Towards Hybrid Economy-Wide Frameworks for the Distributional Assessment of Climate Policies

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April 2026

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Abstract

This paper develops IO-DASMOD, an integrated macro-micro framework for the distributional assessment of climate policies in the Czech Republic. The model combines a price-quantity input-output system with household-level microsimulation data, allowing policy-induced shocks to propagate through production networks, factor incomes, and heterogeneous household consumption baskets within a single system. The framework is applied to four stylized policy scenarios: an economy-wide CO2 price, a household energy price shock, an ETS2-style carbon price proxy, and an agri-food greenhouse-gas price. The results show that average burden, sectoral origin, and regressivity are distinct dimensions of policy incidence. Broad carbon pricing generates the largest aggregate adjustment, while narrower food-system pricing can produce a more regressive burden because food accounts for a larger share of expenditure among lower-consumption households. The paper's main contribution is methodological: it provides a transparent economy-wide tool for tracing distributional climate-policy effects across heterogeneous households.

Keywords: Input-output analysis; Microsimulation; Carbon pricing; Distributional analysis; Household heterogeneity

JEL codes: C67, D31, H23, Q52, Q58

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1 Introduction

Greenhouse gas emissions must be drastically reduced to mitigate the most severe consequences of climate change. Achieving deep decarbonization requires transformations of production systems, consumption patterns, and economic structures that are not neutral in their socioeconomic effects. Climate policies-carbon pricing, green taxation, targeted subsidies-affect households and industries in heterogeneous ways. Fullerton (2011) identifies at least six types of distributional effects of environmental policies, including those across income groups, generations, regions, and sectors. This recognition highlights the importance of analytical frameworks that capture the wide-ranging implications of decarbonization on different segments of the population.

To analyze such impacts, researchers rely on multi-sectoral, economy-wide models. Within this tradition, Input-Output (IO) models and Computable General Equilibrium (CGE) models are the most widely applied approaches (Carbone et al., 2022). IO models are valued for their transparency, relatively low data requirements, and their ability to quantify both direct and indirect effects across sectors. In their standard form, IO models distinguish two independent modules: a demand-driven quantity model, where sectoral output is determined by final demand, and a cost-push price model, where prices are determined under constant returns to scale and average cost pricing (Oosterhaven, 2019). This separation has long been recognized as a limitation when studying feedback effects between prices, incomes, and quantities.

Extensions have been proposed to partially bridge this gap. Semi-closed IO models endogenize the income-consumption loop, enabling analysis of how household spending feeds back into production (Miyazawa, 2012; Chen et al., 2016). More recently, Cardenete et al. (2024) presented a methodology for price-quantity interaction in IO modeling, applied to the analysis of NextGenerationEU funds. However, that work does not incorporate household-level microdata or distributional analysis.

In a separate literature strand, considerable effort has been devoted to linking household microdata with multisectoral models for distributional analysis. Cazcarro et al. (2022) provide a methodology for linking consumption surveys with IO frameworks for the European Union, addressing the classification bridges and valuation conversions that arise when household survey data (in COICOP categories and purchaser prices) must be mapped into the IO framework (in CPA or NACE categories and basic prices). Fredriksson et al. (2021) and Böhringer et al. (2022) analyze the distributional impacts of carbon pricing at the EU level, but rely on CGE-based or sequential macro-micro linkages rather than an integrated IO core. Temursho et al. (2025) develop a macro-micro framework for projecting household expenditures, combining a Taylor expenditure model with a Leontief IO structure in a multi-regional setting. These contributions solve important data-integration and methodological problems, but the price-quantity IO strand and the

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household-microdata strand remain only partially integrated in the published literature.

This paper contributes to the intersection of these two lines of research by developing IO-DASMOD, a fully integrated macro-micro framework that combines an integrated price-quantity IO model with household-level data for the Czech Republic. The model embeds approximately 3 233 individual households, each with its own factor endowment profile and consumption basket, directly into the system of equations, creating a nonlinear system solved simultaneously. This distinguishes it from sequential top-down approaches in which a macro model is first solved, and results are then imputed to a microsimulation model.

IO-DASMOD makes four contributions. First, it extends the Cardenete et al. (2024) integrated price-quantity IO methodology by coupling it with individual household-level microsimulation data, creating endogenous feedback between household demand and sectoral output. Second, it advances the household microdata integration methodology of Cazcarro et al. (2022) by providing a transparent way of deriving bridge matrices between COICOP and CPA classifications in a setting where access to bridge matrices produced by statistical offices is not made available. Third, by embedding individual households rather than representative groups, the model preserves the full micro-heterogeneity of the underlying survey data through to the model solution, avoiding the aggregation bias inherent in grouped approaches. Fourth, it provides the first such framework for a Central European economy, filling a geographic gap in the applied distributional analysis literature.

To illustrate the analytical capabilities of the framework, the paper applies IO-DASMOD to four stylized policy scenarios for the Czech Republic: a uniform economy-wide CO2 price, a household energy price shock, an ETS2-style carbon price proxy, and an agri-food greenhouse-gas price. The aim of these applications is not to provide a full policy appraisal, but to show how the model distinguishes between broad and narrow pricing instruments, between emissions-based and non-emissions-based cost shocks, and between energy- and food-system channels of household incidence. In this way, the scenarios serve as an empirical demonstration of the model's ability to trace policy-induced cost shocks through production networks, price formation, factor incomes, and heterogeneous household consumption baskets.

The remainder of the paper is organized as follows. Section 2 describes the data sources and bridging procedures used to construct the integrated macro-micro database. Section 3 presents the model structure and system of equations. Section 4 introduces the illustrative policy scenarios. Section 5 reports the results. Section 6 concludes and discusses possible extensions of the framework, including dynamics and a richer treatment of the power sector.

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2 Methods and data

The model is calibrated for the Czech Republic using the following data:

- **Supply and Use Tables:** Eurostat 2024-vintage SUTs at 89-industry NACE Rev. 2 detail, in basic prices.
- **Household Budget Survey (HBS):** Czech Statistical Office, providing household-level expenditure data classified under COICOP. Five parent COICOP categories (01, 14, 25, 26, 27) are disaggregated into sub-categories using HBS-derived weights, yielding 77 COICOP categories.
- **EU-SILC:** European Union Statistics on Income and Living Conditions, providing household income decompositions (labor income by industry, capital income, transfers) and demographic characteristics.
- **National Accounts:** Eurostat household final consumption by CPA product and by COICOP category, and the valuation tables (`naio_10_cp16`) for the PP-to-BP conversion.
- **Air Emissions Accounts:** Eurostat, providing emission intensities by NACE industry for CO_2, CH_4, N_2O, and other greenhouse gases.
- **Elasticities:** Own-price, cross-price, and income elasticities of demand, loaded from an external file. In the current implementation, these are drawn from the literature and allowed to vary across household groups. A QUAIDS demand system (Banks et al., 1997) is currently being estimated with Czech HBS data (Opatrny and Scasny, 2025).

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2.1 Input-Output framework

The macroeconomic backbone is derived from Eurostat Supply and Use Tables (SUTs) in basic prices. Let V denote the Make matrix (products $\times$ industries), U the Use matrix, $(\mathbf{q} - \mathbf{m})$ the domestic production output vector by CPA product, and $\mathbf{g}$ the gross output vector by NACE industry.

The model adopts the fixed-product-sales assumption to convert the Supply and Use Tables into a square industry-by-industry system. The transformation matrix is:

$$T_{i,c} = \frac{V_{c,i}}{(q-m)_c}, \qquad (q-m)_c > 0 \tag{1}$$

where $V_{c,i}$ is the element of the Make matrix and $(q-m)_c$ is total domestic output of product c. The industry-by-industry technical coefficients matrix is then:

$$a_{i,j} = \frac{\sum_c T_{i,c} \cdot U_{c,j}}{x_j^0}, \qquad x_j^0 > 0 \tag{2}$$

where x_j^0 is benchmark gross output of industry j.

Value added is decomposed into wages, social contributions, other net taxes on production, consumption of fixed capital, and net operating surplus. Emission intensities per unit of industry output are computed from Eurostat Air Emissions Accounts by NACE activity.

2.2 Household consumption bridge

One of the most distinctive features of IO-DASMOD is the multi-stage bridge that traces each household's expenditure from survey records to industry-level quantities in the IO framework. Building on Cazcarro et al. (2022) and Mongelli et al. (2010), the full chain is summarized below: 1. annualization and scaling, 2 COICOP-to-CPA bridging, 3. purchaser-price to basic-price conversion, and 4. domestic share and industry transformation.

$$\underbrace{\mathrm{HBS}_{h,q}}_{\text{COICOP PP}} \xrightarrow{\text{scale}} \underbrace{\tilde{c}_{h,q}}_{\text{COICOP PP}} \xrightarrow{B^{\mathrm{C}\to\mathrm{P}}} \underbrace{c^{0,\mathrm{PP}}_{c,h}}_{\text{CPA PP}} \xrightarrow{\mathbf{C}^{\mathrm{PP}\to\mathrm{BP}}} \underbrace{c^{0,\mathrm{BP}}_{c,h}}_{\text{CPA BP}} \xrightarrow{\times\alpha_c} \underbrace{c^{0,\mathrm{dom}}_{c,h}}_{\text{CPA BP dom.}} \xrightarrow{T} \underbrace{c^{0,\mathrm{NACE}}_{i,h}}_{\text{NACE BP dom.}}$$

As in Cazcarro et al. (2022), the translation of the HBS microdata into our IO framework consists of four sequential steps, detailed below.

