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The Incidence of Carbon Pricing: From Input–Output via Microsimulation to General Equilibrium

Christoph Böhringer^a Florian Landis^b Miguel A. Tovar Reaños^c

Abstract

To combat global warming many countries have pledged drastic reductions of CO₂ emissions and intend to achieve these via stringent carbon pricing. The societal acceptance of such carbon pricing will critically hinge on the magnitude and distribution of induced economic adjustment costs across heterogeneous households. To inform decision makers on the incidence of carbon pricing, economists draw upon three established quantitative methods: input–output, microsimulation, and computable general equilibrium. This paper provides a cross-comparison of the three methods applied to the illustrative example of carbon pricing in Germany. We highlight that – in comparison to a general equilibrium analysis – input–output and microsimulation analyses neglect important behavioral responses of economic agents in production and consumption and hence tend to underestimate both emissions reductions and economic adjustment costs of carbon pricings.

Keywords

CO₂ Pricing, Incidence, Input–Output, Microsimulation, Computable General Equilibrium

JEL codes

Q58, H22, H23, C67, C68, D57, D58

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1. Introduction

Under the Paris Agreement the world community agreed on the goal to limit global warming to well below 2°C compared to pre-industrial levels. From a climate science perspective this goal implies that major economies around the world must decarbonize their production and consumption patterns to become climate neutral. Economists since Pigou (1920) propose CO₂ emission pricing as a cost-effective instrument to reduce CO₂ emissions. As a matter of fact, many signatories to the Paris Agreement have meanwhile adopted CO₂ pricing to reduce domestic emissions – both in the form of explicit CO₂ taxes or as scarcity value of tradable emission allowances. However, the acceptance of more stringent CO₂ emission pricing will critically hinge on the magnitude and distribution of economic adjustment cost across heterogeneous households in the society. Regulatory policies that impose a heavy burden on low income individuals can be very costly from a social perspective since they may undermine social cohesion. As a case in point, the yellow vests movement in France for (more) economic justice has been sparked in 2018 by announced increases in fuel prices.

CO₂ pricing creates costs and rents which translate into the incidence for households via changes in commodity prices (the expenditure side), factor remuneration and potential transfers (the income side). On the expenditure side, CO₂ pricing will be regressive to the extent it increases prices for commodities where low-income households tend to spend larger shares of their budgets. Such commodities typically include electricity, home heating fuels, gasoline, and other energy-intensive goods. On the income side, CO₂ pricing affects factor productivity and thus the remuneration to labor and capital. Another key driver of the incidence is how rents from regulation are recycled. Revenues from emission pricing can be recycled by the government explicitly via direct (lump-sum) transfers or tax reforms that attenuate regressive effects or even render progressive impacts at the end.

To put the climate policy debate and decision making on an informed basis, there is the need for comprehensive economic impact assessment of CO₂ emission pricing. The quantification of economic impacts calls for the use of numerical model simulation techniques in order to assess systematically the interference of the many forces that interact in the economy. Compared to stylized analytical models, the numerical approach facilitates the analysis of complex system interactions and the impact assessment of structural policy changes.

In this paper we provide a cross-comparison of three model types that are widely used for the economic impact assessment of policy regulations such as CO₂ pricing: input-output (IO), microsimulation (MS), and computable general equilibrium (GE). The models differ in their assumptions on the scope of price-responsive behavior on the supply and demand side. The IO model assumes fully price-inelastic behavior. A CO₂ price increases producer and consumer prices, but does not lead to any adjustment effects in the pattern of production or consumption. In the MS model, households are assumed to respond to changes in consumer prices. Based on empirically estimated elasticities, households adjust their consumption plans to maximize consumption utility. As in the IO model, the MS model abstracts from price-induced substitution across inputs of production which would affect both the relative market prices of goods but also factor prices and hence factor incomes. The GE model, on the other hand, captures price-responsive behavior on behalf of consumers and producers and thereby captures in a comprehensive manner the structural change in production and consumption induced by policy measures; it does not only account for complex interactions on goods markets (including feedback effects from international markets) but also the impacts on factor markets such that income-expenditure cycles for households and the government are reflecting changes in factor income, tax payments, and transfers.

While it has been acknowledged before that GE models stand out for their comprehensive representation of economic responses to policy reforms (e.g., Shoven and Whalley (1992), Böhringer and Löschel 2006, Rausch et al. 2011), a systematic cross-comparison with popular competing or complementary methods such as input–output and microsimulation analysis is missing. Our principal research interest is to provide robust insights on how the degree of endogeneity in economic responses across the three model types translate into differences on the incidence of CO₂ pricing across heterogeneous households. As an illustrative empirical application for the three models, we investigate the economic impacts of CO₂ pricing in Germany where revenues are recycled lump-sum to household. In our numerical analysis we decompose the incidence across households into a CO₂ pricing effect (revenue collection effect) and a revenue recycling effect. The pricing effect captures the economic incidence of CO₂ pricing to households without revenue rebates. The revenue recycling effect quantifies how households are affected by revenue-neutral transfers of additional income from the government to the households. We find that the partial equilibrium nature of input–output and microsimulation models can lead to substantial underestimation of the incidence from CO₂ pricing across households. Across all three model variants, we find that the pricing effect is regressive but dominated by a progressive recycling effect. However, both the input–output as well as the microsimulation approach tend to underestimate economic adjustments substantially since they neglect important responses on the consumption and production side of the economy as compared to the general equilibrium approach.

Our paper is organized as follows. Section 2 provides a non-technical description of the three modelling approaches to quantify the economic impacts of CO₂ pricing. Section 3 describes the empirical data underlying our illustrative simulation analysis of CO₂ pricing in Germany. Section 4 presents an economic interpretation of simulation results Section 5 concludes.

2. Modeling framework

In the following we provide a non-technical description of the three different model types that are used successively to assess the incidence of CO₂ pricing across heterogeneous households. Detailed algebraic description of the more complex microsimulation and general equilibrium models are provided in Appendices A and B respectively.

2.1 Input–output model (IO)

Simple static IO models are widely used for comparative-static impact analysis. IO quantity models calculate the direct and indirect effects on production induced by exogenous changes in demand. Input–output price models are employed to calculate the sectoral price effects of exogenous policy reforms such as the imposition of CO₂ prices on the carbon content of goods. The basis for input–output analysis is an input–output table (matrix) which depicts the inter-industry relationships within an economy. An input–output table captures intermediate and factors inputs of production (input side) and the supply of sectoral output to other sectors and final demand (output side). Static IO analysis builds on the assumption of Leontief production technologies where the use of inputs (primary factors and intermediates) are proportional to the level of production. Likewise, the composition of final demand vectors for private households, investment, or government consumption is taken as fixed. The final demands of private households for production goods as provided in the input–output tables can be transformed via a bridge matrix into expenditures on consumer good categories. The coefficients of the bridge matrix provide information on the proportions in which the production goods are included in the various expenditure categories of private final demand.

2.2 Microsimulation model (MS)

Microsimulation models are used in applied economic research for ex-ante analyses of the consequences of economic policy measures - such as reforms of the tax and transfer system. They operate at the micro level, i.e. at the level of individual economic agents, thereby accommodating a high degree of heterogeneity. The effects of policy reforms are determined by the individual characteristics of the economic agents. The fundamental approach of microsimulation is to represent individual economic transactions in a detailed manner largely dispensing from aggregation – impact assessment can thus be carried out at a very refined level subject to a variety of socio-demographic characteristics. Obviously, the more detailed a microsimulation model the more excessive are the data requirements.

The core of our microsimulation model for the incidence analysis of CO₂ pricing is an econometrically estimated demand system. Using empirical data from income and expenditure surveys, households are characterized in terms of their factor endowments from which they derive income and their expenditures across consumption categories. Behavioral parameters such as price and income elasticities are estimated as a function of disposable income (expenditure budget) and consumer goods prices. These elasticities then drive demand responses to changes in consumer prices and disposable household income. Demand systems are often estimated using *Almost Ideal Demand System* (AIDS) models, which, in line with microeconomic household theory, assume that consumers make demand decisions as if they maximize utility subject to a budget constraint (Deaton and Muellbauer 1980). In contrast to the representation of consumer preferences via utility or expenditure functions with constant elasticities of substitution, price elasticities are not constant in the AIDS model, but vary with total expenditure. Even more flexible than the AIDS approach is the so-called "*Exact Affine Stone Index*" (EASI) demand system (Lewbel and Pendakur 2009) that we use for our present analysis to represent the behavior of heterogeneous households. More specifically, EASI is less restrictive as compared to AIDS when it comes to the estimation of income effects, i.e. the functional relationship between income and the consumed quantity of a good. As a prime example, AIDS assumes linear relationships between income and demand for goods, whereas EASI allows the estimation of non-linear Engel curves and thus avoids an estimation-related bias of income effects which might be especially relevant in our case with respect to CO₂-intensive consumption goods such as electricity, heat or transport (Tovar and Wölfling 2018).

2.3 General equilibrium model (GE)

Computable or applied general equilibrium models are well-established for the comprehensive impact assessment of policy reforms based on rigorous microeconomic theory and empirical data. The GE approach combines assumptions about optimization behavior of economic agents with the analysis of equilibrium conditions. The behavioral assumptions for producers and consumers (households) are rooted in standard microeconomic theory. Accounting for technological restrictions (the production possibility frontiers), producers combine primary factors and intermediate inputs at the lowest possible cost in order to achieve a certain production level of goods. Consumers maximize their well-being (utility) for given preferences, considering their budget constraints. The sectoral decomposition of the supply side based on multi-sector input-output tables tracks the structural change induced by policy reforms. On the demand side, the decomposition of a representative consumer into different household categories allows for an in-depth incidence analysis. Due to the microeconomic welfare foundation, alternative policy reforms can be ranked in terms of their overall (allocative) efficiency effects; furthermore, potential trade-offs between overall resource efficiency and distributional goals can be identified. Contrary to partial-analytical IO and MS model, GE models do not only capture the incidence of policy reforms on the expenditure side via changes in

consumption prices, but also the implications on factor earnings (wages, interest rates, resource rents), tax payments and transfers on the income side.

Production

Industry and service sectors produce goods using primary factors labor and capital as well as composite inputs of energy and non-energy intermediates (material). The production technologies are described by *constant elasticity of substitution* (CES) cost functions, which reflect substitution possibilities of inputs at different stages of the production process by constant elasticities of substitution. The elasticities of substitution indicate how easily an input in the production process can be replaced by another input depending on relative prices. Trade-offs between different energy carriers or intermediate non-energy inputs with the composites of energy and material are likewise captured by CES cost functions. For example, the sector-specific energy aggregate consists of inputs of electricity on the one hand and fossil fuels on the other where the fossil fuel aggregate in turn is a CES function of specific energy goods (coal, oil, gas). All sectors – except for sectors supplying primary fossil fuels – are characterized by constant returns to scale in production; if all inputs are doubled, output also doubles (average costs remain constant as production increases). The production of primary (fossil) energy requires the use of specific energy resources and has diminishing returns to scale (average costs increase with increasing production).

Factor mobility

Primary production factors are labor, capital and fossil energy resources. Labor and capital are assumed to be mobile across sectors, but not across borders. Fossil energy resources (gas, oil and coal in the ground) are specific to the production of the respective energy goods and cannot be used for the production of other goods. Full competition is assumed in factor markets (as in goods markets).

Consumption

Consumption demand results from the utility maximization of households subject to a budget constraint. Households earn income from wages, capital interests and resource rents adjusted for government transfers. Disposable income is then spent on consumption goods according to household preferences. Each consumption good is composed of production goods or services from the different economic sectors according to a consumption-production bridge matrix. Consumption preferences are captured via expenditure systems with empirically estimated elasticities. In our static model setting, savings and thus also investment demand are fixed at the empirically observed initial level.

State

Public authorities levy taxes to finance transfers and the provision of public goods. Public goods are produced with goods or services that are purchased at market prices. Across all policy simulations, the level of public goods provision is kept constant (in real terms), so that welfare changes from policy reforms for private households and are not affected by changes in the supply of public goods (assuming separability between private and public consumption). Additional revenues for the public sector that emerge from policy reforms such as CO₂ pricing are redistributed to economic agents in a revenue-neutral manner, whereby we focus on lump-sum transfers on an equal-per-capita base in our economic assessment of CO₂ pricing.

International trade

In international trade, Germany is assumed to be a price taker, i.e., changes in German import and export volumes have no influence on the international price system – export and import prices in foreign currency (so-called terms of trade) thus remain constant. Domestically

produced goods trade off between supply to the domestic and export markets according to constant elasticities of transformation. Analogous to the export side, product heterogeneity is also assumed on the import side. Domestic producer and consumer have preferences regarding the origin of a product. For example, producers in their intermediate demands view steel made in Germany differently in quality than steel imported from abroad; similarly, consumers differentiate e.g. wine according to the place of origin. The heterogeneity assumption (named after Armington 1969) leads to price differences between domestically produced goods and imports which captures empirically observable intra-industry trade (countries do not perfectly specialize based on comparative advantages). The price-responsive allocation of demand between the imported and the domestically produced good variety follow empirically estimated elasticities of substitution. We furthermore assume that policy reforms do not lead to a change in the original balance of payments in the medium to long run. The total value of exports equals the total value of imports, considering the balance of payments in the base year. The balance in foreign exchange determines the real exchange rate between domestic currency and foreign currency.

CO₂ emissions

The combustion of fossil fuels - coal, oil and gas - in production and consumption leads to CO₂ emissions. CO₂ emissions can be reduced in principle through three channels: (i) fuel switching (substitution of fuels for each other), (ii) efficiency improvements (e.g. through investments in more efficient technologies), or (iii) direct energy savings (via reduced production or consumption activities).

3. Data

The data sources to parametrize our models include input–output tables of the German Federal Statistical Office (incl. a production-consumption bridge matrix), data on CO₂ emissions by energy source and economic sector, as well as income and expenditure surveys. Data from the different sources are merged and consolidated to provide a coherent observation of economic flows for 2013 which serves as the base year for our simulation analysis.

3.1 Input–output tables, bridge matrix and CO₂ emissions

The IO and GE models are based on input–output tables with national accounts for the German economy. The first quadrant of the input–output table provides information on intermediate inputs across sectors. The second quadrant provides information on the components of final demand: private and public consumption, investment, changes in stocks and exports. Factor payments to labor and capital (depreciation and operating surpluses) are included in the third quadrant, which also shows imports by good category. The input–output table "Domestic production and imports" at basic prices is supplemented by the import matrix at CIF prices, i.e. at import prices including cost, insurance and freight, as well as by the input–output table "Domestic production" at basic prices. The latter makes it possible to decompose composite intermediate demand and final demand by domestically produced and imported varieties.

For our impact assessment of CO₂ emission pricing, we keep energy carriers and energy-intensive sectors in the dataset disentangled. Energy carriers not only differ considerably in their CO₂ intensity, but also with respect to (interfuel) substitution possibilities - both dimensions play a central role for the scope of economic adjustments to CO₂ pricing. Across energy carriers, we distinguish between three primary energy sources (coal, oil and gas) and two secondary energy sources (mineral oil, electricity incl. heating and cooling supply services).

CO₂-intensive industries are particularly vulnerable to CO₂ pricing and structural shifts away from these sectors are typically of particular (political economy) interest.

