences) and income sources (factor endowments and transfers).

Table 4: Real price changes for consumption goods and primary factors in % from *BaU*

	SOE	*MRT-U*	*MRT-M*
Consumption goods			
Durables	0.20	0.20	0.15
Education	-0.71	-0.90	-0.84
Energy	16.35	18.06	18.94
Food	-0.66	-0.85	-0.80
Housing	-1.63	-1.73	-1.80
Transport	4.82	5.17	5.26
Other goods	-1.66	-1.73	-1.81
Factors			
Capital	-3.63	-3.21	-3.37
Labor	-3.16	-3.26	-3.51
Resource	-3.72	-2.02	-2.29

3.2.2. Household incidence

We break down the economy-wide welfare impact for the representative German household into the incidence for households differentiated by income (deciles). CO_2 emissions pricing creates costs and rents which translate into the incidence for households via changes in prices for consumption goods on the expenditure side and via changes in factor remuneration (plus potential transfers) on the income side. Figures 2 (a)-(d) visualize *BaU* income and expenditure patterns for the household income deciles (*h01*,...,*h10*) in Germany – both in absolute numbers as well as in percentage terms.

On the expenditure side, CO_2 emissions pricing will be regressive to the extent that it drives up prices of consumption goods for which lower-income households tend to expend larger shares of their budgets (such goods typically include electricity, home heating fuels, gasoline, and other energy-intensive commodities). Figure 2 (d) shows that this is the case for Germany. The 10% lowest-income households in Germany (*h01*) spend 6% of their income on electricity and heating (consumption category *energy*) while the 10% highest-income households (*h10*) spend only 2.9% of their income on electricity and heating. For *transport* we observe a similar pattern. The lowest-income households spend 11.4% of their income on *transport*, the highest-income households only 6.9%. Households in the highest income decile (*h10*) in turn spend almost a quarter of their income on *durables* whereas expenditure of the other income deciles range between 3.1% (*h01*) and 8.4% (*h09*).

On the income side, CO_2 emissions pricing changes the productivity and thus the remuneration to the primary factors labor, capital, and specific resources (e.g., fossil fuel resources). Emission regulation will in particular drive down the rents to specific resources in fossil fuel production and emission-intensive industries with relatively inelastic supply characteristics – a cost increase on the input side which cannot be passed through via higher output prices will be shifted back to (inelastically supplied) factors of production such as specific resources. Figure 2c shows that lower-income households tend to get larger shares of their income through labor and transfers, whereas higher-income households earn more through capital income. While *h01* has a capital income share of 10.7% and a transfer income share of 43.7%, *h10* has a capital income share of 37.5% and receives no transfers. To the extent that CO_2 emissions pricing erodes the dominant income sources of lower-income households (such as labor) more than the dominant income sources of high income households (such as capital) it has a regressive effect on the income side.

A key driver of the incidence on the income side is how rents from regulation – in our case: revenues from CO_2 emissions pricing – are recycled. Regulatory rents can be recycled by the government explicitly via lump-sum transfers on a per-household basis. Such lump-sum transfers are clearly progressive in nature. Since each household receives an equal share of CO_2 revenues the recycled amount marks a larger share of additional disposable for lower-income households. If sufficiently high the transfers can mitigate or even overcompensate potentially regressive effects of CO_2 emissions pricing.

Figure 3 shows the percentage change in welfare (HEV) for the ten income deciles decomposed into an expenditure effect (darker-shaded bars) and an income effect (lighter-shaded bars), and in addition the income effect from the CO_2 payments only (transparent bars). Overall welfare is higher for all households under the multi-region-trade setting compared to the small-open-economy setting despite higher CO_2 emissions prices, reflecting our basic welfare considerations laid out in section 3.2.1.

As to regressiveness or progressiveness CO_2 pricing, we first focus on the expenditure effect.[12] The expenditure effect translates real price changes across our scenarios (see Table 4) into welfare changes at the household level. Across all scenarios, lower-income households are more negatively affected than higher-income households, i.e., CO_2 in Germany is regressive on the expenditure side – independently on how we figure in terms-of-trade effects. The underlying reason is the strong price increase for