2.2.1 Annualization and scaling

Raw HBS expenditures are recorded over varying observation periods. Each household's data is annualized and then scaled category-by-category to match National Accounts (NA) aggregates:

$$\lambda_q = \frac{\mathrm{NA}_q}{\sum_h \phi_h \cdot \mathrm{HBS}_{h,q}}, \qquad \tilde{c}_{h,q} = \phi_h \cdot \mathrm{HBS}_{h,q} \cdot \lambda_q \tag{3}$$

where ϕ_h is the annualization factor. This category-specific scaling preserves the cross-household heterogeneity in expenditure patterns while enforcing consistency with official aggregates.

2.2.2 COICOP-to-CPA bridge

To bridge COICOP and CPA product categories, we employ a bridge matrix. The bridge between consumption purpose (COICOP) and product activity (CPA) classifications is estimated via constrained cross-entropy (KL-divergence) minimization:

$$\min_{X_{q,c}} \sum_{(q,c)\in\mathcal{S}} \left[X_{q,c} \ln \frac{X_{q,c}}{X^0_{q,c}} - X_{q,c} + X^0_{q,c} \right] \tag{4}$$

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subject to row-sum constraints $\sum_c X_{q,c} = \mathrm{NA}_q^{\mathrm{COICOP}}$ for all q, column-sum constraints $\sum_q X_{q,c} = \mathrm{NA}_c^{\mathrm{CPA}}$ for all c, and sparsity constraints $X_{q,c} = 0$ for $(q,c) \notin \mathcal{S}$, where $\mathcal{S}$ is a curated admissible support set based on correspondence tables between COICOP and CPA product categories from Statistics Austria (2024). The support set undergoes an LP-based feasibility pruning: cells whose maximum feasible value falls below 10^{-8} are removed. The resulting joint table X yields both bridge directions by normalization: the row-normalized bridge $B_{q,c}^{\mathrm{C}\to\mathrm{P}} = X_{q,c}/\mathrm{NA}_q^{\mathrm{COICOP}}$ gives CPA shares given a COICOP category, while the column-normalized reverse bridge $B_{q,c}^{\mathrm{P}\to\mathrm{C}} = X_{q,c}/\mathrm{NA}_c^{\mathrm{CPA}}$ is used in the price chain.

2.2.3 Purchaser-price to basic-price conversion

Household survey data are recorded in purchaser prices (PP), while the IO framework operates in basic prices (BP). Our conversion approach is based on Mach et al. (2018). The conversion uses household-consumption-specific valuation data from Eurostat:

$$\mathrm{PP}_c = \mathrm{BP}_c + \mathrm{TTM}_c + \mathrm{TLS}_c \tag{5}$$

where TTM denotes trade and transport margins and TLS denotes taxes less subsidies on products.

The PP-to-BP conversion matrix $\mathbf{C}$ has both diagonal and off-diagonal elements:

$$C_{c,c'} = \underbrace{\hat{C}^t_{c,c'}}_{\text{diagonal: tax + margin removal}} + \underbrace{C^m_{c,c'}}_{\text{off-diagonal: margin reallocation}} \tag{6}$$

For products with positive embedded margins ($\mathrm{TTM}_{c'} > 0$):

$$\hat{C}^t_{c',c'} = \frac{1}{(1+m_{c'})(1+t_{c'})} \tag{7}$$

$$C^m_{c,c'} = \frac{-\xi_c \cdot m_{c'}}{(1+m_{c'})(1+t_{c'})} \quad \text{for margin-providing products } c \tag{8}$$

where $m_{c'}$ is the margin rate, $t_{c'}$ is the tax rate, and ξ_c is the redistribution share for margin-providing products. The off-diagonal elements reallocate positive margins to wholesale, retail, and transport services.

2.2.4 Domestic share and industry transformation

The domestic share of household consumption in CPA basic prices is

$$\alpha_c^{\mathrm{dom}} = \mathrm{UseTable}(c, \mathrm{HH})/\mathrm{BP}_c^{\mathrm{total}},$$

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derived from the Use Table. The final step applies the transformation matrix T from Eq. (1) to convert CPA product categories to NACE industries.

2.3 Household income treatment

Each household's reference person is assigned to a NACE industry based on their recorded NACE industry in the EU-SILC data. Labor income is allocated to the identified industry; for retired or inactive households with positive labor income, a weight vector distributes income across sectors using observed sector weights combined with small seeds for industries with NA compensation but zero micro-level coverage. A separate rescaling step aligns each industry's total labor income to the NA compensation of employees.

Capital income by industry (consumption of fixed capital plus net operating surplus) is distributed across households (that actively hold capital income according to SILC data) proportionally to each household's share of total micro capital income:

$$k^0_{h,i} = \frac{\text{capitalIncome}^{\text{micro}}_h}{\sum_{h'} \text{capitalIncome}^{\text{micro}}_{h'}} \cdot (\text{CFC}_i + \text{NOS}_i) \tag{9}$$

This assumes that each household's capital is diversified across all industries in proportion to the NA capital composition. In the absence of additional data on capital ownership by household, this simplification ensures exact consistency with the NA value-added accounts.

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3 Model

The IO-DASMOD framework extends a standard Input–Output model by integrating price and quantity determination within a single system of nonlinear equations, while embedding approximately 3,233 individual households directly into the model structure. This section presents the formal system of equations that constitutes the model. The data sources and bridging procedures that calibrate these equations are described in Section 2.

The model determines simultaneously: industry output levels x_i, industry basic prices p_i, the aggregate wage w, the aggregate rental rate of capital r, household disposable incomes m^d_h, household consumption demands $d_{h,k}$ across product categories, household-specific price indices P^{HH}_h, sectoral abatement rates $\mu_{i,e}$, and total environmental-policy revenue R^E. All variables are endogenous and solved in benchmark-consistent levels. All price variables are normalized to unity.

3.1 Model equations

Production block

The quantity side of the model follows a standard Leontief structure. Total output of industry i must satisfy intermediate demand from all industries, investment demand, exogenous final demand, budget-neutral policy investment, and endogenous household consumption:

$$x_i = \sum_{j \in I} a_{i,j} x_j + \sigma_i \sum_{j \in I} \Theta_j^K x_j + \bar{f}_i + G_i^{pol} + \sum_{h \in H} \sum_{k \in K} \Gamma_{h,k,i}\, d_{h,k} \tag{10}$$

where $a_{i,j}$ is the technical coefficient giving the input of industry i per unit of output in industry j, derived from the industry-by-industry transformation described in Section 2.1. The term $\sigma_i \sum_j \Theta_j^K x_j$ represents investment demand, where $\sigma_i = I_i^0/K^0$ gives the investment good of type i per unit of benchmark aggregate capital. Investment is proportional to aggregate capital use. The term $\bar{f}_i$ collects all exogenous components of final demand: government consumption, non-profit consumption, exports, inventory changes, acquisitions less disposals, the fixed household component (imputed rents), and a micro–NA demand absorber that closes the rounding discrepancy introduced by the multi-step household bridging chain. The term $G_i^{pol} = \alpha_i^{inv} R^E$ represents a policy-financed investment out of recycled revenue, where α_i^{inv} is the share of environmental-policy revenue allocated to investment in industry i and R^E is total policy revenue defined below. At benchmark, $R^E = 0$.

The final term links the microsimulation layer to the production system. The bridge parameter $\Gamma_{h,k,i}$ converts one unit of household h's spending on DAS product category k (in purchaser prices) into industry-level demand in NACE basic prices. This parameter is precomputed from the full household bridging chain described in Section 2.2 and encodes, for each household, the back-allocation to COICOP categories, the COICOP-to-CPA bridge, the purchaser-price to basic-price conversion (including off-diagonal margin redistribution), the domestic share, and the CPA-to-NACE industry transformation. Because $\Gamma_{h,k,i}$ varies across households, the model preserves the full micro-heterogeneity of consumption composition through to the quantity system.