The bridge matrix links production goods by production sector according to CPA (*Statistical Classification of Products by Activity*) with the consumption of private households by consumption categories according to COICOP (*Classification of Individual Consumption by Purpose*) as used in the German sample survey of income and expenditure (EVS) for private households (the latter being the data source for our econometric estimation of the household demand system).

For our impact assessment of CO₂ pricing the COICOP consumption categories are aggregated into eight expenditure groups with a focus on energy-intensive consumer goods such as electricity, heat and transport. Furthermore, we distinguish expenditures for food, housing, education and leisure, durable consumer goods as well as expenditures for other goods and services are distinguished.

The Federal Statistical Office records direct CO₂ emissions from combustion of fossil fuels in production sectors (according to CPA) and for private households. The energy carriers are thereby much more differentiated than in the IO table - for example, petroleum products are differentiated according to petrol and diesel or coal according to hard coal and lignite. It is therefore necessary to aggregate the energy carriers from the CO₂ emission flow accounts to the respective composite energy carriers in the IO table.

The consolidated data on input-output production structure, consumer demand as well as CO₂ emissions provide the empirical foundation of for our IO simulations. The initial data set is also used for the parametrization (calibration) of our GE model. As usual in applied general equilibrium analysis, the calibration procedure uses quantity and price observations for the base year to determine free parameters in the functional forms that describe production technologies and consumer preferences – more specifically, calibrated parameters include cost shares in production and expenditure shares in consumption; in addition, substitution elasticities are incorporated as econometric estimates. For our analysis, consumer preferences are empirically rooted in our estimated EASI demand system whereas substitution elasticities in production are taken from the pertinent econometric literature.

3.2 Income and expenditure survey

The sample survey of income and consumption (EVS) provides statistical information on income, consumption expenditure and other important socio-economic characteristics of private households. Households groups with different characteristics are weighted such that the EVS information is representative for all households. In the EVS, approximately 60,000 private households in Germany are surveyed every five years. We use the five recent waves for the years 1993, 1998, 2003, 2008 and 2013 to estimate the EASI demand system. For our simulation analysis of CO₂ pricing with the IO, MS, and GE models households are divided into 10 expenditure deciles and the respective price and income elasticities are estimated for the eight consumer goods categories.

3.3 Data reconciliation

For the integration of the MS demand model into the GE model, the household-specific EVS data on income and consumption expenditure must be matched with the data for the representative household in the input-output table. The EVS data are provided with statistical weights indicating how many of the actual German households in the survey are represented by a household. The figures on income and consumption expenditure aggregated via EVS households

in general do not match the data in the national accounts. For the econometric estimates of the EASI demand system, we must use expenditure shares of households as they are recorded in the EVS. Therefore, differences in the EVS data to the consumption expenditure reported in the IO table are matched in the IO data via changes in government consumption. The data adjustment implies that private consumption demand for goods reacts less or more elastically depending on whether government consumption is increased or decreased compared to the base-year values in the IO table. On the income side, capital and labor income are scaled uniformly across all households. Household savings are derived from the EVS data as the difference between income and expenditure and are then scaled to align with the IO data for the representative household.

3.4 Base-year statistics

With the consolidated data set for the year 2013, we can calculate key figures leading our economic intuition on the potential incidence of CO₂ pricing for different households, i.e., CO₂ intensities of production or consumption goods as well as consumption and income patterns of households.

First, CO₂ intensities determine how strongly the prices of individual product or consumer goods groups are affected by CO₂ pricings. Second, the higher the expenditure share is a household spends on CO₂-intensive consumer goods, the more adversely the household will be affected *ceteris paribus* on the expenditure side by CO₂ pricing. Third, changes in household income must be accounted for. CO₂ pricing affects factor prices such as wages and interest rates via structural changes in consumption and production. Depending on how relative factor prices change and how households' income sources are composed, the incidence effect on the expenditure side can be strengthened, weakened or even reversed. Last but not least, the distributional effects of CO₂ pricing also depend on how additional revenues are redistributed. For our simulation analysis, we assume that revenues from CO₂ pricing are recycled on a uniform per capita base (a so-called eco-bonus).

Reflecting inter-industry relationships, the economic impacts of CO₂ pricing are not only driven by the direct CO₂ emission intensities, but also by the indirect emission intensities. Direct CO₂ emissions arise from the combustion of fossil fuels. Indirect emissions are associated with the implicit (*embodied*) CO₂ content of other intermediate inputs. For example, electricity is partly produced in coal and gas-fired power plants; whenever electricity is then used as an input in the production process, its indirect emissions must be taken into account when calculating the total emissions intensity of a sector. Using the IO model, the so-called Leontief inverse can be used to calculate the total emission intensity, that is how many kg of CO₂ are emitted in the production of a unit of output value (e.g. in €) by sector. The direct emission intensity is obtained by dividing the direct emissions from the combustion of fossil fuels, which are listed in the Federal Statistical Office's physical CO₂ emission input-output tables by the monetary production value in the supply and use IO tables of the respective sector. The indirect emission intensity then equals the difference between the total emission intensity and the direct emission intensity. Fig. 3.1 shows the direct and indirect emission intensities for the 10 economic sectors with the highest CO₂ intensities in our base-year dataset. Electricity has by far the highest CO₂ intensity - both in term of direct and indirect emissions. This reflects the fact that in 2013 the share of fossil energy sources in gross electricity generation amounts to 73% which also explains a considerable indirect emission contribution via electricity own-consumption. The importance of indirect emissions is evident for various emission-intensive sectors such as iron and steel, paper and pulp, or non-ferrous metals, where the indirect emission intensity is several times higher than the direct emission intensity.

Using the bridge matrix, the emission intensities of the production sectors can be transferred into the CO₂ intensities for consumer goods (see Fig. 3.3). The three consumer goods with substantial CO₂ intensities are electricity, heat, and transport. Electricity also has the highest CO₂ intensity on the consumption side, closely followed by heat and then, at some distance, transport. The other consumer goods play only a subordinate role. For the incidence of CO₂ pricing on the expenditure side it will hence be important how high the expenditure shares of different households are for electricity, heat, and transport.

For our analysis, we aggregate the households covered in the EVS into expenditure deciles. The choice of expenditure deciles instead of income deciles follows the life-cycle hypothesis, according to which households adjust their consumption expenditure over their lifetime based on expected future income; therefore, annual expenditure is a better indicator of the social status than annual household income. An expenditure decile is represented in the following by the average household in that decile (i.e., we do not consider variation of consumption patterns within deciles).

Table 3.1 shows important characteristics of household deciles by household size (number of persons in the household), average annual expenditure, and average annual gross income for the base-year 2013.

The size of a household plays a role when we must refer to per capita figures – for example, when rebating revenues from CO₂ pricing on a per-capita-basis or when calculating equivalized incomes in welfare appraisal.

Fig. 3.3 shows for the base-year 2013 the expenditure shares of households for the three consumer goods categories that stand out for the highest CO₂ intensities: electricity, heat and transport. It can be seen that poorer households have higher expenditure shares for heat, transport and electricity. For example, the first decile has an expenditure share of about 19%, while the expenditure share for the tenth decile is only 10% – almost half as much.

With the consumption patterns described in Fig. 3.3, one could expect that CO₂ pricing has an regressive effect. Poorer households are burdened more than richer households because they spend higher shares of their expenditure budget for emission-intensive goods and are therefore also relatively more affected by CO₂ prices.

Finally, and as pointed out before, the incidence of CO₂ pricing does not only depend on the expenditure-side effects, but also on how factor and transfer incomes of households are affected. Supply- and demand-side responses to CO₂ pricing affect factor inputs, marginal factor productivities and thus factor remunerations. Ultimately, all goods and factor prices are affected by the regulatory intervention, so that nominal transfer incomes can also change (depending on the change in the price index for the transfer).

Fig. 3.5 shows the income components for the household deciles for the EVS in 2013. Poorer households have a lower share of capital income and a higher share of transfer income (calculated as the sum of public and non-public transfer payments minus tax payments) than the richer households. The incidence of CO₂ pricing on the income side depends on the policy-induced changes in factor and transfer prices as well as the respective composition of households' income.

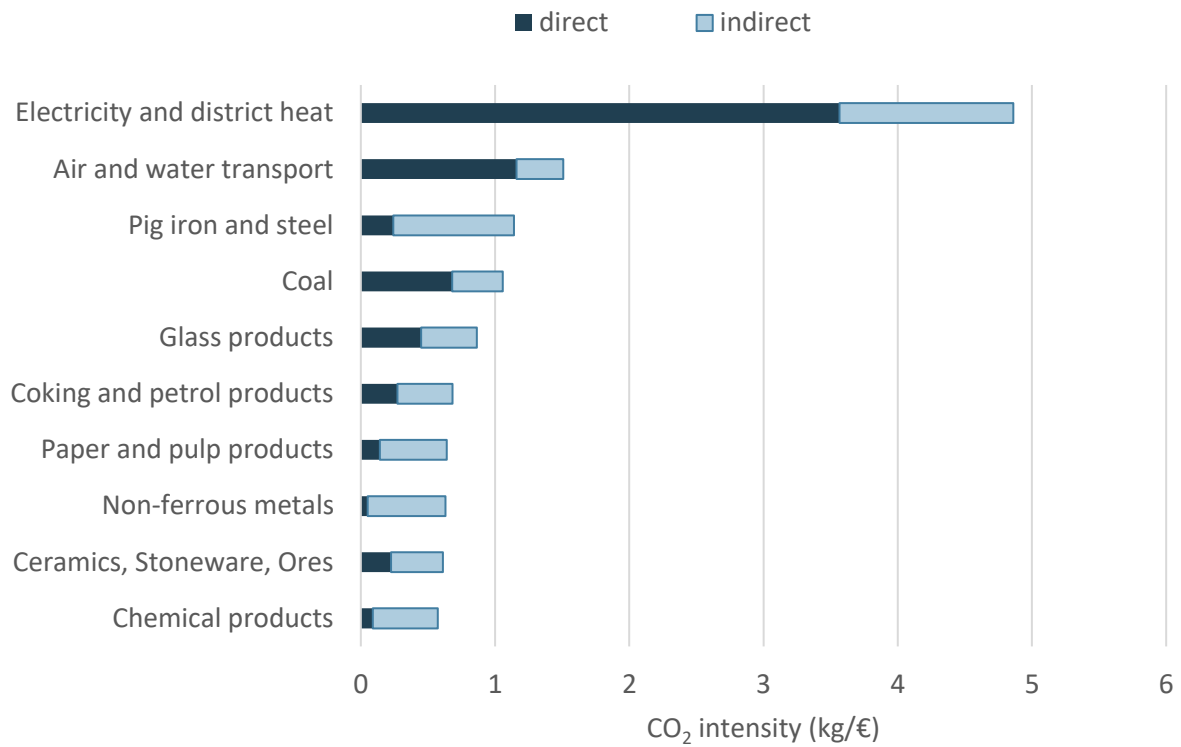


Fig. 3.2 Top 10 sectors in terms of direct and indirect emission intensities (kg CO₂/€)

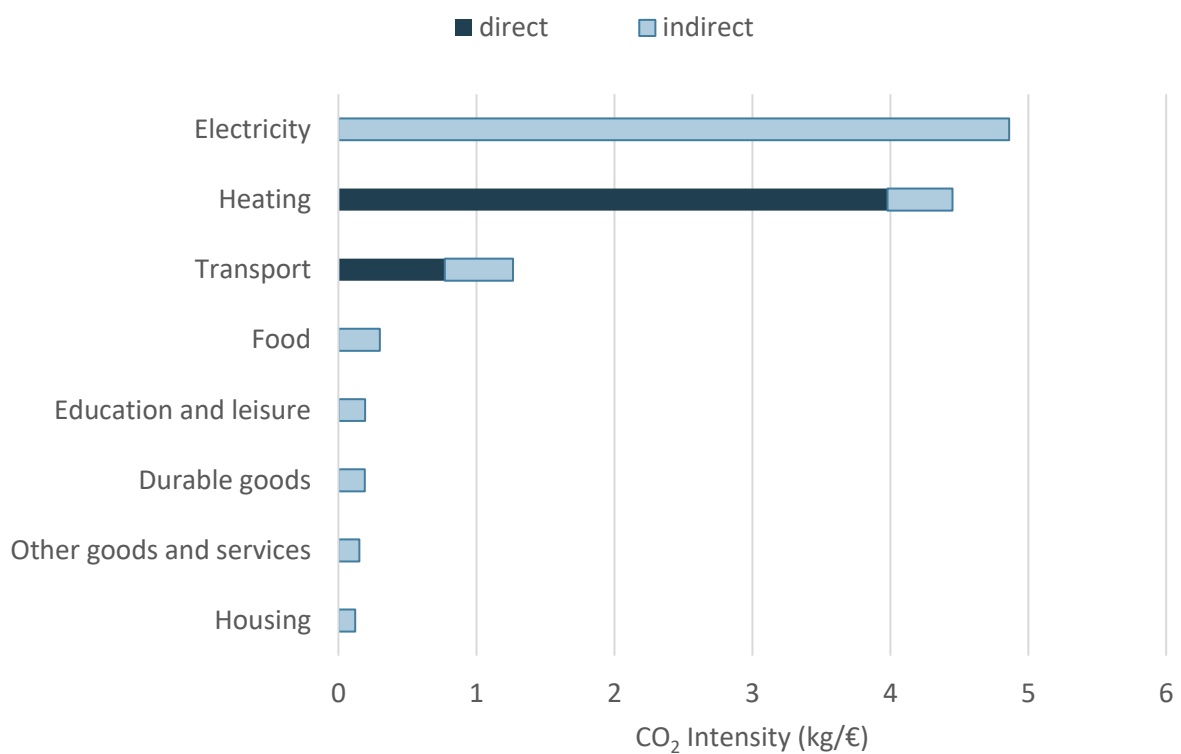


Fig. 3.3 Emission intensities (kg CO₂/€) of consumer goods

Table 3.1 Characteristics of the household deciles (2013)

Expenditure decile	Size (Ø persons)	Expenditure (€/year)	Gross income (€/year)
1	1,073	11065	14396
2	1,309	15464	22018
3	1,572	18845	27728
4	1,819	22035	32903
5	2,096	25357	39270
6	2,301	28947	45866
7	2,509	32903	51738
8	2,767	37632	59556
9	2,919	44756	69607
10	2,941	71742	86341

Source: Survey of income and expenditure (EVS) 2013

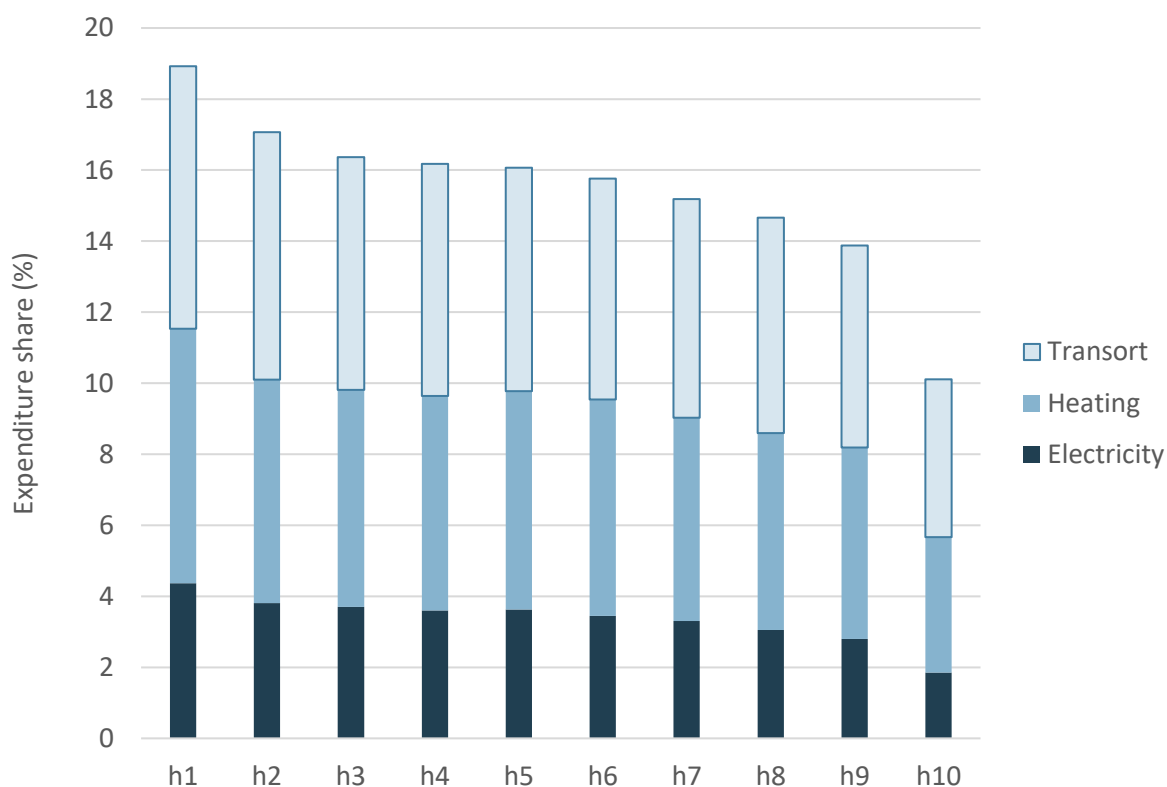


Fig. 3.4 Household expenditure shares for electricity, heat and transport (%) in 2013. Based on Income and Consumption Statistics (EVS) 2013.