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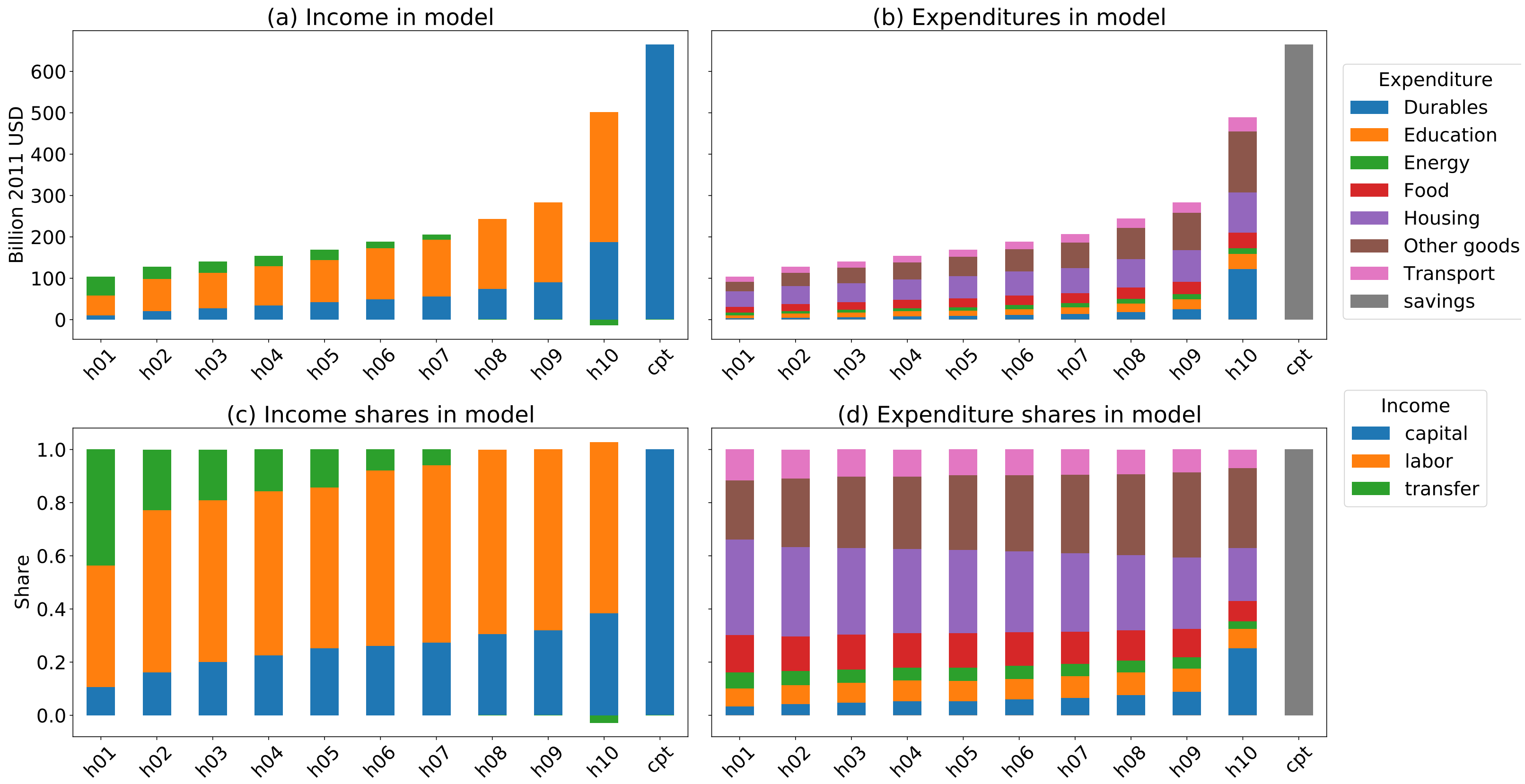
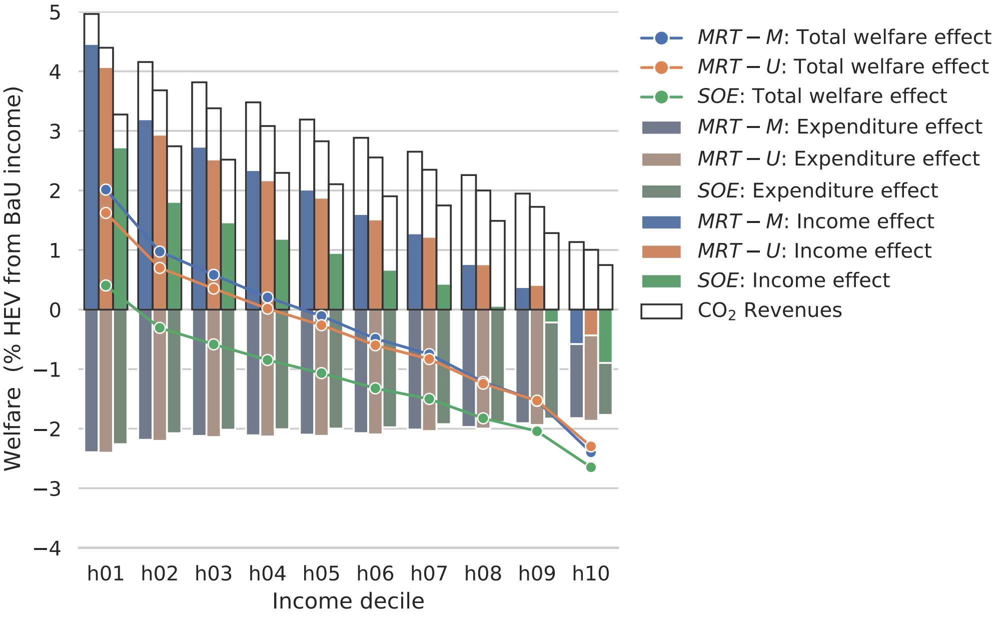
[12] As to the notion of regressiveness and progressiveness, note that our analysis uses income deciles and does not account for further in-group heterogeneities and socio-economic factors such as urban, rural, or household size.