Leontief price equation

Prices are determined by a zero-profit condition. The price of each industry's output equals the sum of intermediate input costs, labor costs, capital costs, a unit cost add-on (covering net taxes and imports), any exogenous price shock, the cost of emissions charges on effective (post-abatement) emissions, and the resource cost of abatement:

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$$p_i = \sum_{j \in I} a_{j,i}\, p_j + \Theta_i^L\, w + \Theta_i^K\, r + u_i + \bar{s}_i + \sum_{e \in E} \left[\tau_{i,e}^E\, \epsilon_{i,e} (1 - \mu_{i,e}) + \tfrac{1}{2} \varphi_{i,e}\, \mu_{i,e}^2 \right] \tag{11}$$

where $\Theta_i^L = \sum_h \theta_{h,i}^L$ and $\Theta_i^K = \sum_h \theta_{h,i}^K$ are the aggregate labor and capital intensities of industry i, u_i is the unit cost add-on, $\bar{s}_i$ is an exogenous price shock instrument, $\tau_{i,e}^E$ is the emissions price on pollutant e in industry i, $\epsilon_{i,e}$ is the baseline emissions intensity (tonnes per unit of output), $\mu_{i,e} \in [0, 1)$ is the endogenous abatement rate, and $\varphi_{i,e} > 0$ governs the curvature of the marginal abatement cost function. At benchmark, all emissions prices are zero, so $p_i^0 = 1$ for all i.

The emissions-related terms in the price equation reflect two distinct cost channels. The first, $\tau_{i,e}^E \epsilon_{i,e}(1-\mu_{i,e})$, is the charge on residual emissions after abatement. The second, $\frac{1}{2}\varphi_{i,e}\mu_{i,e}^2$, is the per-unit-output resource cost of undertaking abatement. Together, these terms create two margins through which a carbon price can affect the economy: an output-contraction margin operating through the standard Leontief linkages, and an emissions-intensity margin operating through endogenous abatement.

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Emissions abatement

The optimal abatement rate in each industry–pollutant pair is determined by equating the marginal cost of abatement to the marginal benefit of avoided emissions charges:

$$\varphi_{i,e}\, \mu_{i,e} = \tau_{i,e}^E\, \epsilon_{i,e} \tag{12}$$

This yields $\mu_{i,e} = \tau_{i,e}^E \epsilon_{i,e} / \varphi_{i,e}$, so that abatement is increasing in the emissions price and in the baseline emissions intensity, and decreasing in the abatement cost curvature. For industry–pollutant pairs with zero baseline emissions, $\mu_{i,e}$ is fixed at zero. The abatement rate is bounded above by a parameter $\bar{\mu} < 1$ to prevent corner solutions. At the benchmark, all emissions prices are zero.

Return to capital

The rental rate of capital is determined by an aggregate scarcity condition:

$$r = r^0 \left(\frac{\sum_{i \in I} \Theta_i^K\, x_i}{K^0} \right)^{\beta_K} \tag{13}$$

where $K^0 = \sum_{h,i} k_{h,i}^0$ is benchmark aggregate capital and β_K is the elasticity of the rental rate with respect to aggregate capital utilization. This specification ensures that the return to capital responds to the scarcity of capital relative to its benchmark level, but does not respond mechanically to changes in the price of investment goods. In a previous model version, the rental rate was multiplied by an investment-good price bundle

$\sum_j \delta_j p_j$, which caused any cost-push price increase to feed directly into capital income and, through the household demand system, back into aggregate demand. Removing this price-bundle multiplier shuts down a major channel through which a carbon-cost shock was mechanically converted into a capital-income windfall. Capital use by each household is simply defined as:

$$K_h^U = \sum_{i \in I} \theta_{h,i}^K \, x_i \tag{14}$$

where $\theta_{h,i}^K = k_{h,i}^0 / x_i^0$ is the capital intensity of industry i belonging to household h.

Wage determination

The aggregate wage is determined by a labor-scarcity condition with a controlled degree of CPI indexation:

$$w = w^0 \left(\frac{\sum_h L_h^U}{L^0} \right)^{\beta_L} \cdot \left[1 + \max\Big(0,\ \rho\,(\mathrm{CPI} - 1)\Big) \right] \tag{15}$$

where $L^0 = \sum_{h,i} l_{h,i}^0$ is benchmark aggregate labor, β_L is the elasticity of the wage with respect to labor demand, $\rho \in [0, 1)$ is the CPI recovery parameter. The max operator is smoothly approximated to maintain differentiability: $1 + \frac{1}{2}(z + \sqrt{z^2 + \gamma^2} - \gamma)$ with a small smoothing parameter $\gamma = 10^{-4}$.

The CPI recovery parameter ρ governs the extent to which cost-push inflation is passed through into labor income. Currently, ρ is set to zero, so that wages respond only to labor-market scarcity and not to contemporaneous consumer-price changes. This prevents a carbon-cost shock from being mechanically recycled into higher wages, which would in turn feed into higher household incomes and demand.

Labor use by each household is:

$$L_h^U = \sum_{i \in I} \theta_{h,i}^L \, x_i \tag{16}$$

where $\theta_{h,i}^L = l_{h,i}^0 / x_i^0$ is the labor intensity of industry i belonging to household h.

Price indices

The model uses two price indices. The first is an economy-wide consumer price index (CPI), computed as a weighted average of DAS purchaser-price changes across all households:

$$CPI = \sum_{k \in K} \sum_{h \in H} \frac{d_{h,k}^0}{\sum_{h',k'} d_{h',k'}^0} \cdot \frac{\tilde{p}_k}{\tilde{p}_k^0} \tag{17}$$

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where $\tilde{p}_k$ is the DAS purchaser price of category k and $d^0_{h,k}$ is benchmark expenditure. The CPI enters the wage equation and equals unity at benchmark by construction.

The second is a household-specific Laspeyres price index:

$$P^{HH}_h = \sum_{k \in K} \omega^c_{h,k} \cdot \frac{\tilde{p}_k}{\tilde{p}^0_k} \tag{18}$$

where $\omega^c_{h,k} = d^0_{h,k} / \sum_{k'} d^0_{h,k'}$ is the benchmark expenditure share of household h on category k. This index captures the fact that different households face different effective price changes depending on their consumption baskets. It is used to deflate nominal disposable income in the demand equation, ensuring that the demand system responds to purchasing power rather than to nominal income alone. At benchmark, $P^{HH}_h = 1$ for all h.

DAS purchaser prices are themselves a linear function of industry basic prices, computed through a precomputed price bridge:

$$\tilde{p}_k = \sum_{i \in I} \Pi_{k,i}\, p_i \tag{19}$$

where $\Pi_{k,i}$ is the price bridge parameter that maps NACE basic prices to DAS purchaser prices. This parameter encodes the full chain from industry basic prices through the industry-to-product transformation, the basic-price to purchaser-price conversion (including margin reallocation and tax addition), the CPA-to-COICOP bridge, and the COICOP-to-DAS aggregation.

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Disposable income

Disposable income for household h is:

$$m^d_h = (1 - t_h)(1 - s_h) \left[w\, L^U_h + r\, K^U_h \right] + \bar{tr}_h + \alpha^{hh}_h\, R^E \tag{20}$$

where t_h is the effective income tax rate, s_h is the savings rate, $\bar{tr}_h$ is the exogenous benchmark transfer (needed to close the household account), and $\alpha^{hh}_h R^E$ is the recycled policy transfer. The parameter α^{hh}_h gives the share of environmental-policy revenue recycled as a transfer to household h. At benchmark, $R^E = 0$.

The budget-neutral recycling mechanism ensures that policy transfers are financed from realised policy revenue rather than added as exogenous demand injections.

Consumption demand

Household consumption demand follows an isoelastic specification with own-price, cross-price, and income effects:

$$d_{h,k} = d^0_{h,k} \left(\frac{\tilde{p}_k}{\tilde{p}^0_k} \right)^{1+\eta^{own}_{h,k}} \cdot \prod_{k' \neq k} \left(\frac{\tilde{p}_{k'}}{\tilde{p}^0_{k'}} \right)^{\eta^{cross}_{h,k,k'}} \cdot \left(\frac{m^d_h}{P^{HH}_h \cdot m^{d,0}_h} \right)^{\eta^{inc}_{h,k}} \tag{21}$$

where $\eta^{own}_{h,k}$, $\eta^{cross}_{h,k,k'}$, and $\eta^{inc}_{h,k}$ are own-price, cross-price, and income elasticities that may vary across households and product categories of the microsimulation model, DASMOD. For the remainder of the paper, these product categories are simply detoned "DAS".

Importantly, the ratio $m^d_h/(P^{HH}_h \cdot m^{d,0}_h)$ measures the change in real disposable income: nominal disposable income m^d_h is deflated by the household-specific Laspeyres price index P^{HH}_h and expressed relative to the benchmark. In a previous specification, the demand system used $m^d_h/m^{d,0}_h$ as the income shifter, which is a pure nominal ratio. When a carbon price pushed up the CPI, wages and capital returns partially followed through indexation and price-bundle effects, causing nominal income to rise. The demand system then treated this nominal increase as additional purchasing power, generating a spurious expansionary feedback. By deflating with P^{HH}_h, the current specification ensures that a pure cost-push shock that raises both prices and nominal incomes proportionally, is read as welfare-neutral rather than welfare-improving.