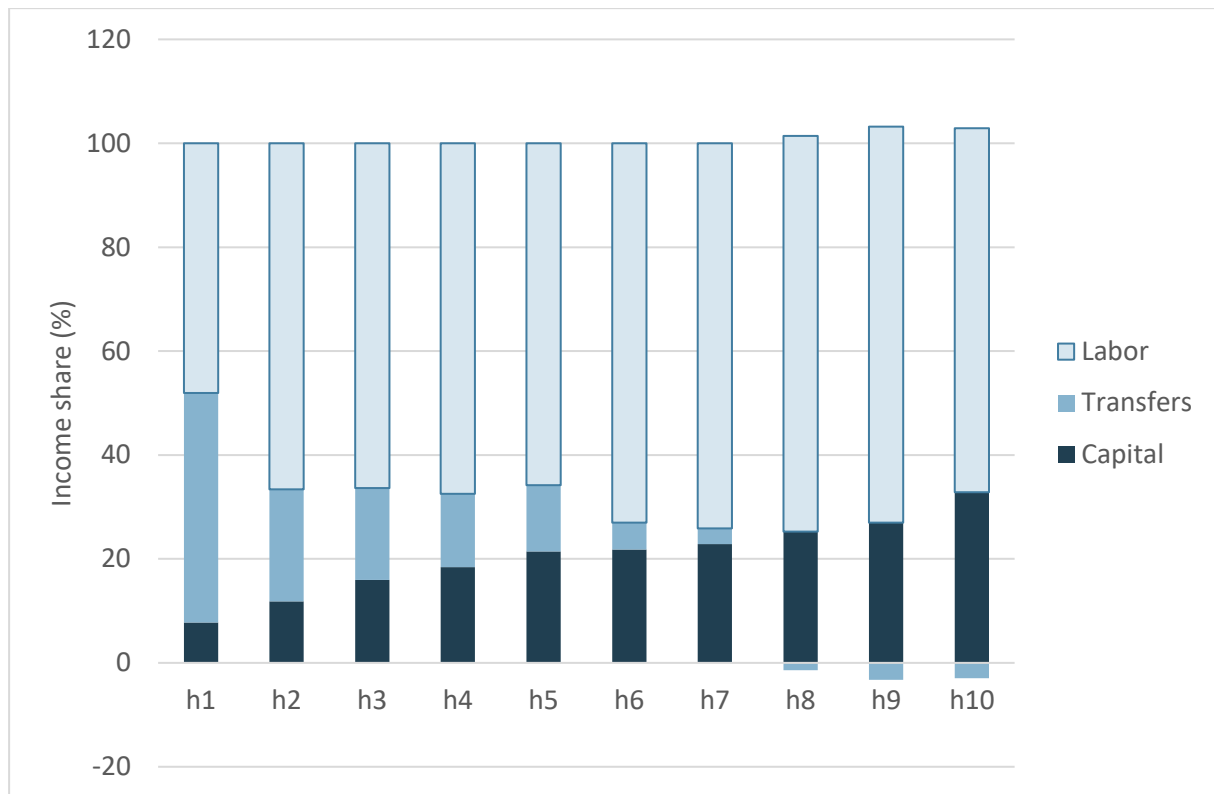


Fig. 3.5 Household income shares (%) in 2013. Based on Income and Consumption Statistics (EVS) 2013.

4. Scenarios and simulation results

In our scenarios, we consider the economic effects of a comprehensive pricing of the CO₂ content of the various fossil energy sources in Germany. We assume a uniform CO₂ price across fuels and sectors but consider different levels of the price to see how results change with increasing policy stringency. In reality, the German government has envisaged a CO₂ price of €25/tCO₂ on the use of fossil fuels in the transport and building sectors for 2021. This is to be implemented through a national emissions trading system for emissions in these sectors. The national emissions trading system is complementary to the EU-wide one (the EU ETS), which covers CO₂ emissions released by industry and the energy sector and has been in place since 2005. Through both regulations, the vast majority of CO₂ emissions generated in Germany will then be subject to CO₂ pricing. The segmentation into two separate emissions markets threatens to result in additional macroeconomic costs of CO₂ abatement, since the prices or marginal abatement costs in the two markets will generally not match and thus emissions abatement will not take place where it is cheapest. However, the CO₂ price in the EU ETS has settled in the €25 range over the last two years, so the potential additional costs of market segmentation for CO₂ rights should currently be low. The CO₂ price in the national ETS is then expected to more than double to €55 by 2025 and to increase significantly thereafter to converge with higher estimates of the societal costs of climate damage from CO₂ emissions. An increase in the CO₂ price is also anticipated in the EU ETS, so that under the optimistic assumption of an even price development in both segments, our stylistic representation of CO₂ pricing in Germany can be justified.

The overall incidence of a CO₂ price reform can be decomposed into a collection-side effect of CO₂ pricing (collection effect) and a redistribution effect of additional government revenues (redistribution effect). The introduction of a CO₂ price leads to additional revenues, which can be

used for the pursuit of ecological, economic or social policy goals. It is obvious that the way these revenues are used - the so-called *revenue recycling* - can play an important role for the efficiency and incidence effects of CO₂ pricing. The current simulation analysis is limited to *revenue recycling* in the form of a per capita bonus (climate premium), in which the tax revenue is redistributed to households through lump-sum payments. This redistribution has a progressive effect, as the uniform per capita premiums are higher in relation to income at the lower end of the income distribution than at the higher end. The progressive effect of a climate premium can thus counteract the rather regressive effect of the CO₂ price and, if necessary, lead to a progressive overall effect.

The simulation results discussed below are to be interpreted as *what-if analyses* and not as forecasts. Based on well-defined and controllable assumptions, impact estimates are made for future reforms prior to their implementation. In other words, ex-ante comparisons show the effects induced by hypothetical policy reforms compared to a reference situation without regulatory change.

The quantitative impact analysis is divided into four parts. First, the short-term incidence of a CO₂ price on household deciles resulting from the simulations with the IO model is discussed. It is assumed that there are no adjustment possibilities in production and consumption patterns. In the second part, the IO short-term analysis is compared with the medium- to long-term effects of a CO₂ price in the MS and GE models. In the partial-analytical MS approach, substitution possibilities of households in consumption to changing prices are taken into account. In the GE approach, adjustment effects on the production side, factor markets and international trade are also included. The comparison between the IO, MS and GE results then makes it clear what role the successive endogenization of demand- and supply-side behavioral responses has for the strength and direction of the economic effects of a CO₂ price. The third part of the presentation of results shows changes in macroeconomic and sectoral indicators that can be quantified in the impact analysis with the GE model. In the fourth part, the central simulation results are summarized and classified across the three model variants.

To measure the incidence of a CO₂ price, the welfare concept of so-called equivalent variation is used. The equivalent variation compares the utility levels of a household between the initial and the new equilibrium. It indicates which change in income for the household, if that household still faced the market price levels of the initial equilibrium, would lead to the new utility level. The equivalent variation can be expressed as an absolute value in monetary units or in relative values, i.e. as a percentage change in the utility level compared to the initial situation.

In addition to the incidence at the level of individual household types (here: expenditure deciles), an evaluation of CO₂ pricing at the macroeconomic level – especially with regard to distributive justice – is also of interest for the socio-political discussion. For this purpose, changes in individual benefits are aggregated via a social welfare function into a social welfare measure. Aggregation requires an explicit (cardinal) interpersonal utility comparison and is thus subject to normative evaluations that must be disclosed in the analysis. Thus, by merely adding up the equivalent variations across households, one can indeed determine a macroeconomic welfare change for a policy reform, but in doing so one has already adopted a utilitarian perspective. With the unweighted addition of the individual benefits to the total benefit, one assumes the complete substitutability of the benefits of different individuals. Irrespective of the individual affectedness, the utilitarian norm is about maximizing the total benefit for all those affected ("the greatest happiness of the greatest number"). The other extreme is the so-called Rawlsian maximin criterion, according to which the benefit of the worst-off individual is to be maximized under aspects of justice. In the discussion of social welfare effects, recourse is usually

made to a generalized social welfare function that allows alternative parameterizations of inequality aversion in the sense of an open normative discourse.

When interpreting the welfare results, it is important to note that avoided climate damages due to the reduction of CO₂ emissions are not taken into account. In any case, it should be noted that the costs of CO₂ pricing shown in the current analysis are not to be interpreted as an argument against climate protection, but are attributable to a lack of monetarization of climate damage.

4.1 The short-term incidence of a CO₂ price in input–output analysis

With the IO model, the short-term effects of a CO₂ price can be determined under the assumption that there are no substitution reactions on the supply and demand side. The prices levied on the production side for the CO₂ content of fossil energy sources are then passed on in full as additional costs to the consumption prices of private households.

Fig. 4.1 shows the percentage price changes resulting from different CO₂ prices for the 10 production goods of the highest CO₂ intensity. Corresponding to the highest CO₂ intensity, the production sector "Electricity and district heat" has the highest price mark-up. The price premiums are shown for alternative CO₂ prices of 25, 50, 100 and 200 €/tCO₂. Ultimately, however, there is a simple proportionality relationship here – if the CO₂ price doubles, the price surcharge also doubles.

The price increases on the production side result in the price increases for the individual consumer goods via the bridge matrix (thus reflecting the respective CO₂ emission intensities in consumption) – see Fig. 4.2. Here, electricity and heat in particular, but also transport, become more expensive. For example, the consumer price for electricity increases by almost half with a CO₂ price of €100/tCO₂ compared to the initial level. The price increases induced by CO₂ pricing for the respective consumer goods can be linked to the consumption patterns or the bundle of goods demanded by private households. In this way, the direct additional costs due to a CO₂ price are obtained for the average household of each expenditure decile (collection effect). The redistribution of additional revenues via a per capita climate premium results in a relief redistribution effect. The sum of the collection and redistribution effects yields the net incidence per household decile.

Fig. 4.3 shows the absolute collection and redistribution effects as well as the net incidence of households over the year for a CO₂ price of 100€/tCO₂. In the fixed IO structure, the respective effects can be scaled up or down proportionally with the level of the price. In the interpretation, it must be taken into account that both expenditure and income are standardized with a household-specific consumption price index. These are therefore real household-specific purchasing power variables as they are required for a welfare economic analysis on the basis of the equivalent variation. For the redistribution effect via a per capita premium, household size also plays a role in the resulting equivalized income. The richer a household is (measured by the expenditure budget), the higher its absolute cost burden from the collection effect. This is not surprising, since richer households have significantly higher absolute expenditures than poorer households in the CO₂-intensive consumer goods categories (electricity, heating, transport). Conversely, the richer households also receive a higher rebate in absolute terms via the climate premium, which is mainly due to household size, but which in addition looks bigger compared to the household-specific consumption price index, which is used to convert nominal payments to households into real purchasing power in each case (e.g., with a CO₂ price of €100/tCO₂, the consumption price index increases by 7.7% for the poorest household, and by 4.7% for the richest household). If one adds up the negative collection effect with the positive redistribution effect, one sees that only the two top household deciles lose from such a CO₂ price reform, while all other deciles gain.