Figure 2: Income and expenditure patterns for income deciles in Germany



Note: Resource rents are included in capital income. In the model, where we distinguish between resource rents and other capital income, resource rents and capital income are assigned to households according to the same shares shown here.

Figure 3: Decompostion of the total welfare effect into expenditure and income effects across household deciles – scenarios: *SOE*, *MRT-U*, and *MRT-M*



energy and transport services. However, while the overall level of the expenditure effect is slightly lower for exogenous terms of trade (*SOE*) compared to endogenous terms of trade (*MRT-U* and *MRT-M*) due to lower CO_2 emissions prices for the *SOE* case, the expenditure effects are quite similar across the different scenarios.

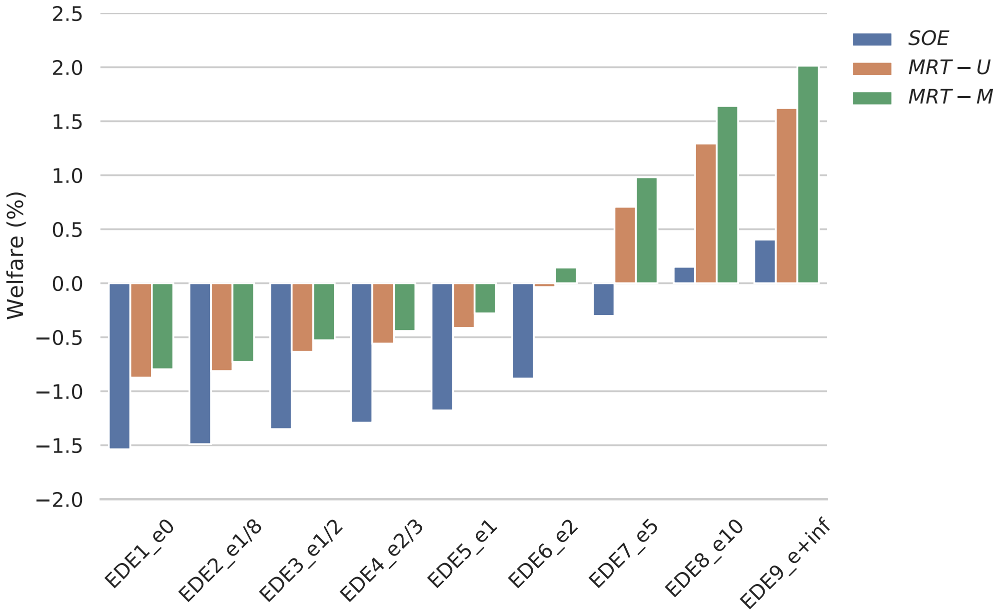
The income effect, on the other hand, exhibits more substantial differences. As compared to the small-open-economy setting, the multi-region-trade settings exhibit higher CO_2 emissions prices, which show up as higher CO_2 revenues for households. Additionally, the multi-region-trade settings provide the ability for export sectors to pass through costs to international trade partners via higher export prices. Such terms-of-trade gains show up as additional income which – on top of the direct revenues from CO_2 pricing – make all households better off under the multi-region-trade setting as compared to the small-open-economy setting. This effect shows up as the difference between the income effect through additional CO_2 revenues (transparent bars) and the total income effect (lighter-shaded bars).