At benchmark, $P^{HH}_h = 1$ and $m^d_h = m^{d,0}_h$, so the income shifter equals unity and the calibration is unchanged.

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Policy revenue and recycling

Total environmental-policy revenue is computed as the product of emissions prices, effective (post-abatement) emissions intensities, and output levels:

$$R^E = \sum_{i \in I} \sum_{e \in E} \tau^E_{i,e} \, \epsilon_{i,e} \, (1 - \mu_{i,e}) \, x_i \tag{22}$$

At benchmark, all emissions prices are zero, so $R^E = 0$. In policy simulations, R^E is endogenous: it rises with the emissions price and with output, and falls with abatement.

The policy-revenue identity allows environmental-policy revenue to be allocated to household transfers, policy-financed investment, or an unrecycled residual that exits the circular flow:

$$R^E = \sum_{h \in H} \alpha^{hh}_h R^E + \sum_{i \in I} \alpha^{inv}_i R^E + R^{sink} \tag{23}$$

$$R^{sink} = \left(1 - \sum_{h \in H} \alpha^{hh}_h - \sum_{i \in I} \alpha^{inv}_i \right) R^E, \tag{24}$$

with $0 \leq \sum_{h \in H} \alpha^{hh}_h + \sum_{i \in I} \alpha^{inv}_i \leq 1$, $\alpha^{hh}_h >= 0$, and $\alpha^{inv}_i >= 0$. Different recycling designs are implemented by varying the α parameters. Full recycling obtains when $\sum_h \alpha^{hh}_h + \sum_i \alpha^{inv}_i = 1$, in which case $R^{sink} = 0$. For an equal per-capita dividend, $\alpha^{hh}_h = 1/|H|$ for

all h and $\alpha_i^{inv} = 0$. For a Social Climate Fund-style package combining transfers with investment, both sets of shares are positive. No-recycling scenarios are represented by setting all recycling shares to zero, so that $R^{sink} = R^E$. Intermediate cases correspond to partial recycling, in which only a fraction of total policy revenue is returned to households or reinjected as investment.

4 Application: Policy scenarios

To illustrate the capabilities of the IO-DASMOD framework, we apply the model to four policy scenarios designed to capture distinct channels through which climate and energy policy can affect household welfare and the distribution of costs across the income distribution. All four scenarios share a common analytical purpose: they impose a cost shock on the production system and trace its propagation through inter-industry linkages, factor markets, and the household demand system described in Section 3. They differ, however, in the policy instrument used, the set of industries targeted, the emission accounts activated, and the presence or absence of endogenous abatement. None of the scenarios presented here includes revenue recycling. They thus isolate the *gross* distributional burden of each policy before any mitigating intervention.

Table 1 provides an overview. The remainder of this section describes each scenario in turn, highlighting the model mechanisms that each one activates and the policy motivation behind its design.

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Table 1: Summary of policy scenarios.

ID	Label	Industries targeted	Emission account	Instrument
1A	Uniform CO_2 price	All 89 NACE industries	CO_2	$\tau^E =$ 60 EUR/tCO_2
2A	Household energy price shock	Electricity, gas, steam and air conditioning (NACE D35)	-	$\bar{s} = 5\%$ ad valorem
3A	ETS2-style carbon price proxy	Refined petroleum (NACE C19); Electricity, gas, steam (NACE D35); Land transport (NACE H49)	CO_2	$\tau^E =$ 60 EUR/tCO_2
4A	Agri-food GHG price	Agriculture (NACE A01); Forestry (NACE A02); Fishing (NACE A03); Food products (NACE C10); Beverages (NACE C11)	CO_2-eq.	$\tau^E =$ 60 EUR/tCO_2e

All monetary values are in millions of CZK unless otherwise noted. The euro-equivalent carbon price assumes an exchange rate of 25 CZK/EUR.

The three emissions-pricing scenarios (1A, 3A, 4A) apply an identical price of 1 500 CZK

per tonne of CO2 or CO2-equivalent, depending on the emission account. This is equivalent to approximately 60 EUR/tCO_2 at an exchange rate of 25 CZK/EUR. This level is broadly consistent with the EU Emissions Trading System (EU ETS) carbon price observed during 2023-2024 and lies within the range of prices projected for the new ETS2 in the medium term (Czech National Bank, 2025).

Setting the same price across the three scenarios ensures that differences in outcomes are attributable to the scope and sectoral composition of the carbon price, rather than to its level.

Endogenous abatement is activated in every industry-pollutant pair with positive baseline emissions. The abatement cost curvature parameter $\phi_{i,e}$ is set uniformly at 0.10 across all industries, and the maximum abatement rate is bounded at $\bar{\mu} = 0.95$. Under these parameters, industries with higher baseline emission intensities $\varepsilon_{i,e}$ abate proportionally more for a given carbon price. Because the curvature is uniform, the model currently does not attempt to replicate sector-specific marginal abatement cost curves. Instead, it provides a stylized representation of the production-side adjustment margin that complements the Leontief output-contraction channel. In all four scenarios, wages respond only to aggregate labor-market scarcity ($\rho = 0$ in Eq. (15)).

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4.1 Scenario 1A: Uniform economy-wide CO_2 price

The first scenario imposes a uniform CO_2 price of 60 EUR/tCO_2 on all 89 industries simultaneously. The emissions price enters the Leontief price equation (Eq. (11)) through two cost channels: the charge on residual (post-abatement) emissions, $\tau^E_{i,e}\varepsilon_{i,e}(1-\mu_{i,e})$, and the resource cost of abatement, $\frac{1}{2}\phi_{i,e}\mu^2_{i,e}$. The carbon price applies only to the CO_2 emissions; other greenhouse gases (CH_4, N_2O) are not priced in this scenario. In this scenario the revenue is not recycled: it exits the circular flow, implying that the scenario captures the maximal gross burden on households.

The policy motivation for this scenario is straightforward: a uniform economy-wide carbon price is the textbook first-best instrument for internalizing the climate externality. By pricing all CO_2 emissions at the same rate, it equalises the marginal abatement cost across sectors and avoids the distortions that arise from differentiated or sector-specific pricing. Scenario 1A therefore serves as the reference case in which the cost burden is determined solely by sectoral emission intensities and inter-industry structure.

4.2 Scenario 2A: Household energy price shock

The second scenario applies a 5% ad valorem exogenous price shock to the electricity, gas, steam, and air conditioning supply sector (NACE D35). Unlike the emissions-pricing scenarios, this shock enters the model through the exogenous price shock instrument $\bar{s}_i$ in Eq. (11), which adds a non-emissions-based per-unit cost increase to the price of

the targeted industry. Because the shock is not linked to the emissions accounts, the abatement module is inactive. The policy motivation for Scenario 2A is to provide a counterfactual that captures the distributional impact of energy price increases that do not generate policy revenue. This is relevant both for analyzing the effects of exogenous energy price shocks (such as those experienced during the 2021-2022 energy crisis) in the absence of government intervention in the form of price caps or lump-sum transfers to households.

4.3 Scenario 3A: ETS2-style carbon price proxy

The third scenario applies a CO_2 price of 60 EUR/tCO_2 to three sectors (refined petroleum products (NACE C19), electricity, gas, steam, and air conditioning supply (NACE D35), and land transport and transport via pipelines (NACE H49)) that serve as supply-side proxies for the scope of the EU Emissions Trading System for buildings and road transport (ETS2), expected to be fully active in 2027 (European Commission, 2026). The emissions price operates through the same channels as in Scenario 1A, but restricted to these three industries. ETS2 prices CO_2 emissions from the combustion of fuels used in buildings and road transport. In practice, the compliance obligation falls on fuel distributors rather than on end users. The IO-DASMOD framework, however, operates at the level of NACE industries and cannot distinguish end uses within a sector's output. The three targeted sectors are therefore a *proxy*: refined petroleum products captures the fossil-fuel supply chain for road transport and heating oil; the electricity and gas sector captures gas and district heating for buildings; and land transport captures the direct combustion emissions of road freight and passenger services. This proxy inevitably prices some emissions that fall outside the scope of ETS2 (e.g., industrial process use of petroleum products) while missing others (e.g., direct combustion of biomass in buildings), but it provides the closest available approximation within the industry-level model structure.

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4.4 Scenario 4A: Agri-food greenhouse-gas price

The fourth scenario applies an emissions price of 60 EUR/tCO_2e to five sectors spanning the agri-food supply chain: crop and animal production (NACE A01), forestry and logging (NACE A02), fishing and aquaculture (NACE A03), manufacture of food products (NACE C10), and manufacture of beverages (NACE C11). Unlike the other emissions-pricing scenarios, this one operates on the CO_2-equivalent emission account which aggregates CO_2, CH_4, and N_2O using standard global warming potentials. This choice reflects the composition of agricultural emissions, where methane from manure management, and nitrous oxide from fertiliser application, typically dominate over direct CO_2 emissions (IPCC, 2019).