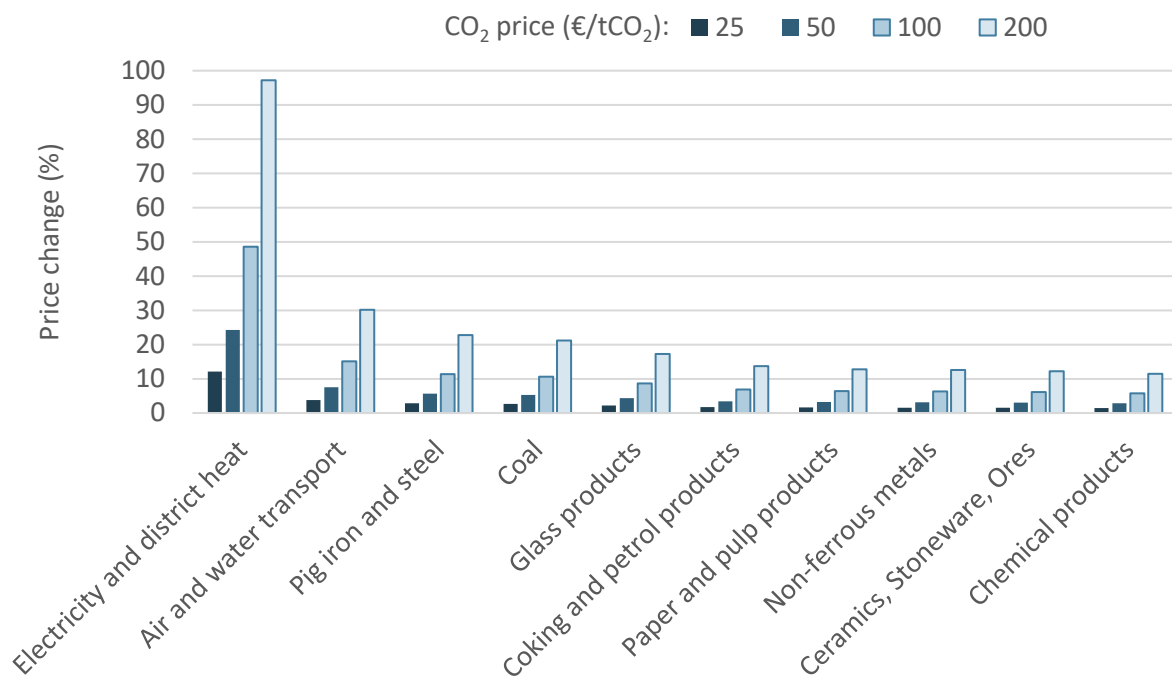


Fig. 4.1 CO₂ price induced price changes of production goods (%)

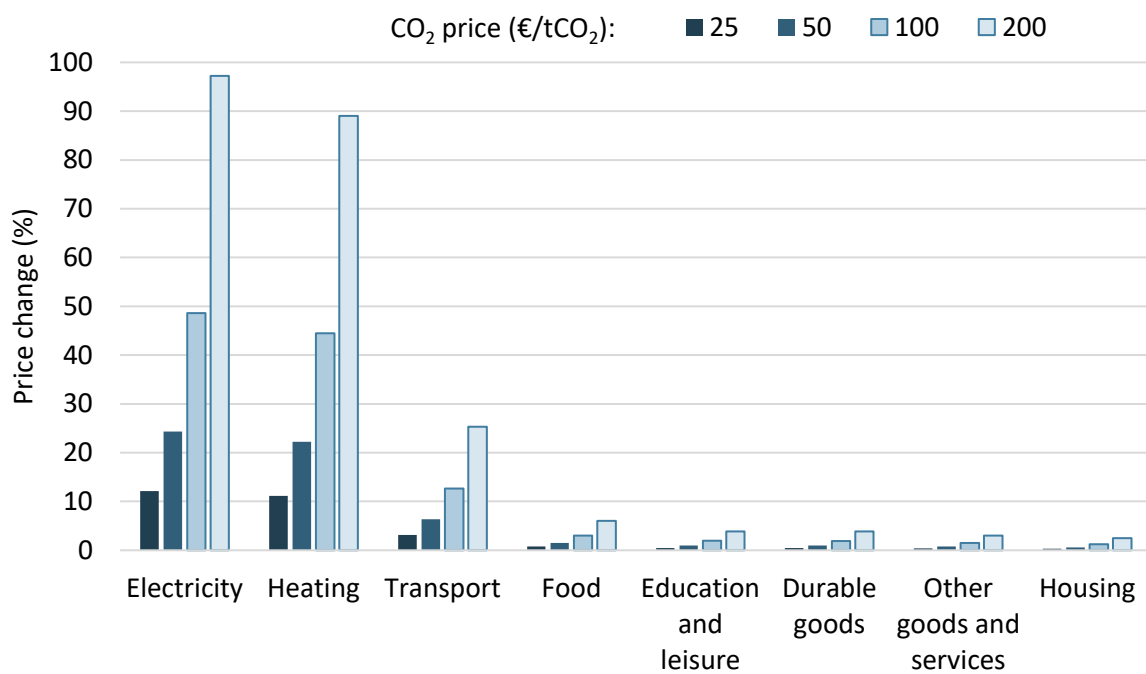


Fig. 4.2 CO₂ price induced price changes of consumer goods (%)

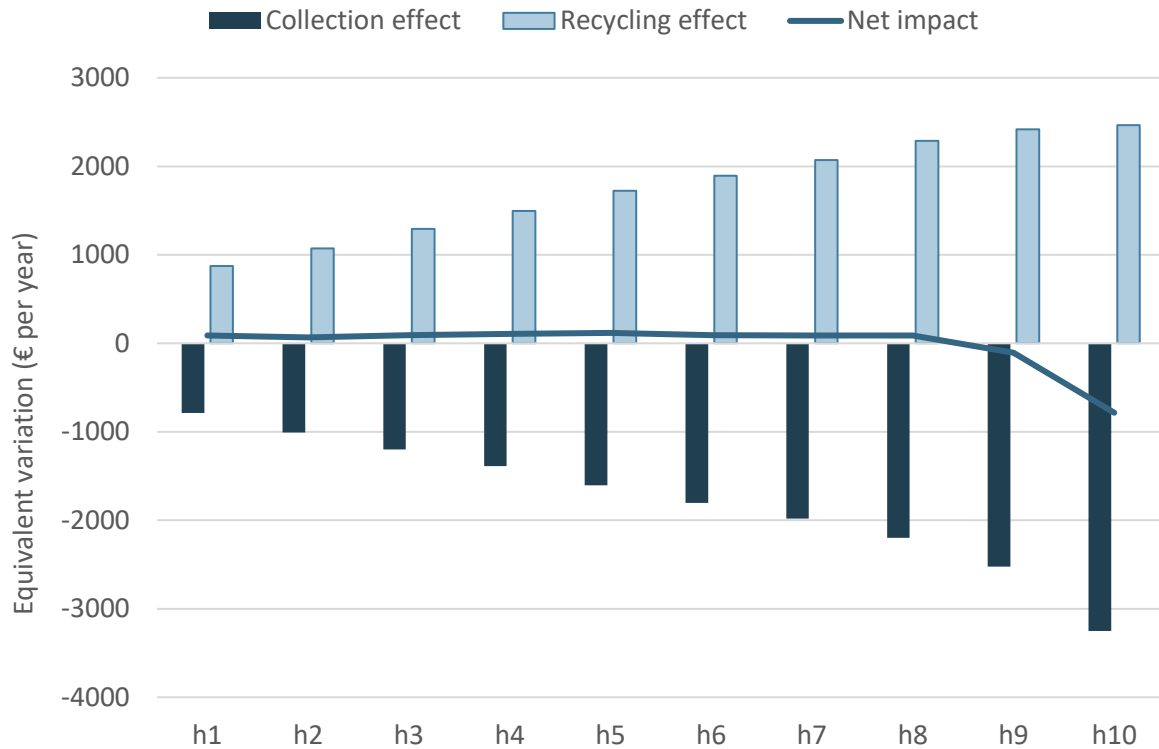


Fig. 4.3 Incidence (in € per year) of a CO₂ price of 100€/tCO₂ – model variant: IO

In order to make statements about the regressivity or progressivity of the expenditure and revenue effects, one must set the absolute burden or relief variables in relation to the respective total expenditure of the households. This is again done for the case of a CO₂ price of 100 €/tCO₂ in Fig. 4.4. As expected from the key figures for the household deciles (cf. Fig. 3.3), the CO₂ price has a regressive effect on the collection side. In particular, there are higher prices for the CO₂-intensive consumption categories electricity, heat and transport, which account for a relatively higher share of total expenditure for low-income earners than for high-income earners. Conversely, the redistribution effect via a per capita premium is progressive, as this transfer is relatively more significant for the lower household deciles than for the upper deciles. In terms of net incidence, the regressive collection effect is dominated by the progressive redistribution effect. A CO₂ tax reform with eco-bonus thus has a progressive effect overall. As Fig. 4.5 shows, this result remains robust across different levels of CO₂ pricing.

It should be noted that there are no allocative efficiency changes in the short-term IO incidence analysis. Typically, direct or even indirect government intervention in the market-based price system leads to distortions in supply and demand decisions. However, if one assumes, as in the IO analysis, that production and demand structures are completely price inelastic, there are also no allocative effects. The IO approach underestimates potential adjustment costs of a CO₂ price on the supply and demand side, such as the costly switch to more energy- or CO₂-efficient production technologies or the loss of benefits through a forced substitution to less CO₂-intensive consumption (e.g. the restriction of private air travel). The IO incidence analysis is thus limited to an efficiency-neutral redistribution. From a utilitarian perspective, one considers a zero-sum game between the different households, in which the welfare changes across all households add up to zero.

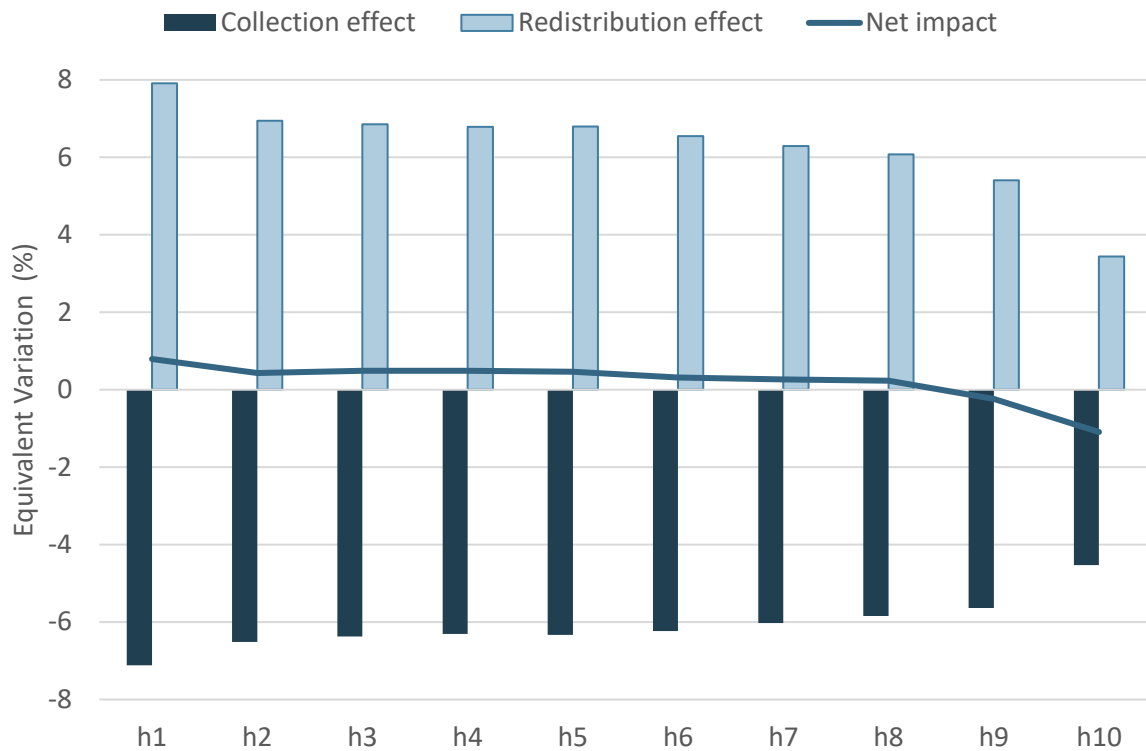


Fig. 4.4 Incidence of a CO₂ price of 100€/tCO₂ – model variant: IO

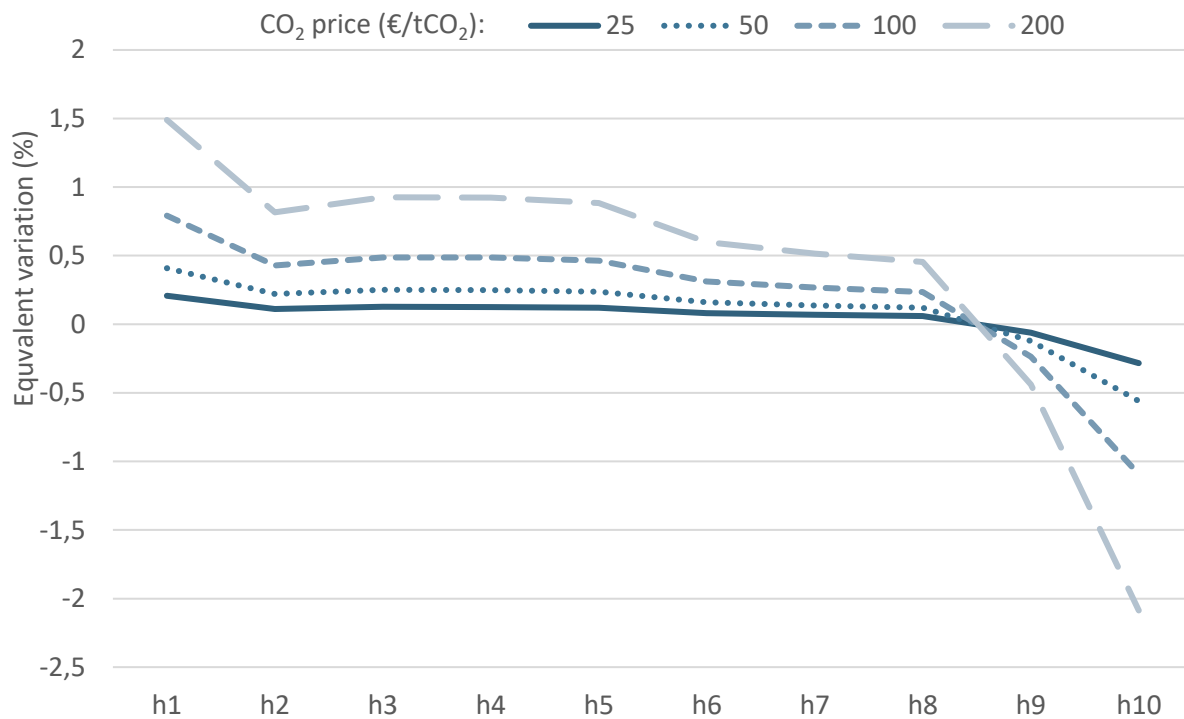


Fig. 4.5 Net incidence of a CO₂ price – model variant: IO

4.2 Effects of CO₂ pricing in comparison: IO, MS and GE analyses

In the medium to long term, a CO₂ price leads to adjustments in both the consumption patterns of households and the production structure of the economy. Households will demand CO₂-intensive consumer goods less or substitute them with the consumption of other, less CO₂-intensive goods. Companies will replace CO₂-intensive energy sources such as coal with less CO₂-intensive energy sources such as gas, increase their energy efficiency through increased capital investment and also adjust the level of production. On the one hand, decarbonization of the economy in production and consumption is the declared goal of climate policy measures, but on the other hand it causes economic adjustment costs for producers and consumers. In the MS model, adaptation costs are only taken into account through evasion reactions in consumption by households. The GE model also includes evasive reactions in production. It should be emphasized once again that the model-based welfare analyses do not take into account any benefits from avoided climate damage, so that changes in consumption and production structures inevitably lead to efficiency losses (economic adjustment costs) compared to the reference situation.

Fig. 4.6 shows the percentage change in welfare as an arithmetic average over all households or persons.