When comparing the small-open-economy setting with the multi-region-trade settings in terms of their regressiveness or progressiveness, we observe the following trade-off. In the multi-region-trade setting, we need higher CO_2 emissions prices because EITE sectors are now able to pass through part of their additional CO_2 input costs to their importing trading partners – therefore, domestic EITE sectors do not reduce output as much. Higher CO_2 emissions prices in turn increase domestic prices for emission-intensive final consumption goods such as electricity, natural gas for heating, and fuels for transport. This tends to be regressive on the expenditure side. At the same time, the additional income generated through higher export prices (terms-of-trade gains) in the *MRT* settings implicitly contributes to higher CO_2 revenues. As the latter gets redistributed in equal shares to households, the recycling effect is progressive since it adds relatively more disposable income to lower-income households. We find in our scenarios that the additional regressive impact on the expenditure side when moving from *SOE* to the *MRT* variants is rather moderate while the income side dominates the differences in the overall welfare results for households.

We conclude that a small-open-economy setting in the case of Germany not only overstates economy-wide welfare costs of emission abatement but also understates the progressiveness of lump-sum revenue recycling to households.

We can summarize the individual effects on different households from an overall societal perspective when adopting a social welfare function (SWF) where we capture alternative degrees of inequality aversion. In Figure 4 we present social welfare impacts as changes in the equally distributed equivalent income as defined by Atkinson (Atkinson, 1970). With an inequality aversion of zero we adopt a purely utilitarian perspective where consumption welfare of different income deciles are perfect substitutes in social welfare. The social welfare outcome in this case is identical to our aggregate welfare figures in section 3.2.1. As we increase inequality aversion, Germany's CO_2 reduction policy has a progressive impact across all three scenarios, indicating that poorer households are less adversely (or more favourably) affected. Towards a Rawlsian perspective, where only the welfare of the lowest-income household matters, social welfare actually increases beyond *BaU* levels. Finally, we observe for the case of Germany that the incorporation of terms-of-trade effects not only improves overall welfare but also increases progressiveness of CO_2 emissions pricing.

Figure 4: Atkinson equally distributed equivalent income with different degrees of inequality aversion for *SOE*, *MRT-U* and *MRT-M*



4. Concluding remarks

Germany – as other countries – committed itself under the Paris Agreement to greenhouse gas emission reductions, where targets are communicated via so-called Nationally Determined Contributions (NDCs). The societal acceptance of the actual NDCs and future pledges required to effectively combat global warming will critically hinge on the magnitude and distribution of economic adjustment costs.

Applied economic analysis can contribute to the climate policy debate with a rigorous quantification of economic impacts triggered by regulatory policy reforms such as the implementation of NDCs. Results from model-based analysis are inherently model-dependent. For robust policy advice it is particularly important to understand how structural model assumptions affect model results.

Against this background, our paper highlights the importance of international spillovers for assessing the magnitude and distribution of economic impacts from CO_2 emissions pricing to meet NDCs under the Paris Agreement. For our analysis we adopt a CGE model which permits to decompose the contribution of changes in terms of trade to economic outcomes triggered by policy reforms. We apply this model with alternative trade closures to investigate the economic impacts of CO_2 emissions pricing for the German economy where CO_2 revenues are recycled lump-sum to heterogeneous households (income deciles).

We find that in a small-open-economy setting which abstracts from terms-of-trade effects the CO_2 emissions price needed to meet the emissions reduction target is lower but overall economic adjustment costs are higher compared to a multi-region-trade setting with terms-of-trade effects. The reason is that in the multi-region-trade setting Germany is able to pass through part of CO_2 abatement costs to trading partners via higher export prices thereby reaping terms-of-trade gains. At the same time, output in EITE industries is less adversely affected, implying higher domestic CO_2 emissions prices to achieve the emissions reduction target. With respect to overall welfare the positive income effect through terms-of-trade gains more than offsets the adverse impacts of higher CO_2 emissions prices.

At the household level, the incorporation of international market responses not only improves welfare for each individual income decile but also enforces the progressiveness of Germany's climate policy.