The scenario is motivated by the growing policy interest in extending carbon pricing to the food system. Agriculture has so far been exempt from carbon pricing in the EU. Yet, it accounts for a substantial share of total greenhouse-gas emissions. Proposals to include agricultural emissions in climate policy frameworks raise immediate distributional concerns because food expenditure constitutes a larger share of the budget for low-income households than for high-income households (European Environment Agency, 2025; Merkle and Dolphin, 2024). Endogenous abatement is active in this scenario and operates on the CO_2-equivalent emission account.

5 Results

The four scenarios show that emissions effectiveness, average price pressure, and distributional incidence do not move together mechanically. Figure 1 shows that the broad economy-wide carbon price (Scenario 1A) produces the largest aggregate adjustment: it generates the largest emissions reduction, the highest policy revenue, and the largest increase in the average household price index, while not ranking as the most regressive scenario under a simple bottom-to-top decile burden ratio (D1/D10). By contrast, the agri-food greenhouse-gas price (Scenario 4A) has a much smaller aggregate effect on emissions and average prices, but it has the highest value of this simple D1/D10 burden ratio. The energy-price shock (Scenario 2A) and the ETS2-style proxy (Scenario 3A) lie between these two. Taken together, these results show that the overall scale of the shock and the way that shock is distributed across consumption categories are analytically distinct dimensions of policy incidence.

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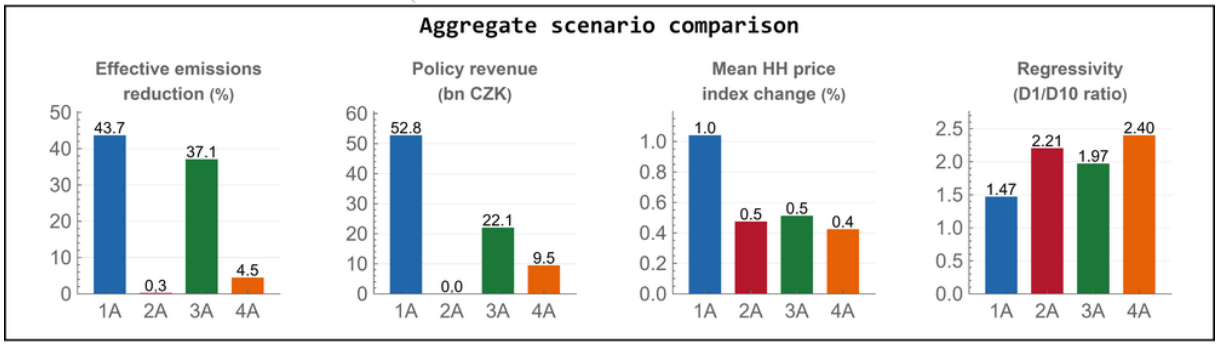

Figure 1: Aggregate comparison of scenario outcomes.

The common mechanism across all scenarios is the same. A cost shock enters the production system, propagates through inter-industry linkages, alters purchaser prices through the price bridge, and is then filtered through heterogeneous household consumption baskets. What changes across scenarios is how broad the initial shock is, and the margins through which the model allows adjustment. In the emissions-pricing scenarios, the shock works through both the charge on residual emissions and the resource cost of

abatement. In the pure energy-price shock, by contrast, there is no emissions charge, no endogenous abatement, and no endogenous policy revenue. This makes Scenario 2A a useful benchmark: it isolates the price-transmission channel of an energy cost increase, stripped of the abatement and fiscal dimensions that characterize carbon pricing.

Figure 2 shows how this propagation looks on the production side under Scenario 1A. The left panel ranks the largest sectoral price increases, and the pattern is highly revealing: electricity and gas, mining-related sectors, and basic materials sit at the top. These are not only emissions-intensive sectors; they are also upstream suppliers to many other activities. In a Leontief framework, their higher costs cannot be substituted away, so they are passed forward through the production network. The right panel shows the corresponding output responses. Read together, the two panels make clear why a broad carbon price has such wide household effects: the policy does not only hit "dirty" sectors in isolation, but revalues central inputs that are deeply embedded in the rest of the economy.

This production-side logic helps interpret the narrower scenarios. Scenario 3A, the ETS2-style proxy, uses the same carbon-pricing logic as 1A but applies it only to refined petroleum, electricity and gas, and land transport. Its aggregate effect is therefore smaller, but the burden is more focused in categories that households observe directly and frequently. Scenario 2A goes one step further: it removes emissions pricing altogether and applies an exogenous price shock only to electricity and gas. Because that sector is both a direct household purchase and a universal intermediate input, the shock reaches households through two routes at once: directly through household energy bills, and indirectly through higher downstream production costs. That is why even a narrowly targeted non-emissions shock can still have economy-wide distributional consequences.

Figure 3 translates the sectoral effects into the consumer categories that affect household welfare. Scenario 1A shows the broadest pattern: bars are elevated across many categories, with particularly strong increases in electricity and gas, solid fuels and heat, liquid fuels, and transport-related items. Scenario 3A is narrower and more concentrated, with the most visible effects in household energy and transport. Scenario 2A also concentrates in energy-related categories, but without the wider carbon-pricing pattern. Scenario 4A stands apart most clearly in food-related items: meat, food at home, and other food-system categories are where its price effects are visually strongest.

Figure 4 provides part of the explanation for why the agri-food scenario is more regressive than the energy-focused ones. The figure should be read as a set of explanatory budget-share profiles. It shows budget-share Engel curves for energy and food, constructed from binned weighted means over baseline per-capita consumption. The main point is the global pattern: the food budget share declines more steeply than the energy budget share, indicating that poorer households allocate a larger fraction of their budgets to food. This helps explain why a food-price shock, even if modest in aggregate terms, can generate a more regressive burden.

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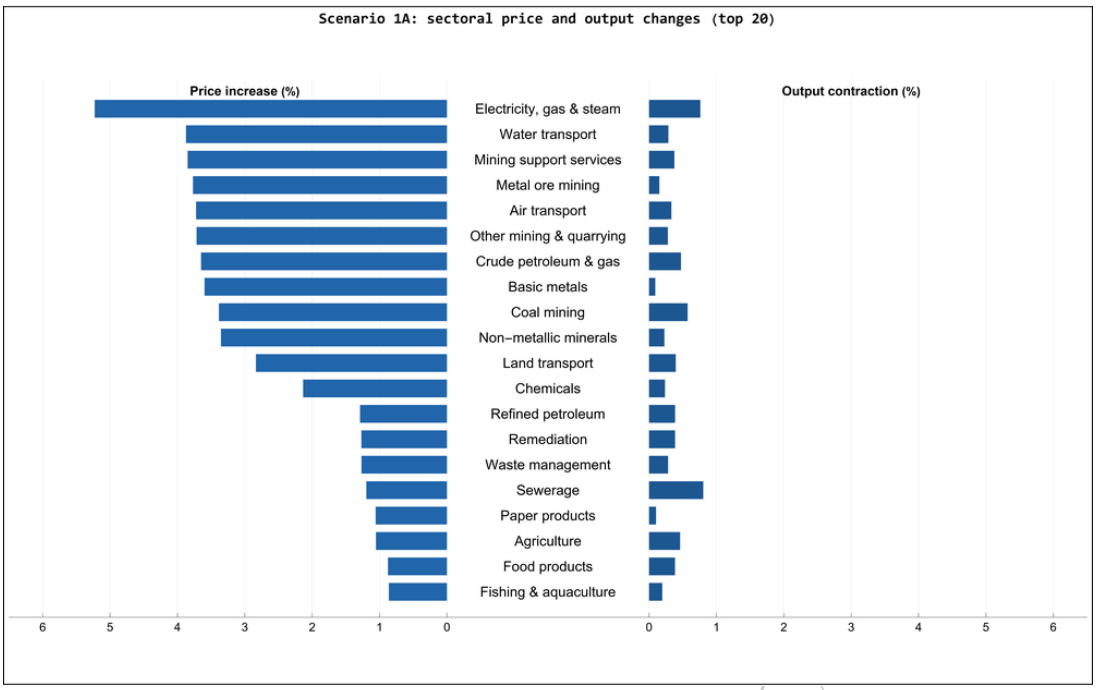

Figure 2: Scenario 1A: Top 20 sectors by price increase, with corresponding output contractions.