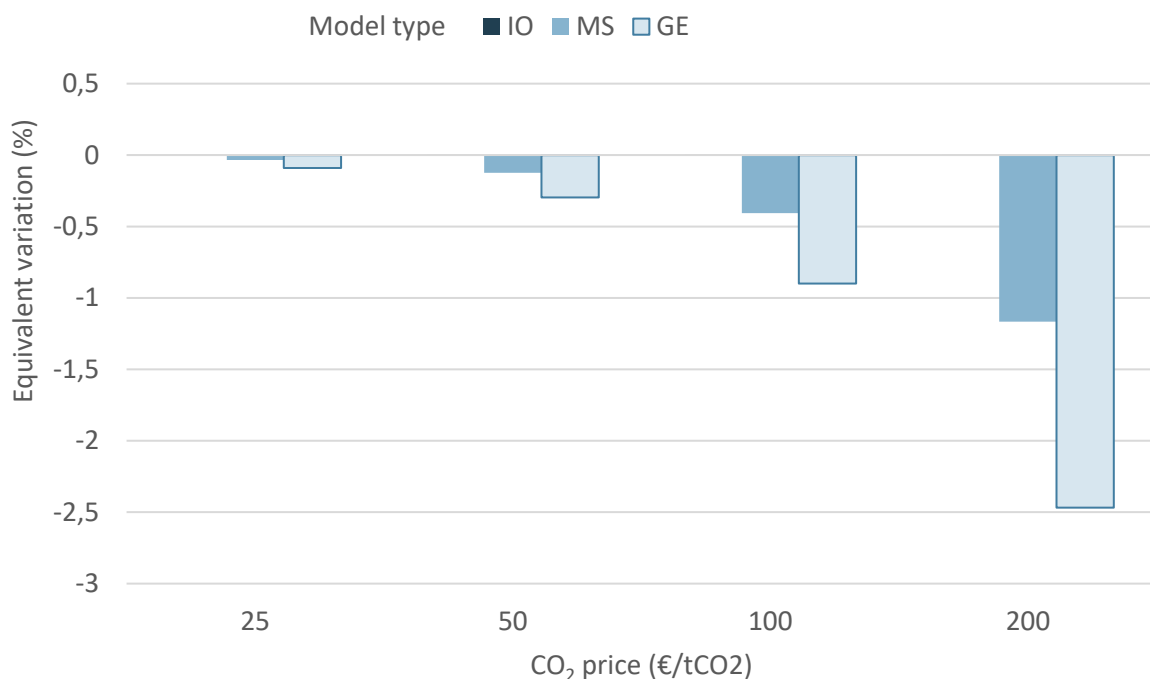


Fig. 4.6 Average welfare loss across all households – model comparison

This welfare change reflects the allocative efficiency losses in production and consumption caused by CO₂ pricing. For the IO model variant, there are, by assumption, no efficiency losses due to the lack of behavioral responses. First of all, it should be noted that the evasive reactions to CO₂ prices and thus the adjustment costs of decarbonization are higher the higher the CO₂ prices are. The costs of CO₂ pricing rise disproportionately in the CO₂ price: If, for example, the CO₂ price quadruples from €25/tCO₂ to €100/tCO₂, then the adaptation costs increase more than tenfold. The MS model shows significantly lower overall economic adjustment costs than the GE model, as the allocative effects of a CO₂ price on the supply side are neglected – at the

respective tax rates, the MS model underestimates the costs by more than half compared to the GE model. The GE model simulation thus shows that the negative impact of a CO₂ price on the marginal productivity of the factors labor and capital and thus factor income is considerable. While the IO model completely hides the macroeconomic efficiency losses, the MS model significantly underestimates the adjustment costs of the economy to CO₂ prices.

Fig. 4.7 shows that across all model variants, the CO₂ price in combination with a per capita climate premium is progressive. However, it should again be noted that with the consideration of allocative efficiency losses, the welfare effect in the MS model and especially in the GE model is significantly more negative than in the IO model.

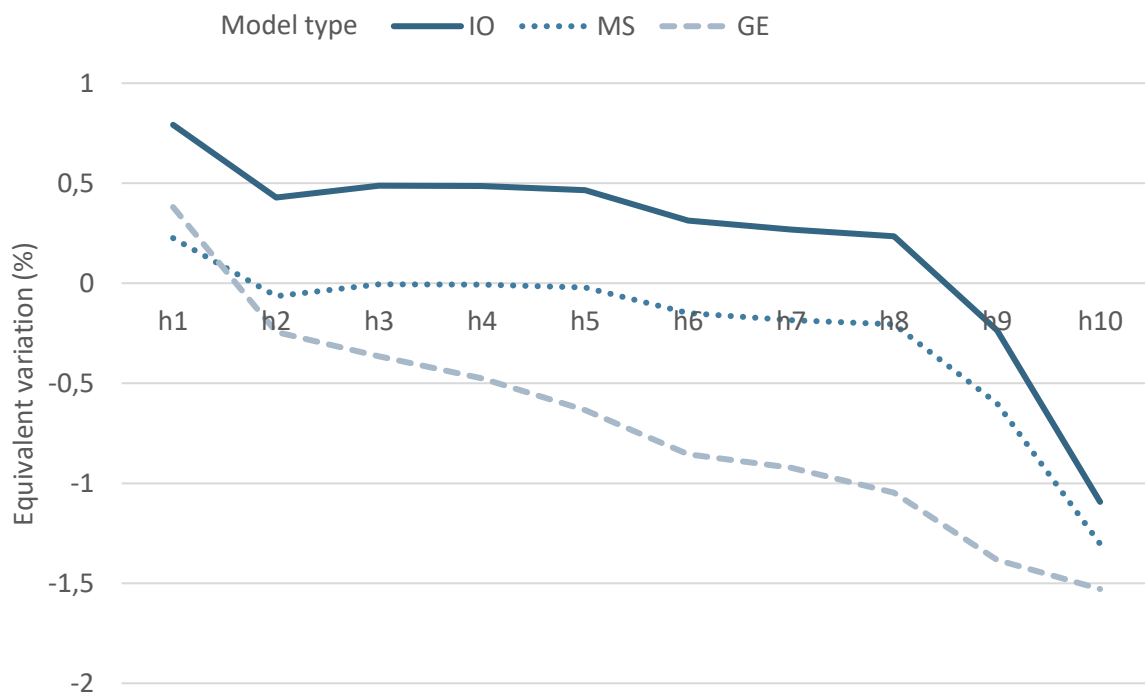


Fig. 4.7 Net incidence of a CO₂ price of 100€/tCO₂ – model comparison

The welfare evaluation of individual utility changes across all household deciles requires a social welfare function that makes individual utility interpersonally comparable. In applied economic policy analysis, a generalized utilitarian welfare function is often used, which incorporates the so-called Atkinson measure (Atkinson 1970). Here, a constant parameter for inequality aversion is used to indicate how large the welfare difference of an additional euro is between persons with different incomes. The larger the parameter, the higher the influence of outcomes for low-income households for the determination of social welfare. If the parameter approaches zero, one adopts a utilitarian perspective. The distribution of income is then irrelevant for society.

Fig. 4.8 shows the social welfare effects of a CO₂ price of 100€/tCO₂. The progressive effect of a CO₂ price reform with a climate premium results in a redistribution to poorer households.

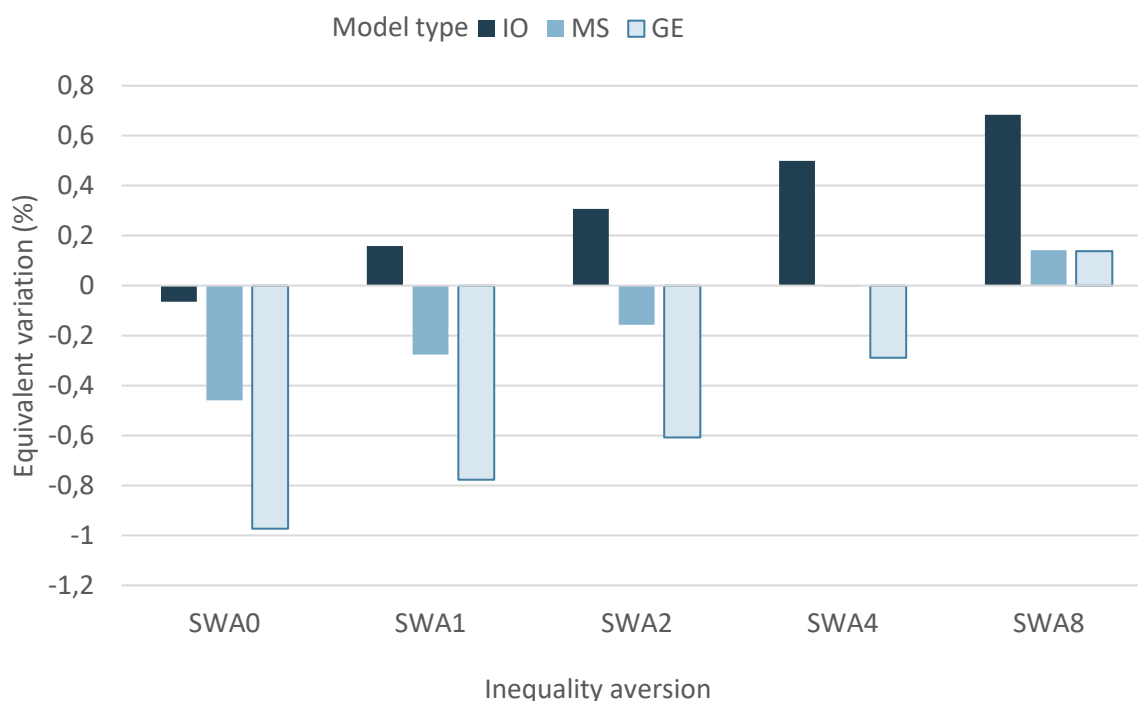


Fig. 4.8 Social welfare effects of a CO₂ price (100€/tCO₂) – model comparison

The progressive effect explains why, with increasing inequality aversion, the social costs of CO₂ pricing decrease and – with sufficiently high inequality aversion – even turn into social welfare gains. In the case of the IO analysis, in which there are no substitution or evasion reactions and thus no efficiency losses of a CO₂ price, it is a pure redistribution effect. It should be noted that the IO analysis also has a welfare effect with an inequality aversion of zero (SWA0). This is due to the fact that the welfare function takes into account the equivalized income per person and not the average income (cf. Fig. 4.6). Even in the case of pure redistribution, there is a welfare effect related to households' different sizes due to economies of scale in consumption. With an equivalence scale, incomes are weighted according to household size and composition in order to make the incomes of adults and children living in households of different sizes comparable. For the MS and especially GE model variants, there are considerable adjustment costs to a CO₂ price, which can, however, be more than overcompensated from a social perspective as net inequality decreases via redistribution. When classifying the results, however, it should be noted that an inequality aversion of 8 is extremely high from an empirical point of view. Empirical studies on inequality aversion show values between 0.2 at the lower and 3 at the upper end (Creedy and Sleeman 2006; Pirttilä and Uusitalo). Thus, for the MS and GE model variants, a societal welfare gains from a CO₂ price reform (without taking into account the avoided environmental damage) seems rather unrealistic.

Fig. 4.9 shows the CO₂ reductions associated with CO₂ pricing for the MS and GE model variants. It should be noted that only the consumption-side emissions are shown for the MS variant, i.e. only the direct emissions that are saved through the reduction in demand for consumer goods. In the GE variant, the consumption-side CO₂ savings are close to the values of the MS variant, as the same empirically estimated household demand system is used in both variants. By substituting CO₂-intensive consumption with less CO₂-intensive consumption as well as a decrease in overall purchasing power demand, CO₂ emissions in consumption fall by 2% for €25/tCO₂ and up to more than 10% for €200/tCO₂. Note again that emission reduction grows

less than proportionally to the tax rate – CO₂ reduction becomes increasingly expensive as the economy is being decarbonized. In the economy-wide GE approach, the overall emission reductions turn out to be significantly higher than in the ME approach, since all production-side CO₂ savings (especially those from electricity generation) are also included here. Thus, if the production-side adjustments are included, the CO₂ emissions for a CO₂ price of 100€/tCO₂ do not only decrease by about 7%, but by more than 30%. For the IO variant, the CO₂ changes are marginal and result only from efficiency-neutral income redistribution effects between households that have different CO₂ intensities in their different (but fixed) consumption bundles.

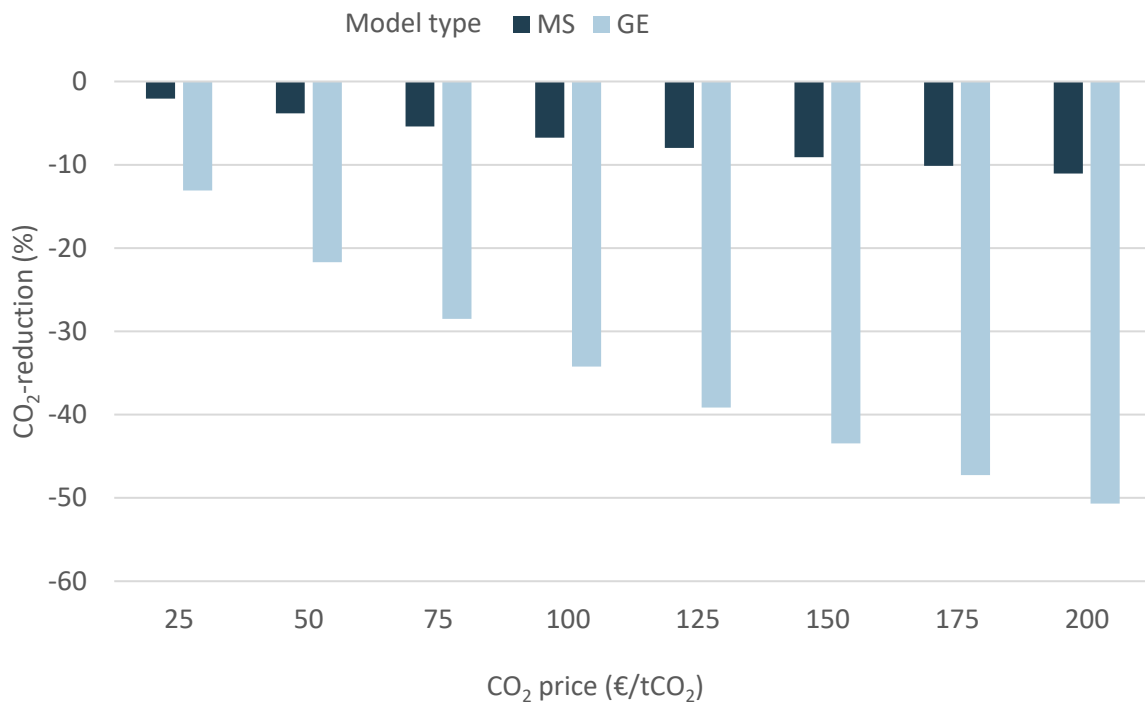


Fig. 4.9 CO₂ emission reduction – GE and MS model variants

4.3 Macroeconomic effects of a CO₂ price in general equilibrium

In Fig. 4.10 the welfare effects of a CO₂ price are set in relation to the gross domestic product (GDP) in the initial year (2013). The income variations are aggregated across all households with an inequality aversion of zero, so that the adjustment costs are considered here from an allocative efficiency perspective and without taking distribution effects into account. In a cost-benefit analysis, these costs can be interpreted as a lower limit for what should be gained in terms of avoided climate damage through reduced CO₂ emissions. At a CO₂ price of 100€/tCO₂, which leads to a CO₂ reduction of more than 30% compared to the baseline situation, the adaptation costs amount to less than 0.5% of the gross domestic product in the baseline year.

In addition to changes in the consumption structure, the GE model also allows us to quantify the effects of a CO₂ price on the production structure. Fig. 4.11 shows the percentage change in production across different economic sectors for CO₂ prices of 25 and 100€/tCO₂.

