**CLIMATE CHANGE, PRODUCTION NETWORKS, AND HOUSEHOLD HETEROGENEITY**

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We study how the effects of climate change propagate through global production networks and shape the distribution of household income and wealth. Modern economies are tightly linked through trade in intermediates and cross-border supply chains, yet exposure to physical climate risk and capacity to cushion shocks differ starkly across countries and across households. Most work on climate damages either imposes reduced-form output losses at the aggregate level or works with representative households. We take a different route. Empirically, we construct sectoral exposure to temperature shocks worldwide using geolocated firm-level data and auxiliary sources to recover revenue shares where data are missing. This delivers granular country–sector damage estimates from climate-econometric models. We embed these damages in a heterogeneous-agent input–output model with incomplete markets, rich production networks, and an explicit climate block, and use it to trace how physical and transition shocks are amplified and redistributed through trade and fiscal policy.

The empirical contribution is twofold. First, we build a new dataset that matches firm-level locations to sectors and countries, and combine this with gridded temperature and precipitation data. For firms and sectors without complete coverage, we use auxiliary sources to impute revenue shares and construct country–sector exposure weights. This yields a panel of country–sector temperature and precipitation series aligned with economic activity rather than population. Second, we estimate climate-econometric modules that relate changes in log sectoral revenues and intermediate input use to flexible polynomials in these weather variables, with appropriate fixed effects and differencing to purge trends. The resulting coefficients give us sector- and country-specific damage schedules. Feeding these damages through observed bilateral input–output linkages shows that climate risk is not local: openness, coupled with low substitution elasticities in production and trade, generates sizeable exposure to foreign climate shocks. Even countries with relatively mild local warming are hit via their dependence on climate-vulnerable upstream suppliers and downstream markets.

We then embed these empirically disciplined damages in a multi-country, multi-sector production network model with heterogeneous households. On the production side, each sector in each country uses labour and a CES aggregate of intermediates sourced from all countries. Trade in intermediates forms a weighted, directed network of bilateral input flows. Climate damages enter as sector- and country-specific reductions in effective productivity, derived from the estimated damage schedules. Producers choose input

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bundles, abatement, and trade patterns optimally, taking wages, intermediate prices, and policy instruments as given. This generates a system in which physical climate shocks and transition policies (such as carbon prices or emission standards) are transmitted along supply chains and across borders, with the strength and sign of spillovers determined by network centrality, substitution possibilities, and sectoral composition.

On the household side, we build a standard incomplete-markets environment in each country. Households differ by financial wealth and idiosyncratic labour productivity and hold a single liquid asset, subject to borrowing constraints. Labour income depends on sectoral wages and employment, which in turn reflect how climate damages and policy shocks hit different parts of the production network. Consumption is a CES aggregate over goods from all countries, so trade-induced price changes feed directly into real incomes. The joint distribution of wealth and productivity in each country is governed by Hamilton–Jacobi–Bellman and Kolmogorov–Forward equations, and fiscal policy—taxes, transfers, and public spending—determines how much of the shock is absorbed by the public budget and how much is passed on to households at different points of the wealth and income distribution.

We use this framework to quantify how production networks and heterogeneity jointly shape the incidence of climate shocks. Physical damages and transition shocks, such as tighter carbon policy, both operate through the same network structure: they hit some sectors harder than others, change relative prices, and reallocate demand and income across sectors and countries. We show that network linkages amplify and redistribute these shocks. Sectors that are central in the input–output network and disproportionately important for high-marginal-propensity-to-consume (high-MPC) households generate large distributional effects. When such sectors are adversely affected by climate damages or carbon pricing, the resulting income losses are concentrated on households with high MPCs, which depresses aggregate demand and shifts the wealth distribution leftward. In contrast, when shocks fall on sectors that mainly employ or pay low-MPC households, the same aggregate damage can be absorbed with much smaller effects on the lower tail of the wealth distribution.

A key lesson from the model is that the role of heterogeneity hinges on how fiscal transfers are designed. When MPCs differ across households and public spending or transfers are aligned with network exposure—so that regions and households most exposed to climate risk or carbon policy receive more support—household heterogeneity strongly shapes the dynamics of consumption, saving, and inequality. In that case, the same physical shock can have very different aggregate and distributional consequences depending on how carbon revenues are recycled, how social insurance responds, and how public investment is targeted across the network. By contrast, when MPCs are similar across households or transfers are poorly correlated with exposure, the influence of heterogeneity is muted: aggregate outcomes are close to those in a representative-agent model and the distributional footprint of climate policy is modest.

Our results speak directly to ongoing debates about climate policy design in highly open economies. First, they underscore that climate risk is a network phenomenon: exposure is shaped at least as much by trade patterns and substitution elasticities as by local hazard levels. Second, they highlight that distributional consequences are central to the macro response. Policies that ignore who works where in the network and who holds which assets can inadvertently magnify inequality even when they look efficient in aggregate. Third, they show that well-designed fiscal transfers can address heterogeneity: by targeting high-exposure, high-MPC households and sectors, governments can stabilise both aggregate demand and the wealth distribution. Our heterogeneous-agent input–output-climate framework thus provides a tractable quantitative tool for evaluating climate policies—carbon pricing, green industrial policies, or adaptation investment—through the joint lenses of production networks, international spillovers, and inequality.