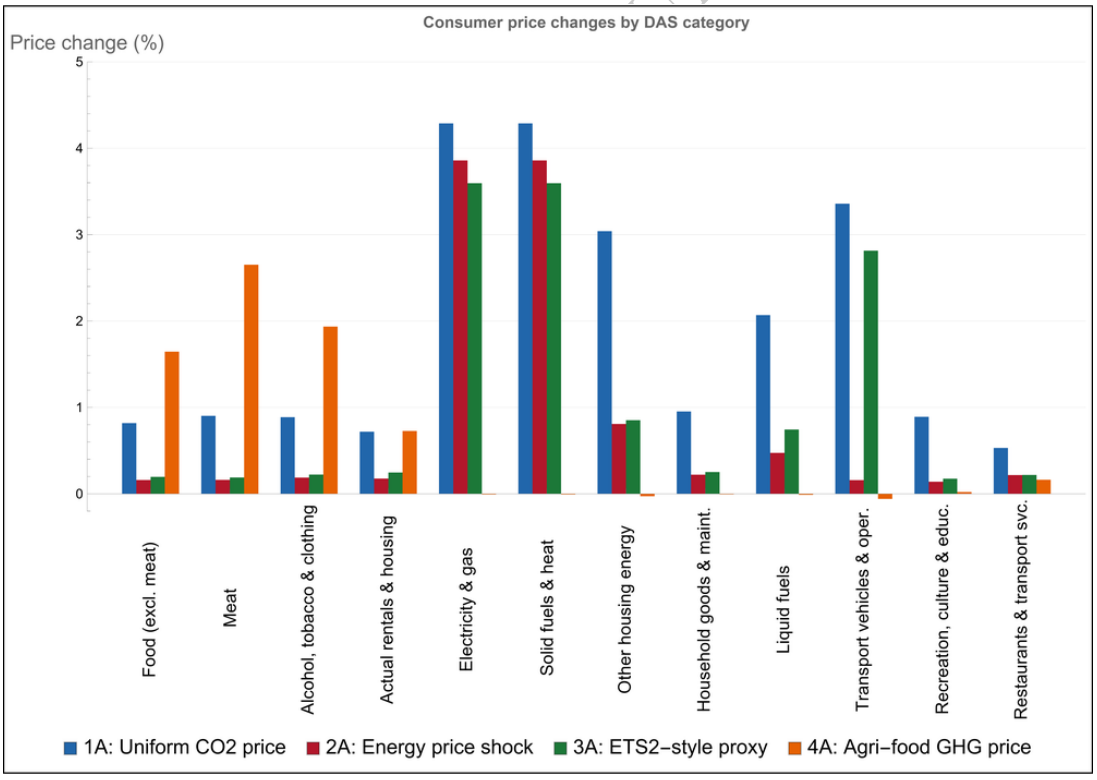

Figure 3: Consumer price changes by DAS consumption category (relative change).

The burden profiles by baseline living standard in Figure 5 summarize this point most directly. In all four scenarios, the curves slope downward with baseline living standard, which indicates regressive price incidence: poorer households face larger proportional

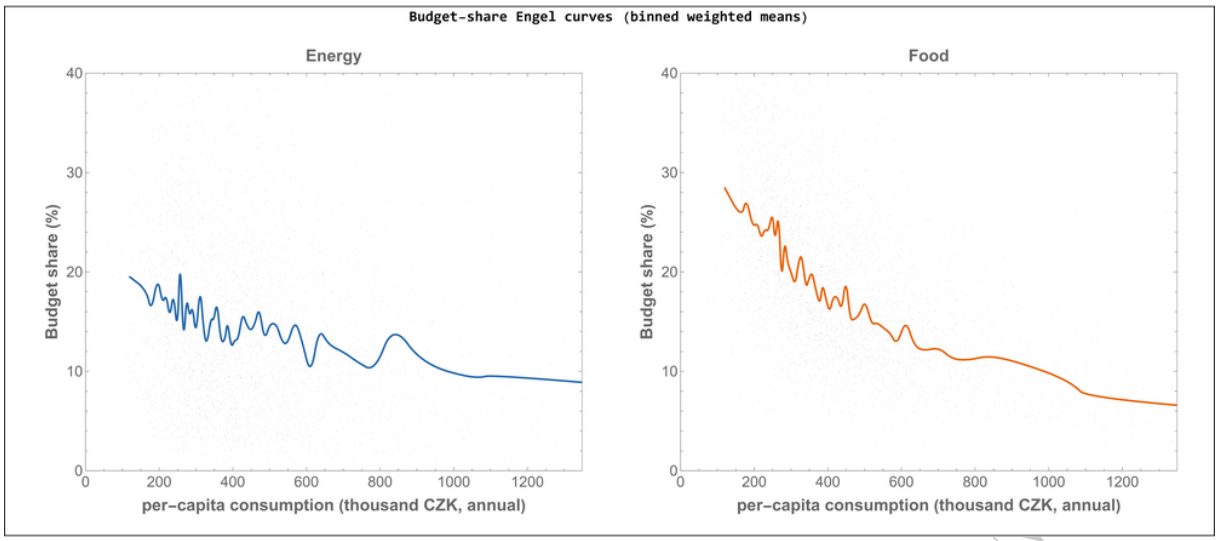

Figure 4: Budget-share Engel curves for energy and food.
Notes: Curves show binned weighted mean budget shares by baseline per-capita consumption.

increases in their household price index than richer households. The vertical position of each curve shows the burden at a given level of baseline living standard, while a curve that lies above another over most of the distribution indicates a larger burden on average. The extent of its decline over the distribution captures how strongly that burden is concentrated toward lower-consumption households.

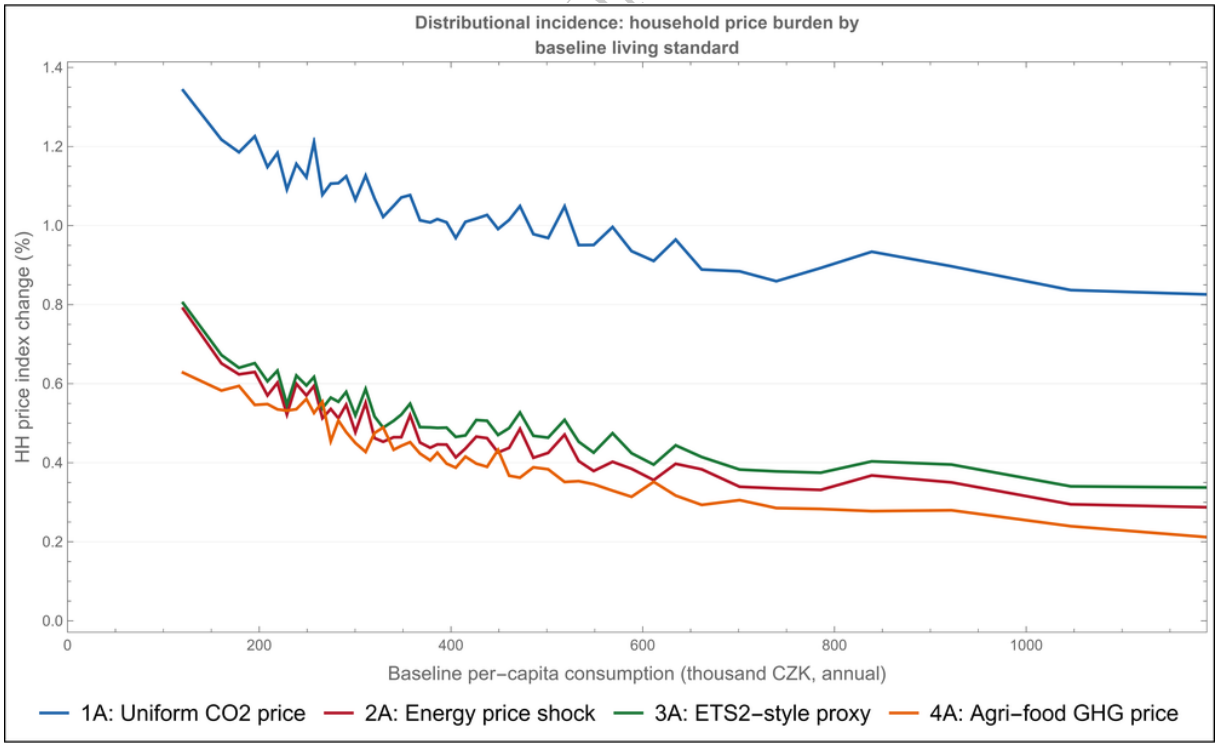

Figure 5: Burden profiles across the consumption distribution.

Scenario 1A lies clearly above the other three curves across most of the distribution, showing that it imposes the largest average household burden. By contrast, Scenarios 2A,

3A, and 4A are closer together. Notably, scenario 4A combines a lower average burden than Scenario 1A with a more pronounced low-to-high living-standard contrast, consistent with stronger regressivity. Scenarios 2A and 3A also display regressive incidence and remain close to one another over much of the distribution, with the pure energy shock in Scenario 2A appearing somewhat more concentrated toward the bottom than Scenario 3A in the lower and middle ranges. The main implication is that the scenario with the largest average burden is not necessarily the one with the strongest concentration of burden on poorer households.

Figure 6 re-expresses the incidence result in cumulative form. The concentration curves for all four scenarios lie above the Lorenz curve of baseline consumption, which confirms that the burden is concentrated more heavily among poorer households than consumption itself. But the distance between the scenario curves is informative. The curve for Scenario 4A sits highest over much of the distribution, consistent with the strongest concentration of burden among poorer households and therefore the greatest regressivity. Scenario 1A lies lower, confirming that its burden is more diffuse across the distribution even though its average effect is larger.