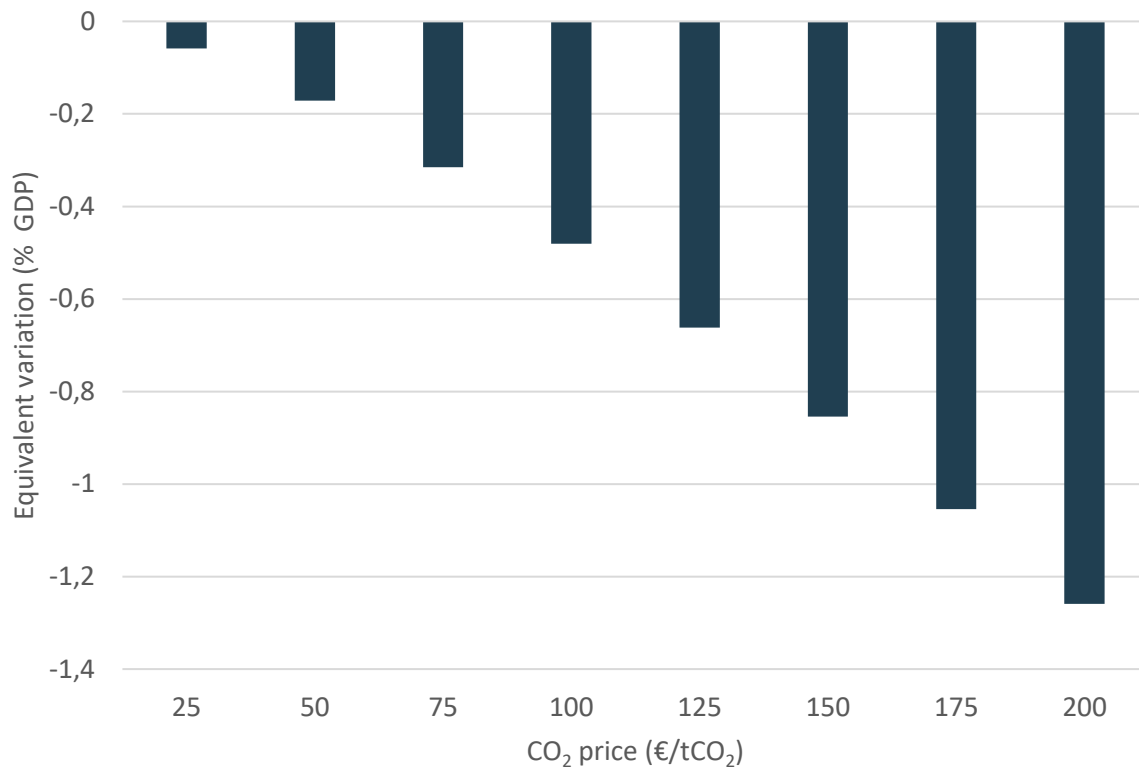


Fig. 4.10 Welfare effects of a CO₂ price (% GDP)

The aim of a uniform CO₂ price is to reduce CO₂ emissions in a way that is as fair as possible to the cause and with the greatest possible incentive effect. It is in the nature of things that CO₂ pricing primarily burdens CO₂-intensive sectors. These will react to the costs of direct and indirect CO₂ inputs by switching to less CO₂-intensive production processes. However, the remaining cost pressure also leads to a decline in production, as higher costs can only be passed on to domestic customers to a limited extent (especially depending on demand elasticities) and export has to compete against fixed world market prices. The higher the CO₂ price, the greater the decline in production in CO₂-intensive industries, *ceteris paribus*. Conversely, CO₂-extensive sectors benefit from the shifts in cost structures.

For the classification of sectoral effects, it should be noted that the primary criterion for the selection of explicit sectors from the national accounts input-output tables is their (direct and indirect) CO₂ intensity, and trade intensity is used as a second selection criterion. The sectors selected according to these criteria tend to be most negatively affected by a CO₂ price and are therefore the focus of structural policy interest, even if their share of overall economic production or value added is often well below one percent. For example, the sector "chemical products", as the most important emissions- and trade-intensive individual sector, only has a production share of a good 3% and a value-added share of a good 1% in the baseline year, while the aggregated economic sectors "services" and "manufacturing and processing" together have a production share of a good 61% (services 51%) and a value-added share of 75% (services 67%).

The foreign trade effects also reflect the changes in the relative cost structures of production and thus the changed prices of the goods produced. When interpreting the results, it is important to bear in mind that Germany is assumed to be a price taker in international trade. CO₂-intensive sectors such as "electricity and district heat", "pig iron and steel" or "chemical products" massively lose international competitiveness due to the cost increases, which is reflected in a corresponding decline in exports (see Fig. 4.12). For example, exports of chemical products fall

by a good 10% with a CO₂ tax of €25/tCO₂ and by more than 30% with a CO₂ tax of €100/tCO₂. Again, it should be noted that the explicit sectors in the dataset for the model simulations were selected according to emission and trade intensity criteria and are small compared to aggregate sectors such as "services" and "manufacturing and processing". For example, the sector "chemical products", as the most important emission- and trade-intensive sector, has a value share of approx. 8% of all exports in the baseline year, while the sector "manufacturing and processing" accounts for approx. 33%.

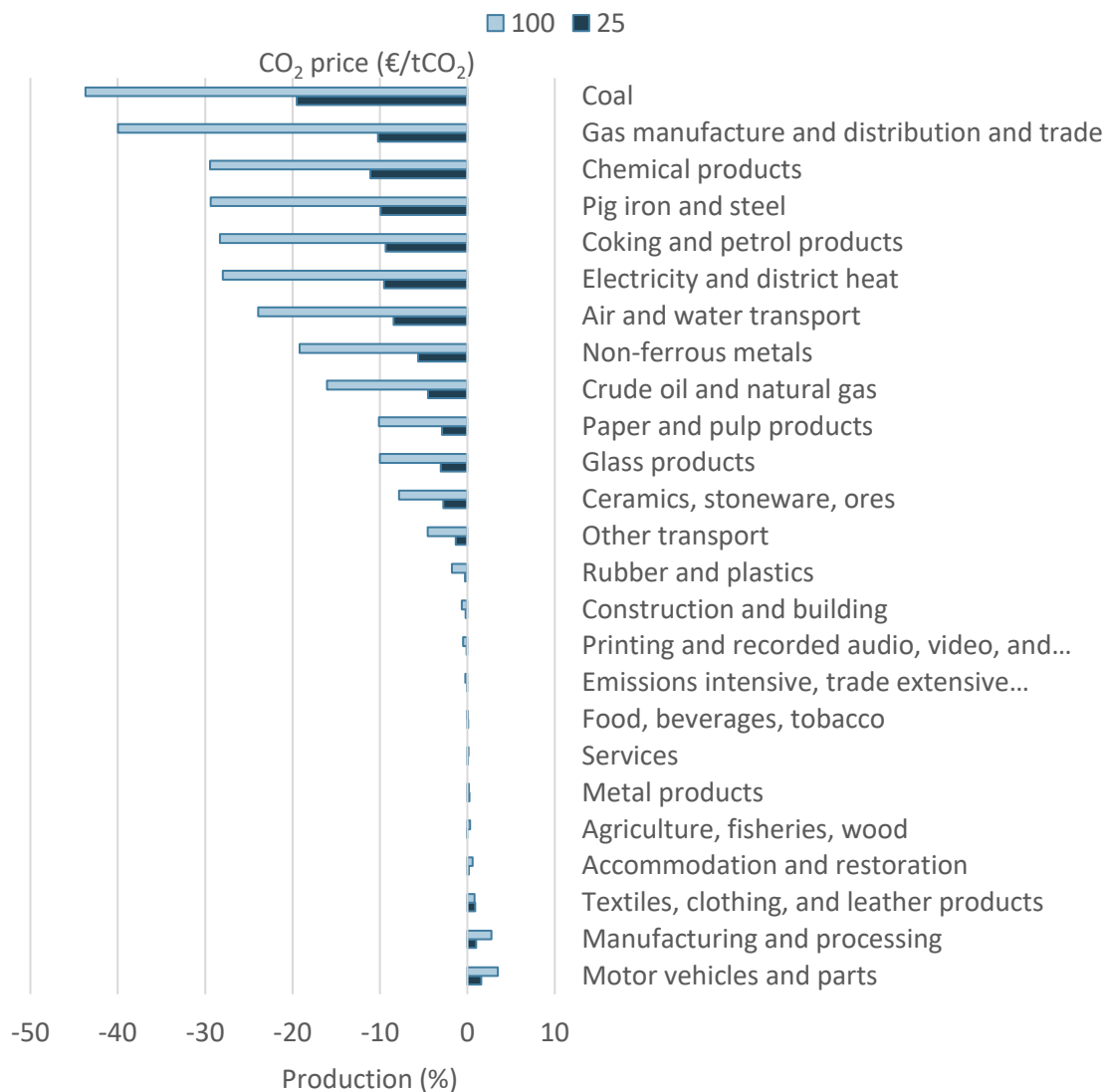


Fig. 4.11 Sectoral output effects of a CO₂ price

In the case of imports, there is a massive decline in fossil primary energy sources (coal, oil and gas), whose domestic consumption is made considerably more expensive by the pricing of CO₂ emissions in production and consumption (see Fig. 4.13). The changes in imports of emission-intensive and trade-intensive goods are determined by the interplay of two opposing effects. The starting point is the fact that products demanded domestically are aggregate goods consisting of a domestically produced variant and an imported variant, whose substitutability is captured by a constant elasticity of substitution. As a result of a CO₂ price, relatively cheaper imports (which are not subject to a CO₂ price) replace the more expensive domestic good – this substitution

effect increases import demand *ceteris paribus* and is all the more pronounced the more expensive the domestically produced good becomes compared to the imported good and how good (according to empirically estimated trade elasticities) the substitutability of domestic products by similar imports is. On the other hand, the demand for emission-intensive goods on the domestic market decreases – a negative demand effect reduces import demand *ceteris paribus*. Depending on which of the two effects dominates, the import demand for a good will increase (e.g. for electricity) or decrease (e.g. for chemical products).

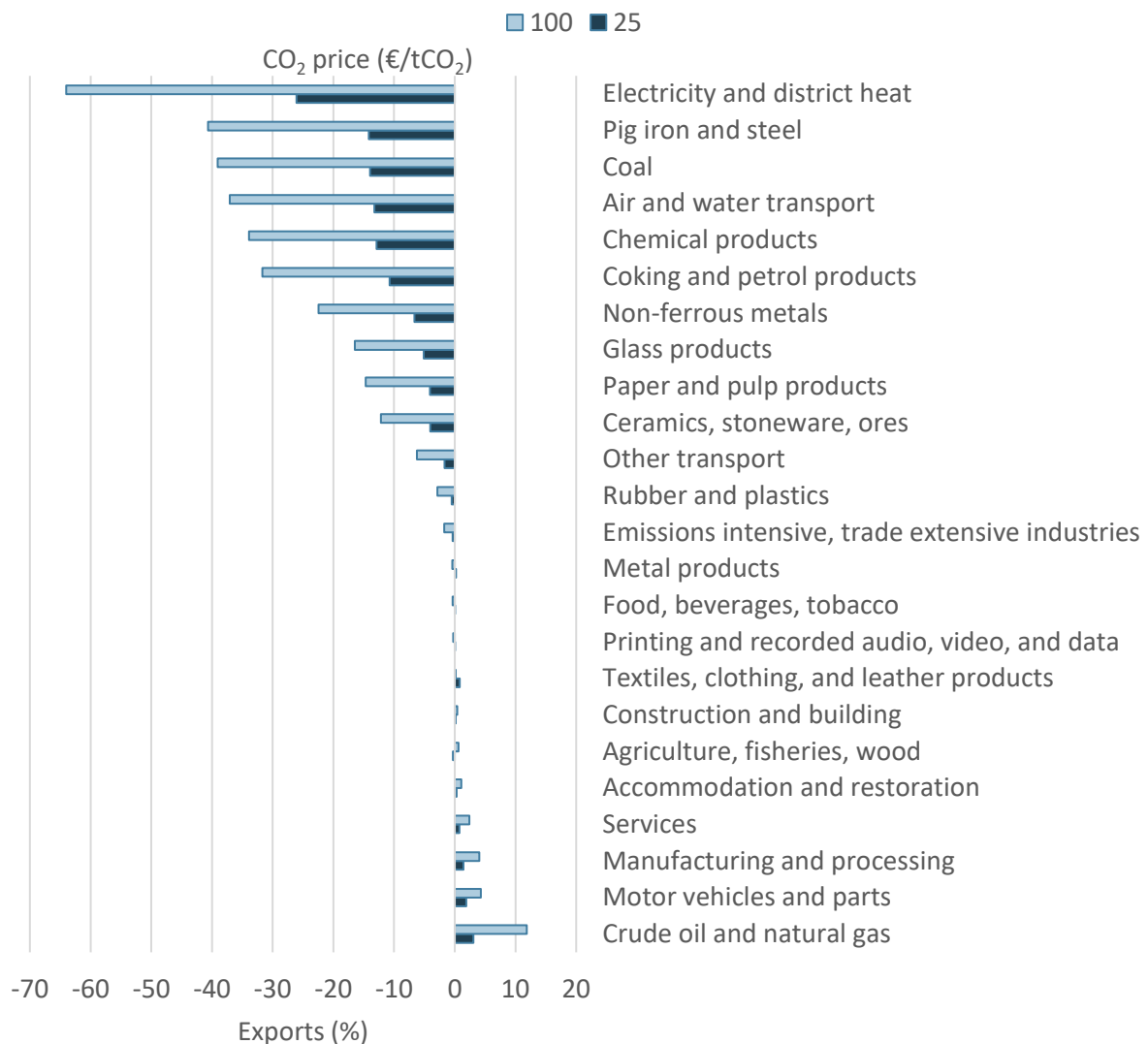


Fig. 4.12 Sectoral export effects of a CO₂ price with climate premium

The sectoral structural change away from emission-intensive production is the logical consequence of a stringent uniform CO₂ price. The steering effect of a CO₂ price should not be thwarted by exemptions for particularly negatively affected industries, provided that important trading partners charge CO₂ prices of a similar magnitude and thus similar competitive conditions exist (this is the case at least for other EU countries within the framework of EU emissions trading for energy-intensive industries). The question of sectorally differentiated regulations arises, however, if major differences in CO₂ prices between trading partners lead to carbon leakage, which may offset a considerable part of domestic emission reductions. For such

constellations, accompanying measures such as a border adjustment levy on the CO₂ content in imports or a free output-based allocation of emission rights to emission- and trade-intensive industries should be considered in the sense of a globally cost-efficient national CO₂ pricing (Böhringer et al. 2012).