We decompose the total welfare effect into an expenditure-side effect and an income-side effect. We find that CO_2 emissions pricing is regressive on the expenditure side as it increases the prices for emission-intensive consumption goods where lower-income households spend larger shares of their income than higher-income households. On the other hand, the lump-sum recycling of additional revenues to households on an equal-per-household basis is clearly progressive. In total, the income-side effect dominates the expenditure-side effect such that the overall welfare impact of Germany's climate policy is progressive.

Regarding the role of terms-of-trade effects in quantitative climate policy appraisal, we conclude that for countries such as Germany which export emission-intensive goods and import fossil fuels the omission of international spillovers is likely to overstate domestic welfare costs of emission reduction and understate the progressiveness of lump-sum equal-per-household CO_2 revenue recycling.

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A. Household Data

For our incidence analysis across heterogeneous households we disaggregate private final consumption as well as factor and transfer income in Germany into income deciles (denoted *h01*,...,*h10*). We use micro data from the German income and expenditure survey for the year 2013 (Statistisches Bundesamt, 2015) aggregated towards the income decile level. The total values in the micro data for expenditures and incomes do not match the values reported in the GTAP database for the base-year 2011. Our strategy for data reconciliation is to adjust the micro data such that total values match the GTAP data on factor income and final consumption expenditures, while maintaining the structural characteristics of German income deciles in terms of their income and expenditure patterns.

Income sources are capital (incl. resources), labor, and transfers. Consumption categories are *food*, *housing*, *energy* (electricity and heating), *transport*, *education*, *durables*, and *other goods*.

The main challenge arises on the income side as GTAP reports much higher capital income than the micro data. The reason is that profits that are re-invested by firms are reported as capital earnings in the GTAP data rather than savings/investment. Conceptually, we address this issue by introducing an additional residual household, a so-called capitalist (denoted *cpt* in Figure A.1), who earns residual capital income which is fully spent on savings/investment.

More specifically, our procedure to adjust the micro data involves three steps:

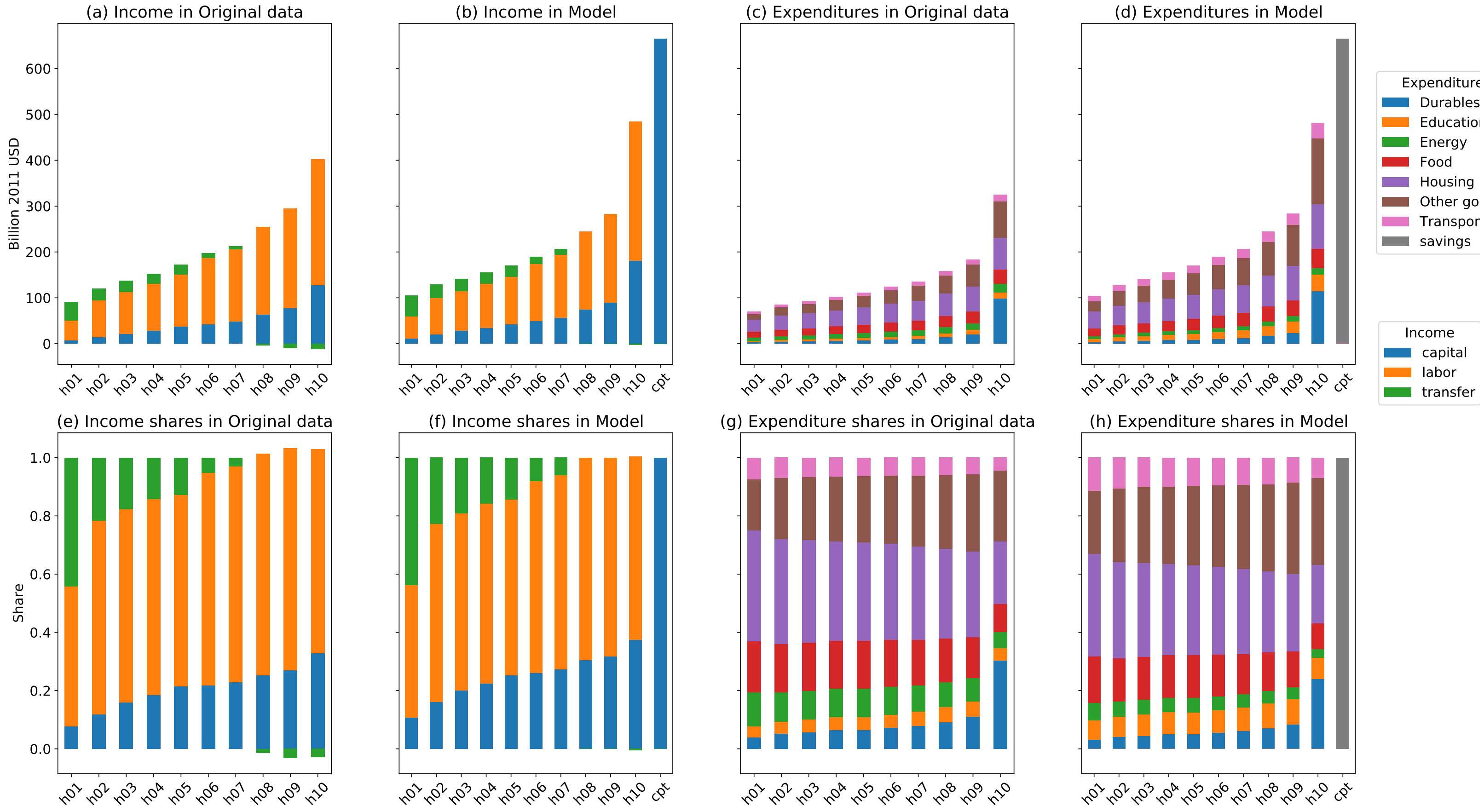
1. After converting the micro data to 2011 USD, we scale the micro data uniformly across households for each income source and each consumption category such that the totals equal the GTAP data. After this step the overall income-expenditure balance is fulfilled, but we still need to enforce the balance for each household, see step 3.