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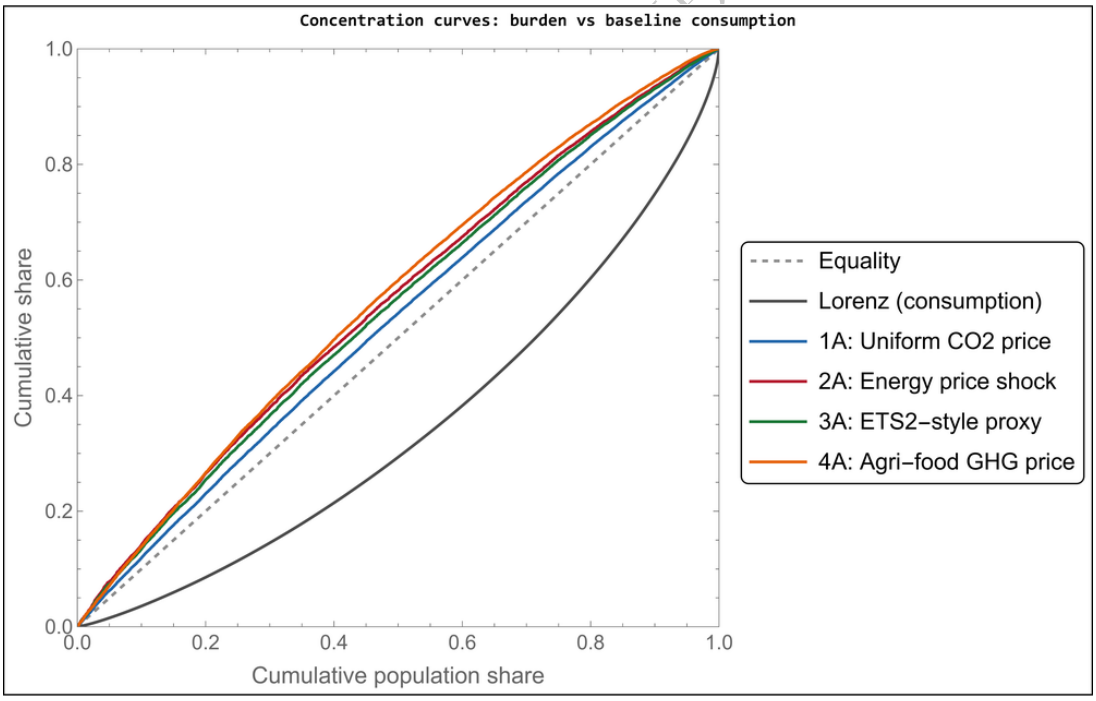

Figure 6: Concentration curves of household price burden, ranked by baseline consumption.

Figure 7 shows the contribution of each consumption group to the decile-average change in the household price index, measured in percentage points, for Scenario 1A (left) and 4A (right). Contributions are shown in raw terms rather than normalized shares, so the total height of each bar equals the average price burden in that decile. In Scenario 1A, the total burden is composed of several sources, with energy products, household

energy, transport, food, and services all playing visible roles. The mix changes systematically across deciles, which is why the scenario is regressive but not overwhelmingly so. In Scenario 4A, by contrast, the decomposition is visually dominated by food across the entire distribution, especially in the lower deciles. The figure makes the mechanism of regressivity concrete: the agri-food price is more regressive not because its aggregate effect is large, but because it is overwhelmingly concentrated in a necessity whose budget share falls strongly with living standard.

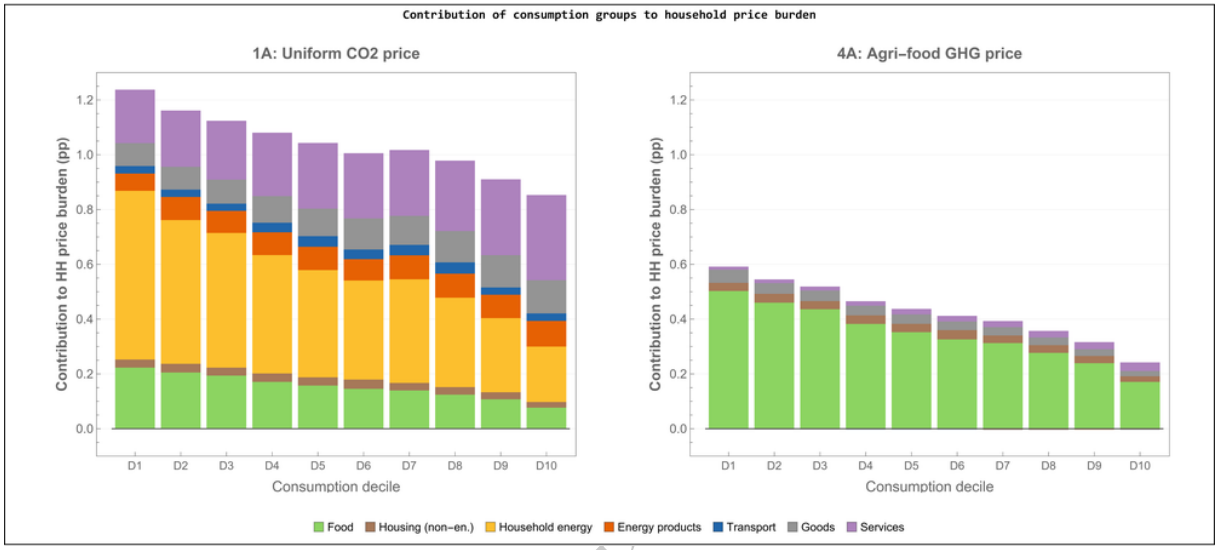

Figure 7: Contribution of broad consumption groups to the household price burden across consumption deciles.

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6 Discussion and conclusion

The results show that the scale of a policy shock, its sectoral point of entry, and its distributional profile are distinct dimensions of incidence. Scenario 1A, the broad economy-wide carbon price, produces the largest aggregate adjustment, including the largest reduction in effective emissions and the largest increase in the average household price index, but it is not the most regressive scenario. By contrast, Scenario 4A, the agri-food greenhouse-gas price, imposes a smaller average burden but a more unequal one, because it is concentrated in food, whose budget share falls strongly with living standard. A policy can therefore generate the largest average burden without being the most regressive, and vice versa.

The production-side results also distinguish the emissions-pricing scenarios from a standard cost-push input-output exercise. Emissions fall not only because output contracts, but also because emissions intensity adjusts endogenously through the abatement block. The strongest abatement appears in electricity and gas under Scenario 1A and in agriculture under Scenario 4A, reflecting differences in baseline emissions intensities. Abatement is therefore both the main source of emissions reduction and a mechanism

that dampens final price increases relative to a pure pass-through case.

On the household side, the results show that average burden and regressivity must also be kept separate.

Figure 8 supports the importance of "fine-grained" household-level modeling even after households are grouped into deciles, or other household groups, as is standard in the economy-wide literature. The violin plots do not simply reproduce the decile means. They show substantial within-decile dispersion in the burden experienced by households with similar baseline living standards. This is not noise. It is the consequence of heterogeneous consumption baskets and therefore of heterogeneous exposure to the same policy-induced price vector. Representative-household approaches smooth away exactly this kind of variation. One of the core contributions of IO-DASMOD is that it preserves this micro-heterogeneity in the final equilibrium solution.