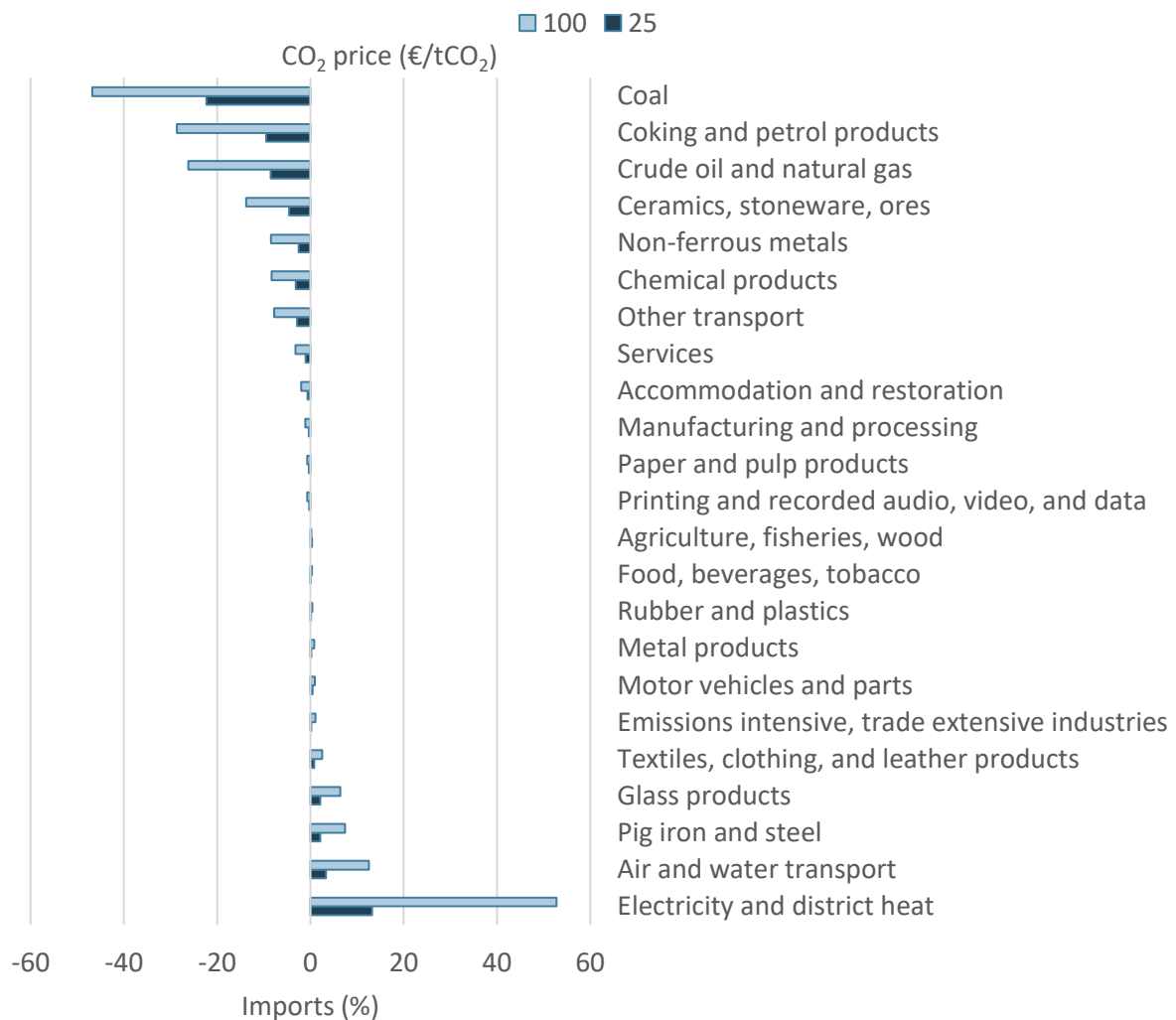


Fig. 4.13 Effects of a CO₂ price with climate premium on imports of production goods

5. Concluding remarks

The results of the simulation analyses provide an initial orientation on the incidence of a CO₂ price. It is shown that partial analytical approaches – illustrated here by the IO and the MS model – make important omissions. This limits their ability of fully assessing the economic and emission effects of an energy price reform. In the case of the IO model with fixed production and demand structures, it is obvious that it only depicts the direct effects on producer and consumer prices in the short term. The increase in consumer prices leads to a loss of real income on the expenditure side, which for the respective household type depends on its fixed consumption structures. The survey-side effect of CO₂ pricing via the expenditure deciles is regressive, as poorer households are more negatively affected than richer households due to their higher

expenditure shares on CO₂-intensive consumer goods categories. Conversely, with a per capita climate premium, there is a progressive redistribution effect that dominates the collection effect and makes the overall CO₂ price reform progressive. Since there are no substitution effects in household production and consumption, the IO analysis is ultimately limited to pure redistribution effects, without there also being allocative efficiency losses due to adjustment in consumption and production structures, which in turn are included in the incidence of a CO₂ price. On the basis of empirically estimated price and income elasticities, the MS model takes into account how households on the demand side react to a change in consumer prices due to the CO₂ price and the redistribution of additional income. In this way, demand-side adjustment costs that can be attributed to behavioral changes or forced evasive reactions of households are taken into account in the MS model framework. Compared to the IO variant, these household-specific adjustment costs lead to an overall incidence that can imply consumption losses even for poorer households in the case of higher CO₂ prices. Overall, the progressive effect of a CO₂ price with eco-bonus remains for different levels of CO₂ pricing. The GE model captures the structural change in production triggered by a CO₂ price in addition to the consumption-side adjustment effects. The latter is co-determined by the CO₂ substitution possibilities in production processes, the inter-industrial linkages and the repercussions in international trade and competition. The adjustments on the production side result in further allocative efficiency losses – compared to the initial situation, production factors such as capital and labor are used less productively when energy use is restricted, which leads to losses in factor income. If these income-side effects of a CO₂ price are systematically captured via the income structures of households, then the adjustment costs for households in the GE model again turn out to be significantly higher than in the MS variant. The fundamental prediction a CO₂ price reform is progressive also remains in the GE model. But, crucially, the qualitative distribution of net policy cost across households of different income changes significantly. As a conclusion of the comparison of different model approaches for the economic and emission-side impact analysis of a CO₂-oriented state pricing of energy carriers, it can be stated that the GE approach includes additional, relevant mechanisms that are necessary for the comprehensive ex-ante analysis of the distribution of policy cost in the realm of price-based energy and climate policy.

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Appendix A: Microsimulation Model (MS)

For the analysis of the effects of price changes in consumer goods (here induced by pricing consumer goods according to their CO₂ intensity) on the purchasing power and consumption demands of households, a partial-analytic microsimulation model of the demand system for heterogeneous households is used. In the demand-side modelling approach, it is assumed that policy reforms do not change the prices of factors of production and thus nominal factor income. In its current application to a CO₂ price reform, the MS model is limited to how the pricing of energy sources according to their CO₂ content changes the prices of consumer goods and thereby affects consumer goods demand and household consumption welfare. Tables A.1-A.3 summarize the algebraic notations in the MS model specification.

Table A. 1 Indices

h	Index for household ($h = 1, \dots, H$)
i	Index for commodity ($i = 1, \dots, n$)
k	Index on household characteristics $1, \dots, K$
r	Index over the exponents $1, \dots, R$ of a polynomial Engel curve (from EASI)

Table A. 2 Variables

X_{ih}	Quantity demanded of commodity i by household h
$U_h(X_{1h}, \dots, X_{nh})$	Consumption utility for household h
$D_{ih}(P_1, \dots, P_n, M_h)$	Demand function of good i by household h as a function of price P_i and consumption budget M_h
$V_h(P_1, \dots, P_n, M_h)$	Indirect welfare function with price P_1, \dots, P_n and consumption budget M_h
y_h	Implicit consumption utility in EASI
w_{ih}	Share of expenditure on commodity i in total expenditure of household h

Table A. 3 Parameters

P_i	Price for good i (P_i as reference price)
θ_i	CO ₂ intensity of good i
M_h	Consumption budget of household h
τ	CO ₂ price
T	Per capita transfer payment
σ	Elasticity of substitution
$a_{ijk}, b_{ij}, c_{ir}, d_{ik}, g_{ik}$	Estimation parameters of the EASI demand system
$\pi_{1h}, \dots, \pi_{nh}$	Household and product-specific prices
z_{hk}	Household-specific characteristics for household property k
δ_{r0}	Kronecker Delta

Budget optimization and welfare analysis

Each household h observes its consumption budget M_h and the prices of consumer goods P_i and chooses its consumption demand X_{ih} in order to maximize its consumption welfare

$U_h(X_1, \dots, X_n)$:

$$\begin{aligned} \max_{X_{1h}, \dots, X_{nh}} \quad & U_h(X_{1h}, \dots, X_{nh}) \\ \text{s. t.} \quad & P_1 X_1 + \dots + P_n X_n \leq M_h. \end{aligned}$$

The solution of this problem for general P_i and M_h gives the Marshallian demand function: $X_{ih} = D_{ih}(P_1, \dots, P_n, M_h)$. In the initial or reference situation without CO₂ pricing the units are chosen so that $P_i = 1$ applies to all prices. With a CO₂ emission intensity θ_i of good i and a CO₂ price of τ the unit price P_i increases to $1 + \tau\theta_i$.

The analysis of the welfare effects of a CO₂ price under the assumption that revenues from the CO₂ price are not distributed back to households is limited to the evaluation of the indirect welfare function:

$$V_h(P_1, \dots, P_n, M_h) := U_h[D_{1,h}(P_1, \dots, P_n, M_h), \dots, D_{n,h}(P_1, \dots, P_n, M_h)]$$

with changed prices P_1, \dots, P_n and constant consumption budget M_h . In the event that revenues from CO₂ pricing are to be refunded to households by means of a per capita transfer payment T to the households, it must be taken into account that the consumption budget of household h grows to $M_h + n_h T$ where n_h is the number of people living in the household. The sum of all transfer payments must correspond to the revenue from the CO₂ price:

$$\sum_h n_h T = \sum_{ih} D_{ih}(P_1, \dots, P_n, M_h + n_h T) \theta_i \tau. \quad (1)$$

The evaluation of the indirect welfare functions V_h for the prices P_1, \dots, P_n and consumption budgets $M_h + n_h T$ in turn provides the resulting welfare levels.

CES utility function

A widely used function in the economic literature for describing consumption utility is the CES utility function. CES utility functions can be represented in the so-called *calibrated share form* on the basis of empirically observable demand quantities and expenditure shares:

$$U_h(X_1, \dots, X_n) = \bar{U}_h \left[\theta_{1h} \left(\frac{X_1}{\bar{X}_{1h}} \right)^\rho + \dots + \theta_{nh} \left(\frac{X_n}{\bar{X}_{nh}} \right)^\rho \right]^{1/\rho}$$

Where $\bar{U}_h, \bar{X}_{1h}, \dots, \bar{X}_{nh}$ denote the utility and consumption quantities in the initial situation, and $\theta_{1h}, \dots, \theta_{nh}$ denote the respective expenditure shares in the initial situation for commodity

i in total expenditure of the household h . From the utility maximisation for a given consumption budget, one obtains the household-specific price (the expenditure) per unit of utility:

$$P_h^U = \left[\theta_{1h} \left(\frac{P_1}{\bar{P}_1} \right)^{1-\sigma} + \dots + \theta_{nh} \left(\frac{P_n}{\bar{P}_n} \right)^{1-\sigma} \right]^{1/(1-\sigma)}$$

where σ denotes the elasticity of substitution between consumer goods. The Marshallian demand functions result in the case of a CES utility function:

$$D_{ih} = \bar{X}_{ih} \left(\frac{P_h^U \bar{P}_i}{P_i} \right)^\sigma \frac{M_h}{\bar{M}_h}.$$

With normalization $\bar{V}_h = \bar{M}_h$ the indirect utility function is as follows:

$$V_h(P_1, \dots, P_n, M_h) = \frac{M_h}{P_{U,h}}.$$

Calibration

For the calibration of the CES demand or CES utility functions to empirically observable values, we set initial values for consumption budgets \bar{M}_h , consumption quantities \bar{X}_{ih} and resulting expenditure shares θ_{ih} (at standardised prices $\bar{P}_i = 1$)

$$\theta_{ih} = \frac{\bar{X}_{ih} \bar{P}_{ih}}{\bar{M}_h}.$$

For a complete specification, the elasticity of substitution σ must be chosen as well. For the analysis in the IO model, we use $\sigma = 0$. For the analysis in the MS and GE model, the elasticity of substitution is set as $\sigma = 0.5$. In the impact analysis of a CO₂ price carried out in this paper, the calibrated CES demands in the MS and GE models are replaced by an econometrically estimated EASI demand system (see below).

Decomposition of the welfare effects

Provided that preferences are homothetic as in a CES specification (the income elasticities are equal to one), the (relative) welfare changes can be decomposed into income and pricing effects:

$$\frac{V_h - \bar{V}_h}{\bar{V}_h} = \frac{\frac{M_h}{P_h^U} - \bar{M}_h}{\bar{M}_h} = \frac{M_h - \bar{M}_h}{\bar{M}_h} - \frac{M_h}{\bar{M}_h P_h^U} \frac{P_h^U - 1}{1} = \hat{M}_h - \frac{M_h/P_h^U}{\bar{M}_h} \hat{P}_h^U$$

Here the relative change in the consumption budget \hat{M}_h represents the income effect, and the pricing effect $-\frac{M_h/P_{U,h}}{\bar{M}_h} \hat{P}_{U,h}$ is quasi-proportional to the relative changes \hat{P}_h^U for small price changes.

EASI demand system

The microeconomic theory underlying the Exact Affine Stone Index (EASI) postulates that welfare y_h for household h is implicitly given by the following system of equations:

$$\log(y_h) = \frac{\log(M_h) - \sum_{i=1}^n w_{ih} \log(\pi_{ih}) + \frac{1}{2} \sum_{k=1}^K \sum_{i,j=1}^n a_{ijk} \log(\pi_{ih}) \log(\pi_{jh}) z_{hk}}{1 - \frac{1}{2} \sum_{i,j=1}^n b_{ij} \log(\pi_{ih}) \log(\pi_{jh})} \quad (2)$$

$$\begin{aligned} w_{ih} = & \sum_{k=1}^K \sum_{j=1}^n a_{ijk} \log(\pi_{ih}) z_{hk} + \sum_{j=1}^n b_{ij} \log(\pi_{ih}) \log(y_h) + \sum_{r=0}^R c_{ir} \log(y_h)^r \\ & + \sum_{k=1}^K [d_{ik} z_{hk} \log(y_h) + g_{ik} z_{hk}] + \varepsilon_{hi} \end{aligned} \quad (3)$$

Here a_{ijk} , b_{ij} , c_{ir} , d_{ik} and g_{ik} are parameters to be estimated empirically. The indices i and j run over all goods $1, \dots, n$, the index k over household characteristics $1, \dots, K$ and the index r over the exponents $1, \dots, R$ of a polynomial Engel curve implied by the EASI demand system. For empirically estimated parameters, the dependent variables are y_h (consumer welfare) and w_{ih} (share of expenditure on goods i of total expenditure) in the system of equations (2) and (3) are dependent on the explanatory variables M_h (household-specific consumption budgets), $\pi_{1h}, \dots, \pi_{nh}$ (household- and good-specific prices) and z_{hk} (household-specific characteristics for household property k) up to an error term ε_{ih} .

Estimation

With observed prices $\bar{\pi}_{ih}$ and total consumption expenditure \bar{M}_h and expenditure shares $\bar{w}_{ih} = \theta_{ih}$ the parameters of the system of equations (2) and (3) are estimated using a 3SLS (*three stage least square*) procedure. In addition to the values for a_{ijk} , b_{ij} , c_{ir} , d_{ik} , and g_{ik} these estimates also yield the residuals $\bar{\varepsilon}_{ih}$ as estimates of the error terms ε_{ih} .

In order to obtain micro-economically consistent demand functions, various homogeneity and symmetry restrictions constrain the estimation:

$$\sum_{j=1}^n a_{ij} = 0 \quad \text{und} \quad a_{ij} = a_{ji}$$

$$\sum_{i=1}^n b_{ij} = 0 \quad \text{und} \quad b_{ij} = b_{ji}$$

$$\sum_{i=1}^n c_{ir} = \delta_{r0}$$

$$\sum_{i=1}^n \sum_{k=1}^K d_{ik} = 0$$

$$\sum_{i=1}^n \sum_{k=1}^K g_{ik} = 0,$$

where δ_{r0} is the so-called Kronecker delta, which takes the value 1 for $r = 0$ and the value 0 in all other cases.