2. We assign to each household *h01,...,h10* capital earnings that are in line with its scaled labor income after step 1 and its capital income share in the original micro data. The residual capital income is assigned to the capitalist. On the expenditure side, the capitalist saves/invests the entire income.

3. We solve a least-square optimization problem where we enforce income-expenditure balances for each household while keeping income shares as close as possible to the micro data.

Figure A.1 shows income and expenditure patterns for household income deciles (*h01,...,h10*) and the capitalist (*cpt*) in the micro data and after the adjustment routine. On the income side – comparing (a) with (b) for absolute values, or (e) with (f) for shares – we see that the addition of the residual capitalist household permits an accurate match of income patterns across income deciles. On the expenditure side – comparing (c) with (g) for absolute values, or (d) with (f) for shares – our data adjustment procedure only slightly increases expenditure shares for *transport* and slightly decreases expenditure shares for *energy*.

Figure A.1: Income and expenditure patterns of income deciles in Germany, adjusted for use in CGE model



B. Computable general equilibrium model

The computable general equilibrium (CGE) model builds on the model developed in Lanz and Rutherford (2016). The model is formulated as a mixed complementarity problem and solved with the PATH solver (Ferris and Munson, 2000) in GAMS. The competitive equilibrium is characterized by three classes of conditions: zero profit conditions for all economic activities, market clearance for all markets, and income balance for all agents. We use the notation Π^u_{ir} to denote the profit function of sector i in region r where u denotes the associated production activity. Indices i and j index commodities, including a composite public good G and a composite investment good I. Indices r and s index regions. The label EG represents the set of energy goods and the label FF denotes the subset of fossil fuels. The notations used are summarized in Tables 5-10.

B.1. Zero profit conditions

1. Production of goods except fossil fuels ($i \notin FF$)

$$\Pi^Y_{ir} = \left[\theta^D_{ir} {p^D_{ir}}^{1-\eta_{ir}} + (1-\theta^D_{ir}) {p^{EX}_{ir}}^{1-\eta_{ir}}\right]^{1-\eta_{ir}} - p^{KLEM}_{ir} \leq 0$$

2. Sector- and region-specific aggregate of value added, labor, energy, and nonenergy inputs ($i \notin FF$)

$$\begin{aligned}\Pi^{KLEM}_{ir} = p^{KLEM}_{ir} - \Bigg[\theta^{KLE}_{ir} \Bigg[\theta^{KL}_{ir} {p^{KL}}^{1-\sigma^{KLE}_{ir}} \\ + (1-\theta^{KL}_{ir}) {p^E_{ir}}^{1-\sigma^{KLE}_{ir}}\Bigg]^{\frac{1-\sigma^{KLEM}_{ir}}{1-\sigma^{KLE}_{ir}}} \\ + (1-\theta^{KLE}_{ir}) \left(\sum_{j \notin EG} \theta^{NE}_{jir} {p^A_{jr}}^{1-\sigma^{NE}_{ir}}\right)^{\frac{1-\sigma^{KLEM}_{ir}}{1-\sigma^{NE}_{ir}}}\Bigg]^{\frac{1}{1-\sigma^{KLEM}_{ir}}} \leq 0\end{aligned}$$