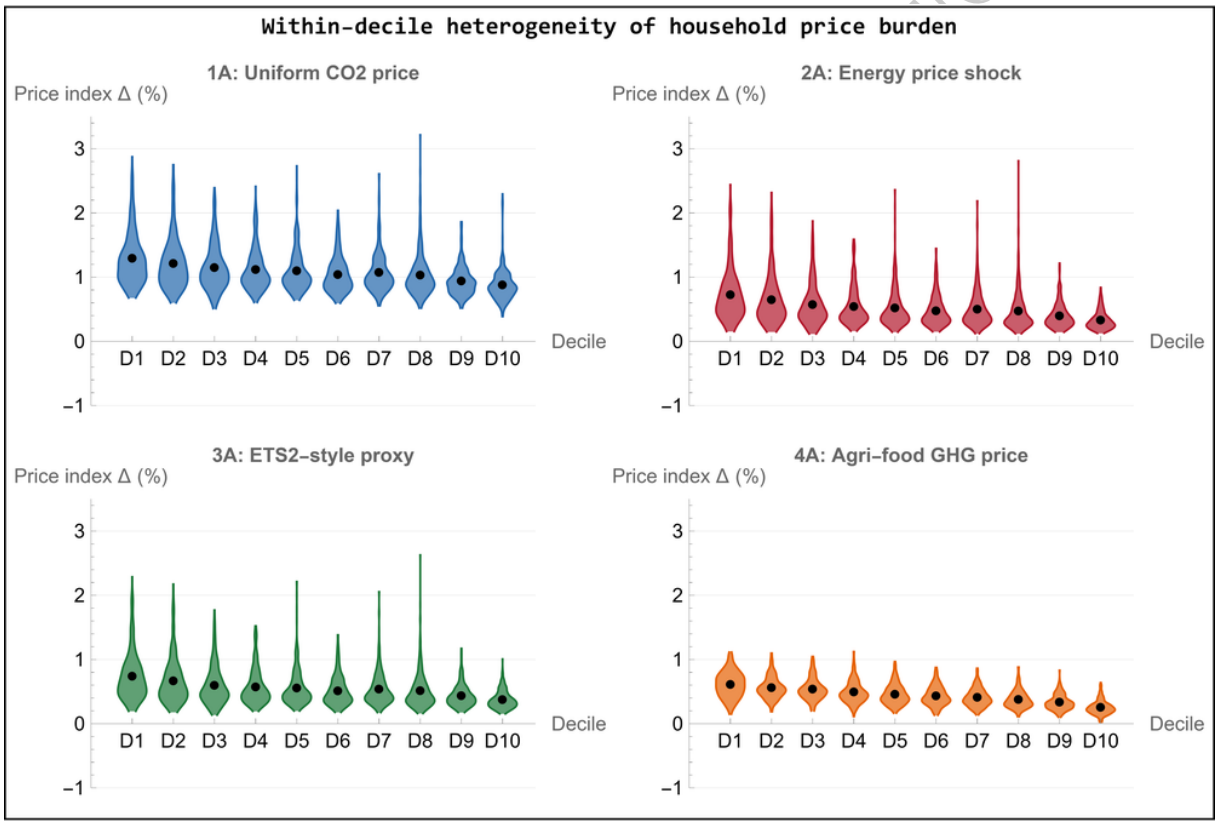

Figure 8: Within-decile heterogeneity of household price burden. Notes: Violin plots show the distribution of household price-index changes within each baseline consumption decile for each scenario. Points indicate decile means.

These results also clarify the analytical framework of IO-DASMOD. It is a comparative-static, price-endogenous input-output model, not a computable general equilibrium model. Four features define that niche. First, production technology is Leontief throughout, so firms cannot substitute between intermediate inputs, labor, and capital in response to relative price changes. The production-side adjustment margins are output contraction and reduced-form abatement. Second, factor markets are represented by aggregate scarcity

conditions rather than by full market-clearing systems. Wages respond to labor use relative to benchmark, and the return to capital responds to utilization, but neither market is modeled in a fully Walrasian way. Third, the model is solved as a single simultaneous system. Household demands feed back into the quantity block, and sectoral outputs feed back into household incomes, so the framework is not a sequential top-down linkage. Fourth, the demand-side closure is designed to prevent cost-push shocks from reappearing mechanically as gains in purchasing power: household demand responds to real rather than nominal income.

These strengths also define the limits of interpretation. The model captures transparent economy-wide cost propagation and rich household heterogeneity, but it does not provide the same behavioral margins as a CGE model with flexible production and demand systems throughout. In particular, the Leontief structure implies that firms cannot substitute away from regulated inputs except through the reduced-form abatement block. While this preserves the transparency of the price system, it is important to note that it is a major simplification of the model.

Additionally, the current elasticities are also still provisional. They are sufficient to demonstrate the model's mechanics, but not yet sufficient to treat the quantitative scenario magnitudes as final estimates. The ongoing QUAIDS estimation is central to the next stage of empirical discipline.

A second limitation is that the present applications focus on *gross* policy incidence. The scenarios in this paper intentionally exclude compensatory transfers and revenue recycling so as to isolate the raw burden imposed by each policy shock. That is analytically useful for demonstrating the model's core mechanisms, but it also means that the paper does not try to answer how different recycling schemes would alter both the average burden and its distribution. In its current setup, the government budget identity already introduced in the model structure introduces high non-linearities, rendering the solver unstable. This will need further work.

Beyond the next calibration stage, two model extensions appear especially promising. The first concerns the power sector. The current model captures electricity and gas as standard industries, but deep decarbonization questions increasingly require a richer representation of generation technologies and electricity-system dynamics. Currently, the first option consists of linking IO-DASMOD iteratively to an external open-source technology model such as FTT:Power (Mercure, 2012).

The second extension is a recursive-dynamic version of IO-DASMOD. The proposed dynamic architecture is based on the PIRAMID approach for baseline model development (Wojtowicz et al., 2019) and adapting (Temursho et al., 2025) by extending the model as a sequence of benchmark-consistent annual equilibria. In each year, the macroeconomic backbone, household microdata, and bridge system would first be projected; the static model would then be recalibrated to that projected benchmark; and only afterwards would

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the true state variables be updated for the following year. This architecture preserves the core strengths of the current model: transparent bridge matrices, exact benchmark replication, and full household heterogeneity, while allowing the framework to analyze the distributional implications of structural change through time.

Overall, the paper's contribution is methodological rather than predictive. The scenario applications are not intended to deliver a final policy assessment for the Czech Republic. Their purpose is to show that a household-rich, integrated price-quantity input-output framework can distinguish clearly between the average size of a burden, its sectoral origin, its regressivity across the income distribution, and its dispersion within deciles. That is already a substantial advance relative to representative-household approaches and possibly to sequential macro-micro linkages.

The broader implication is that IO-DASMOD should be seen as a transparent diagnostic companion to CGE-based policy assessment rather than as a substitute for it. Its main strength lies in tracing policy-induced cost shocks through a fully articulated bridge from industries to products to heterogeneous households. Its next task is to combine that transparency with more disciplined behavioral calibration, richer sector-specific modules, and a dynamic architecture capable of following distributional adjustment over time. If those steps are taken, the framework can become a useful ex-ante tool for analyzing the distributional consequences of climate policy in the Czech Republic and, more broadly, for extending the family of macro-micro models available for distributional climate-policy analysis in Europe.

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Acknowledgments

This research was supported by the European Union's Horizon 2020 Research and Innovation Staff Exchange program under the Marie Skłodowska-Curie grant agreement No. 870245 (GEOCEP).

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A Appendix

A.1 Purchaser-price to basic-price conversion

Let $i \in \mathcal{P}$ denote products and $h \in \mathcal{H}$ household groups. For each household group h, let PP_{ih} denote consumption expenditure of product i in purchaser prices. The objective is to construct BP_{ih} in basic prices.

Valuation identity. For household final consumption,

$$\mathrm{PP} = \mathrm{BP} + \mathrm{TLS} + \mathrm{TTM}$$

where TLS denotes taxes less subsidies on products and TTM denotes trade and transport margins.

Partition of products. Define $\mathcal{P}^+ = \{i : \mathrm{TTM}_i^{\mathrm{HH}} > 0\}$ (products with embedded margins) and $\mathcal{P}^- = \{i : \mathrm{TTM}_i^{\mathrm{HH}} < 0\}$ (margin-providing products).

Implicit rates and shares. For $i \in \mathcal{P}^+$, the margin rate is $m_i = \mathrm{TTM}_i^{\mathrm{HH}}/\mathrm{BP}_i^{\mathrm{HH}}$. For $i \in \mathcal{P}^-$, the redistribution share is $s_i = \mathrm{TTM}_i^{\mathrm{HH}}/\sum_{k\in\mathcal{P}^+} \mathrm{TTM}_k^{\mathrm{HH}}$ (negative, summing to -1). The tax rate is $t_i = \mathrm{TLS}_i^{\mathrm{HH}}/(\mathrm{PP}_i^{\mathrm{HH}} - \mathrm{TLS}_i^{\mathrm{HH}})$.

Conversion steps.

1. Remove taxes: $\text{TLS}_{ih} = \text{PP}_{ih}\, t_i/(1+t_i)$.
2. Extract positive margins: $\text{TTM}^{+}_{ih} = \text{PP}_{ih}\, m_i/[(1+m_i)(1+t_i)]$ for $i \in \mathcal{P}^{+}$.
3. Reallocate to margin-providing products: $\text{TTM}_{ih} = s_i \cdot M_h$ for $i \in \mathcal{P}^{-}$, where $M_h = \sum_{i\in\mathcal{P}^{+}} \text{TTM}^{+}_{ih}$.
4. Basic prices: $\text{BP}_{ih} = \text{PP}_{ih} - \text{TLS}_{ih} - \text{TTM}_{ih}$.

The resulting converter matrix $\mathbf{C}$ satisfies $\mathbf{BP}_h = \mathbf{C}\,\mathbf{PP}_h$ with elements:

$$C_{ji} = \begin{cases} \frac{1}{(1+m_i)(1+t_i)} & \text{if } j = i,\ i \in \mathcal{P}^{+} \\ \frac{1}{1+t_i} & \text{if } j = i,\ i \notin \mathcal{P}^{+} \\ -s_j \cdot \frac{m_i}{(1+m_i)(1+t_i)} & \text{if } i \in \mathcal{P}^{+},\ j \in \mathcal{P}^{-} \\ 0 & \text{otherwise} \end{cases}$$

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