Microsimulation

For parameter estimates a_{ijk} , b_{ij} , c_{ir} , d_{ik} , and g_{ik} in the system of equations (2) and (3), the consumption welfare y_h and the expenditure shares w_{ih} for given consumption goods prices π_{ih} and given consumption budget M_h are determined. With a CO₂ price, the prices of goods P_i and the household-specific prices $\pi_{ih} = P_i \cdot \bar{\pi}_{ih}$ change. Demand D_{ih} is determined by

$$D_{ih} = \frac{w_{ih}(M+n_h \cdot T)}{P_i}. \quad (4)$$

In the case of CO₂ pricing with reimbursement of the revenues from CO₂ pricing to households, the system of equations from (1), (2), (3) and (4) is solved for y_h , w_{ih} , D_{ih} and T . In the case of CO₂ pricing without rebates, the problem is reduced to solving equations (2), (3) and (4) with $T = 0$.

To calculate consumer welfare per household, we use the equivalent variation (EV), which indicates which change in income for the household, measured against the price level of the initial equilibrium, leads to the new utility level (i.e. the utility level after policy reform – here after CO₂ pricing). For the EASI demand system, the equivalent variation is obtained as:

$$\begin{aligned} EV &= \exp(\log C_{0h}(y_h)) - \bar{M}_h \\ &\text{with} \\ \log C_{0h}(y_h) &= \log y_h \left(1 + \frac{1}{2} \sum_{i,j=1}^n b_{ij} \log \bar{\pi}_{ih} \log \bar{\pi}_{jh} + \sum_{i=1}^n d_{ik} z_{hk} \log \bar{\pi}_{ih} \right) \\ &\quad + \sum_{i=1}^n \sum_{r=0}^R \log \bar{\pi}_{ih} c_{ir} y_h^r + \frac{1}{2} \sum_{ih=1}^n a_{ijk} z_{hk} \log \bar{\pi}_{ih} \log \bar{\pi}_{jh} \\ &\quad + \sum_{i=1}^n \log \bar{\pi}_{ih} \left(\sum_{k=1}^K g_{ik} z_{hk} + \varepsilon_{ih} \right) \end{aligned}$$

where $C_{0h}(y_h)$ are the costs (expenditures) to achieve the benefit level y_h at initial prices $\bar{\pi}_{ih}$.

Appendix B: General equilibrium model (GE)

To analyze the macroeconomic effects of policy reforms – in this case a pricing of energy sources according to their CO₂ content – an applied general equilibrium model for the German economy is used (Böhringer et al. 2017). In the following algebraic description, the differentiation of the demand side into several households is omitted, as this is done via integration or iterative coupling with the microsimulation model described in Appendix A (for a description of the iterative coupling procedure, see Rutherford and Tarr 2008).

The basic structure of a general equilibrium model is described by three classes of economic equilibrium conditions: (i) zero profit conditions for producers, (ii) market equilibrium conditions for goods and factors of production, and (iii) budget constraints for all economic agents. In equilibrium, these conditions determine the decision variables of the economic model: from the zero profit conditions one obtains the level variables for economic activities, from the market equilibrium conditions the goods and factor prices and from the budget restrictions the incomes of economic agents.

Tables A.4-A.8 summarize the algebraic notations used in the model description. In the functional relationships, Π_i^z is the unit profit function of the i th economic activity (as the difference between revenue and unit cost), where z captures different sub-activities such as the provision of sector-specific value added or energy or non-energy intermediate aggregates. Via Hotelling's lemma, the price-dependent supply and demand coefficients per economic activity are obtained by taking derivatives of the unit profit function Π_i^z with respect to the respective output and input prices. These derivatives are used to compactly formulate the market equilibrium conditions.

Table A. 1 Indices and sets

Indices	
i (alias j)	Index for all production activities of goods – includes aggregates of private final demand ($i = C$), public demand ($i = G$), and investment demand ($i = I$)
Sets	
M	Material goods (not energy)
E	Energy goods (coal, mineral oil, gas, electricity)
F	Primary energy sources (coal, crude oil, natural gas)
CGO	Fossil energy sources with CO ₂ emissions: Coal, natural gas, mineral oil

Table A. 2 Variables

Activity levels	
Y_i	Domestic production in sector i
X_i	Transformation activity of domestic production of good i into exports and domestic supply
A_i	Production of the Armington aggregate i
Price levels	
p_i	Price for the domestically produced good in sector i (domestic production price)
p_i^{KL}	Price of the value-added aggregate in sector i
p_i^E	Price of the energy aggregate in sector i
p_i^S	Price of good i on the domestic market (domestic offer price)
p^{FX}	Price of the foreign currency (exchange rate)
p_i^A	Price of Armington good i in intermediate and final demand (domestic demand price)
w	Wages
r	Interest on capital
q_i	Return on primary energy resources ($i \in$)
Income levels	
INC	Consumption budget of the representative household

Table A. 3 Cost shares

θ_i^K	Cost share of capital in the value-added aggregate of sector i
θ_i^{ELE}	Cost share of electricity in the energy aggregate of sector i
θ_{ji}^{CGO}	Cost share of energy carrier j in the fuel costs of sector i ($j \in CGO$)
θ_i^{KLE}	Cost share of value-added and energy in the production costs of sector i
θ_i^{KL}	Cost share of the value-added aggregate in the value-added and energy costs of sector i
θ_{ji}^M	Cost share of material input j in the material aggregate of sector i ($j \in M$)
θ_i^Q	Cost share of the fossil energy resource in the production costs of the primary energy sector i ($i \in F$)
$\theta_{\xi i}^F$	Cost share of good j ($\xi = j$) or of labour ($\xi = L$) or of capital ($\xi = K$) in the production costs of the primary energy sector i ($i \in F$)
θ_i^A	Cost share of domestic good in domestic Armington demand for good i
θ_i^X	Value share of exports in the total value of domestic production of good i

Table A. 4 Elasticities

σ_i^{KL}	Substitution between capital and labour
σ_i^E	Substitution between electricity and the aggregate from other energy sources
σ_i^{CGO}	Substitution between coal, gas and petroleum products
σ_i^{KLE}	Substitution between energy and the aggregate of capital and labour
σ_i^{KLEM}	Substitution between the material aggregate and the aggregate of capital, labour and energy
σ_i^M	Substitution between material goods
σ_i^Q	Substitution between fossil energy resources and the aggregate of all other inputs in the extraction of fossil energy sources
σ_i^A	Substitution between imports and domestically produced goods
η_i	Transformation between export supply and domestic supply of goods

Table A. 5 Factor endowments, exogenous activity levels, CO₂ prices and intensities

\bar{L}	National labour supply
\bar{K}	National capital supply
\bar{Q}_i	Fossil energy resources ($i \in FF$)
\bar{G}	Government demand
\bar{I}	Investment demand
\bar{B}	Balance of payments surplus
\bar{p}^{CO_2}	CO ₂ price
$a_i^{CO_2}$	CO ₂ emission coefficient for fuel ($i \in CGO$) (coal, natural gas, petroleum products)

Zero profit conditions

Production of goods

The production of sector-specific goods is characterized by a fourfold nested CES cost function with inputs of labour, capital and sector-specific intermediate input aggregates of energy and material. At the top level, the substitution relationship between the material aggregate and an aggregate of energy, labour and capital is described. At the second level, two CES aggregates describe how (i) material inputs can be substituted for each other and (ii) the price-dependent input relationship between the energy aggregate and value-added. Value-added is again a CES aggregate of labour and capital. The energy aggregate is defined as a CES relationship between electricity and a CES aggregate of fossil fuels (coal, petroleum products, and gas). The CES cost structure nested in this way describes the production technology for all goods including the provision of the aggregate investment good ($i=I$) and an aggregate public good ($i=G$), but not for primary energy (crude oil, coal, gas) and consumer goods.

$$\Pi_i^Y = p_i - \left[\theta_i^{KLE} \left[\theta_i^{KL} (p_i^{KL})^{1-\sigma_i^{KLE}} + (1 - \theta_i^{KL}) p_i^{E1-\sigma_i^{KLE}} \right]^{\frac{1-\sigma_i^{KLEM}}{1-\sigma_i^{KLE}}} + (1 - \theta_i^{KLE}) \left(\sum_{j \in M} \theta_{ji}^M p_j^{A1-\sigma_i^M} \right)^{\frac{1-\sigma_i^{KLEM}}{1-\sigma_i^M}} \right]^{\frac{1}{1-\sigma_i^{KLEM}}} \leq 0$$

These conditions determine the activity levels in equilibrium Y_i .

The cost price index for the sector-specific value-added aggregate of capital and labour is defined as

$$p_i^{KL} = \left[\theta_i^K r^{1-\sigma_i^{KL}} + (1 - \theta_i^K) w^{1-\sigma_i^{KL}} \right]^{\frac{1}{1-\sigma_i^{KL}}}.$$

The cost price index for the sector-specific energy aggregate is defined as

$$p_i^E = \left[\theta_i^{ELE} p_{ELE}^A 1-\sigma_i^{ELE} + (1 - \theta_i^{ELE}) \left(\sum_{j \in CGO} \theta_{ji}^{CGO} (p_j^A + \bar{p}^{CO_2} a_j^{CO_2})^{1-\sigma_i^{CGO}} \right)^{\frac{1-\sigma_i^{ELE}}{1-\sigma_i^{CGO}}} \right]^{\frac{1}{1-\sigma_i^{ELE}}}.$$

Extraction of fossil fuels

In the production of primary fossil energy resources ($i \in F$) all inputs except the sector-specific fossil energy resources are demanded in output-fixed proportions. The fossil energy resource as a sector-specific production factor is in a CES substitution relationship with the aggregate of all other production inputs:

$$\Pi_i^Y = p_i - \left[\theta_i^Q q_i^{1-\sigma_i^Q} + (1 - \theta_i^Q) \left(\theta_{Li}^F w + \theta_{Ki}^F r + \sum_j \theta_{ji}^F (p_i^A + \bar{p}^{CO_2} a_j^{CO_2}) \right)^{1-\sigma_i^Q} \right]^{\frac{1}{1-\sigma_i^Q}} \leq 0.$$

These conditions, in equilibrium, determine the activity levels are Y_i ($i \in F$) for the extraction of fossil fuels.

Transformation of domestic goods into exports and domestic supply of goods

Domestically produced goods can be exported to the world market or offered on the domestic market. Depending on the relationship between the domestic supply price and the exogenous international price, more of the good is sold on the domestic market or more on the world market. The trade-off is described by a constant elasticity of transformation:

$$\Pi_i^X = \left[\theta_i^X (p_i^{FX})^{1-\eta_i} + (1 - \theta_i^X) (p_i^S)^{1-\eta_i} \right]^{\frac{1}{1-\eta_i}} - p_i \leq 0.$$

The transformation activities X_i are determined by these zero gain conditions.

Production of the Armington aggregate

Goods in demand on the domestic market in production and final consumption are a combination of domestically produced and imported product variants. The two variants are combined in a so-called Armington good via a CES function. The zero-profit condition of Armington production for good i is

$$\Pi_i^A = p_i^A - \left[\theta_i^A (p_i^S)^{1-\sigma_i^A} + (1 - \theta_i^A) (p_i^{FX})^{1-\sigma_i^A} \right]^{\frac{1}{1-\sigma_i^A}} \leq 0.$$

These zero profit conditions determine the activity levels for Armington production A_i .

Market equilibrium conditions

Labour

The aggregate labour supply is assumed to be fixed in the static model version. The market equilibrium condition for labour is

$$\bar{L}_i \geq \sum_i Y_i \frac{\partial \Pi_i^Y}{\partial w_i}.$$

The market equilibrium condition for labour determines the wage w .

Capital

The aggregate supply of capital is assumed to be fixed in the static model version. The market equilibrium condition for capital is

$$\bar{K} \geq \sum_i Y_i \frac{\partial \Pi_i^Y}{\partial r}.$$

The interest rate r is determined by the market equilibrium condition for capital.

Fossil energy resources

The supply of fossil energy resources for the production of fossil fuels ($i \in F$) is assumed to be fixed. The market equilibrium conditions for fossil energy resources are

$$\bar{Q}_i \geq Y_i \frac{\partial \Pi_i^Y}{\partial q_i}.$$

These market equilibrium conditions determine the prices of fossil energy resources.

Production output

The goods produced by domestic sectors are demanded by the transformation activity:

$$Y_i \geq X_i.$$

The market equilibrium conditions for sectoral production determine domestic production prices. For final demand goods, a distinction is made between investment ($i = I$), public expenditure ($i = G$) and consumer demand ($i = C$). The investment volume and public expenditure are assumed to be fixed in the model and the corresponding market equilibrium conditions are

$$Y_I \geq \bar{I}$$

and

$$Y_G \geq \bar{G}.$$

For the aggregate consumption good ($i=C$), the market clearing condition results from the final demand by the representative household:

$$Y_C \geq \frac{INC}{p_C^Y}.$$

Supplying the domestic market with domestically produced goods

The good produced by the transformation activity X_i delivered to the domestic market is i is demanded by the Armington production activity A_i demanded. The market clearing conditions are

$$X_i \frac{\partial \Pi_i^X}{\partial p_i^S} \geq A_i \frac{\partial \Pi_i^A}{\partial p_i^S}.$$

The market equilibrium conditions for domestic supply determine the domestic supply price p_i^S which enters into the cost function for the Armington aggregate.

Market clearance for Armington goods

The aggregate good produced by the Armington activity from the domestically manufactured product variant and the imported product variant is demanded as an input by the production activities (incl. production for the final demand categories). The corresponding market equilibrium conditions are

$$A_i \geq \sum_j Y_j \frac{\partial \Pi_j^Y}{\partial p_i^A}.$$

The market equilibrium conditions for Armington production determine the Armington goods prices p_i^A in domestic demand.

Balance of payments

Foreign currency is collected with exports. Imports must be paid for with foreign currency. In equilibrium, it is required that the total value of exports equals the total value of imports, taking into account the balance of payments in the initial year. The market equilibrium condition for foreign currency is

$$\bar{B} + \sum_i X_i \frac{\partial \Pi_i^X}{\partial p^{FX}} \geq \sum_i A_i \frac{\partial \Pi_i^A}{\partial p^{FX}}.$$

It is this balance in foreign exchange that determines the real exchange rate, i.e. the (endogenous) equivalent of the domestic currency in foreign currency.

CO₂ emissions

CO₂ emissions are calculated in proportion to the amount of fossil fuels burned ($j \in CGO$) in the production activities Y_i (incl. production activities for final demand). With the emission intensities $a_j^{CO_2}$ the total economic CO₂ emissions are calculated as

$$CO_2 = \sum_{j \in CGO} \sum_i a_j^{CO_2} Y_i \frac{\partial \Pi_i^Y}{\partial p_j^A}.$$

Budget constraint

The representative household generates income from its factor endowment as well as potential revenues from a CO₂ price (further tax revenues are not shown in the simplified representation). The income available for private consumption demand is obtained after deducting expenditure on fixed public consumption, fixed investment expenditure (savings) and taking into account the balance of payments surplus in the initial year:

$$INC = w\bar{L} + r\bar{K} + \sum_{i \in F} q_i \bar{Q}_i + p^{CO_2} CO_2 - p_I \bar{I} - p_G \bar{G} - \bar{B}.$$