3. Sector- and region-specific value added aggregate ($i \notin FF$)

$$\Pi^{KL}_{ir} = p^{KL}_{ir} - \left[\theta^K_{ir} w_r^{1-\sigma^{KL}_{ir}} + (1-\theta^K_{ir}) v_r^{1-\sigma^{KL}_{ir}}\right]^{\frac{1}{1-\sigma^{KL}_{ir}}} \leq 0$$

4. Sector-specific energy aggregate ($i \notin FF$)

$$\begin{aligned}\Pi^E_{ir} = p^E_{ir} - \Bigg\{\theta^{ELE}_{ir} {p^A_{ELE,r}}^{1-\sigma^E_{ir}} + \theta^{COA}_{ir} (p^A_{COA,r} + p^{CO_2}_r a^{CO_2}_{COA})^{1-\sigma^E_{ir}} \\ + \theta^{GAS}_{ir} (p^A_{GAS,r} + p^{CO_2}_r a^{CO_2}_{GAS})^{1-\sigma^E_{ir}} + \theta^{OIL}_{ir} (p^A_{OIL,r} + p^{CO_2}_r a^{CO_2}_{OIL})^{1-\sigma^E_{ir}}\Bigg\} \leq 0\end{aligned}$$

5. Production of fossil fuels ($i \in FF$)

$$\Pi^Y_{ir} = \left[\theta^D_{ir} p^{D^{1-\eta_{ir}}}_{ir} + (1-\theta^D_{ir}) p^{EX^{1-\eta_{ir}}}_{ir}\right]^{1-\eta_{ir}} - \left[\theta^Q_{ir} q^{1-\sigma^Q_i}_{ir} + (1-\theta^Q_{ir}) \Big(\theta^{FF}_{Lir} w_r \theta^{FF}_{Kir} v_r + \sum_j \theta_{jir} (p^A_{ir} + p^{CO_2}_r a^{CO_2}_j) \Big)^{1-\sigma^Q_i} \right]^{\frac{1}{1-\sigma^Q_i}} \le 0$$

6. Armington aggregate ($i \notin FF$)

$$\Pi^A_{ir} = p^A_{ir} - \left(\theta^A_{ir} p^{D^{1-\sigma^A_{ir}}}_{ir} + (1-\theta^A_{ir}) p^{M^{1-\sigma^A_{ir}}}_{ir}\right)^{\frac{1}{1-\sigma^A_{ir}}} \le 0$$

7. Aggregate imports across regions

$$\Pi^M_{ir} = p^M_{ir} - \Big(\sum_s \theta^M_{isr} p^{EX^{1-\sigma^M_{ir}}}_{is}\Big)^{\frac{1}{1-\sigma^M_{ir}}} \le 0$$

B.2. Market clearance conditions

8. Labor

$$\overline{L}_r \geq \sum_i Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial w_r}$$

9. Capital

$$\overline{K}_r \geq \sum_i Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial v_r}$$

10. Natural resources ($i \in FF$)

$$\overline{Q}_{ir} \geq Y_{ir} \frac{\partial \Pi^Y_{ir}}{\partial q_{ir}}$$

11. Output

$$Y_{ir} \geq \sum_j A_{jr} \frac{\Pi^A_{jr}}{\partial p_{ir}} + \sum_s M_{is} \frac{\partial \Pi^M_{is}}{\partial p_{ir}}$$

12. Armington aggregate

$$A_{ir} \geq \sum_j Y_{jr} \frac{\Pi^Y_{jr}}{\partial p_{ir}} + C_r \frac{\partial \Pi^C_r}{\partial p^A_{ir}}$$

13. Import aggregate

$$M_{ir} \geq A_{ir} \frac{\Pi^A_{ir}}{\partial p^M_{ir}}$$

14. Public consumption

$$Y_{Gr} \geq \overline{G}_r$$

15. Investment

$$Y_{Ir} \geq \overline{I}_r$$

16. CO_2 emissions

$$\overline{CO2}_r \geq \sum_i A_{ir} a^{CO_2}_i$$

B.3. Income balance

$$C_r p_r^C = w_r \overline{L}_r + v_r \overline{K}_r + \sum_{j\in FF} q_{jr}\overline{Q}_{jr} + p_{Ir}\overline{Y}_{Ir} + p_{Gr}\overline{Y}_{Gr} + \overline{B}_r + p_r^{CO_2}\overline{CO2}_r$$

Table 5: Sets and indexes

i, j	Indexes for sectors and goods
r, s	Indexes for regions
EG	All energy goods: Coal, crude oil, refined oil, gas and electricity
FF	Primary fossil fuels: Coal, crude oil and gas

Table 6: Activity variables

Y_{ir}	Production in sector i and region r
E_{ir}	Aggregate energy input in sector i and region r
M_{ir}	Aggregate imports of good i and region r
A_{ir}	Armington aggregate for good i in region r
C_r	Aggregate household consumption in region r

Table 7: Price variables

p_{ir}^D	Domestic supply price of good i produced in region r
p_{ir}^{EX}	Export supply price of good i produced in region r
p_{ir}^{KLEM}	Price of aggregate value-added, energy and non-energy in sector i and region r
p_{ir}^{KL}	Price of aggregate value-added in sector i and region r
p_{ir}^E	Price of aggregate energy in sector i and region r
p_{ir}^M	Import price aggregate for good i imported to region r
p_{ir}^A	Price of Armington good i in region r
p_r^C	Price of aggregate household consumption in region r
w_r	Wage rate in region r
v_r	Price of capital services in region r
q_{ir}	Rent to natural resources in region r ($i \in FF$)
$p_r^{CO_2}$	CO_2 emissions price in region r

Table 8: Cost shares

θ_{ir}^{D}	Share of domestic supply in sector i and region r
θ_{ir}^{KLEM}	Cost share of $KLEM$ aggregate in sector i and region r
θ_{ir}^{KLE}	Cost share of value-added and energy in the $KLEM$ aggregate in sector i and region r
θ_{ir}^{KL}	Cost share of value-added in the KLE aggregate in sector i and region r
θ_{ir}^{K}	Cost share of capital in value-added composite of sector i and region r
θ_{jir}^{NE}	Cost share of non-energy input j in the non-energy aggregate in sector i and region r
θ_{ir}^{E}	Cost share of energy composite in the KLE aggregate in sector i and region r ($i \notin FF$)
θ_{ir}^{Q}	Cost share of natural resources in sector i and region r ($i \in FF$)
θ_{Tir}	Cost share of good i ($T = i$) or labor ($T = L$) or capital ($T = K$) in sector i and region r ($i \in FF$)
θ_{ir}^{ELE}	Cost share of electricity in energy composite in sector i in region r ($i \notin FF$)
θ_{ir}^{FF}	Cost share of fossil fuel FF in energy composite in sector i in region r ($i \notin FF$)
θ_{isr}^{M}	Cost share of imports of good i from region s to region r
θ_{ir}^{A}	Cost share of domestic variety in Armington good i of region r

Table 9: Elasticities

η_r	Transformation between domestic and export supply	Aguiar et al. (2016)
σ_{ir}^{KLEM}	Substitution between KLE aggregate and material inputs	0
σ_{ir}^{KLE}	Substitution between energy and value-added in production	1
σ_{ir}^{KL}	Substitution between labor and capital in value-added composite	Aguiar et al. (2016)
σ_{jir}^{NE}	Substitution between materials	0
σ_{ir}^{Q}	Substitution between natural resources and otherinputs in fossil fuel production calibrated to exogenous supply elasticities μ_{FF}	$\mu_{COA} = 4.0$, $\mu_{CRU} = 1.0$, $\mu_{GAS} = 1.0$
σ_{ir}^{ELE}	Substitution between electricity and the fossil fuel aggregate	0.5
σ_{ir}^{A}	Substitution between the import aggregate and the domestic input	Aguiar et al. (2016)
σ_{ir}^{M}	Substitution between imports from different regions	Aguiar et al. (2016)

Table 10: Endowments and emissions coefficients

$\overline{L}_r$	Aggregate labor endowment in region r
$\overline{K}_r$	Aggregate capital endowment in region r
$\overline{Q}_{ir}$	Endowment of natural resource i in region r
$\overline{G}_r$	Public good provision in region r
$\overline{I}_r$	Investment demand in region r
$\overline{B}_r$	Balance of payment deficit or surplus in region r
$\overline{CO2}_r$	CO_2 emission constraint for region r
$a_i^{CO_2}$	CO_2 emissions coefficient for fossil fuel i

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