We are attaching this extended abstract a slide pack containing further details on our modelling framework. Using our empirical results, the model is now calibrated and we are proceeding to the simulating the effect of climate policy under various recycling options.

# Climate, Production Networks, and Household Heterogeneity

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## Research Question

How does EU carbon pricing propagate through international trade networks, and what are the distributional consequences of a common carbon price?

## Motivation I: Theoretical Gaps

- The macroeconomic effects of carbon pricing are relatively well understood.
- A growing body of work explores the distributional implications of climate policies.
- Limited understanding of how common carbon pricing interacts with international trade when countries differ in major ways (openness, emission intensity, financing conditions...).
- In particular, we know little about how carbon pricing reshapes trade flows and prices and, through that channel, affects heterogeneous households.

$\Rightarrow$ **This project:** Develop a model that integrates heterogeneous households, trade linkages, and carbon pricing to address these gaps.

## Motivation II: Policy Relevance

$\Rightarrow$ **Our framework** provides a basis to address key policy questions:

- How sizable are **competitiveness gains/losses** of a common carbon price **across EU countries** and with respect to the **rest of the world**?
- What is the **optimal** design of **redistribution** policies at the **EU** and **member-state** level?
- How should **non-EU countries respond** to mechanisms such as the Carbon Border Adjustment Mechanism (CBAM)?

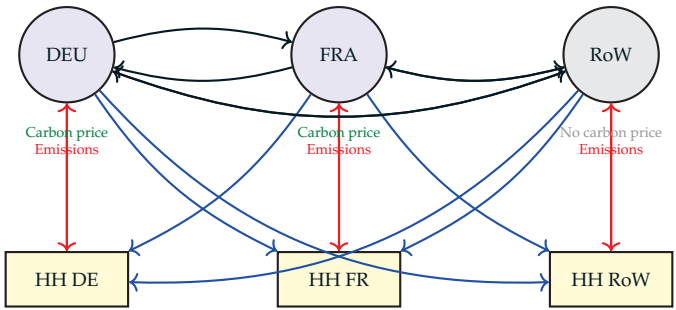
*Beyond carbon pricing, the framework offers a flexible tool to study any policy that jointly affects international trade and income or wealth inequality.*

## Related Literature

- **Input–Output Networks:** Schaab & Tan (2023), Baqaee & Farhi (2024), Poirier & Vermandel (2024).
- **Distributional Effects of Carbon Pricing:** Benmir & Roman (2022), Kanzig (2023).
- **Heterogeneous Agents:** Achdou et al. (2022), Auclert, Rognlie & Straub (2024).
- **Macro–Climate Interactions:** Many foundational contributions from researchers in this room!

# Modelling Framework

# Model Graph




**Legend:**
Red: Labor/capital ↔ wage/return
Blue: Consumption goods flows ($C$)
Black: Intermediate goods flows ($M$)

## HOUSEHOLDS: OVERVIEW

- The economy includes $N$ types of households, each associated with a single employing country $j$.
- In each country, labor supply is inelastic: $\bar{l}_j = 1$.
- Within each country, households are heterogeneous in:
  - Financial wealth $b_{j,t}$
  - Labor productivity $z_{j,t}$
- Households can only hold liquid assets, which are their own country's government bonds.

## Preferences and Consumption

- Households maximize discounted utility:

$$\max_{\{c_t^j\}} \mathbb{E}_0 \int_0^\infty e^{-\rho t} u(c_t^j)\, dt, \quad u(c) = \frac{c^{1-s}}{1-s}$$

- Consumption is a CES aggregator over goods from all countries:

$$c_t^j = \left( \sum_{i=1}^{N} \gamma_{ji}^{1/\sigma_i^c} (c_{i,t}^j)^{\frac{\sigma_j^c - 1}{\sigma_i^c}} \right)^{\frac{\sigma_j^c}{\sigma_j^c - 1}}$$

- Distribution parameters $\gamma_{ji}$ and elasticity of substitution $\sigma_j^c$ are country-specific and estimated jointly.

## Budget Constraint and Income Risk

- Real budget constraint:

$$\dot{b}_{j,t} = r_{j,t}(1 - \bar{\tau}_j)b_{j,t} + w_{j,t}(1 - \tau_j^w)z_{j,t} + f(Tr_{j,t}) - c_t^j$$

- Labor productivity follows a lognormal process:

$$d\ln(z_{j,t}) = -\nu_{z_j} \ln(z_{j,t})\, dt + \sigma_{z_j}\, d\omega_{z_j,t}$$

- Borrowing constraint: $b_{j,t} \geq \underline{b}_j$

## Household Optimization and Distribution

- Household problem yields:
  - Hamilton-Jacobi-Bellman (HJB) equation for value function $v_j(b, z, t)$
  - Kolmogorov Forward (KF) equation for distribution $g_j(b, z, t)$
- These describe:
  - Optimal consumption/savings policy $s_j(b, z, t)$
  - Evolution of the joint distribution of assets and productivity over time
- Income processes, taxes ($\tau^w$, $\tau^r$), and transfers $f(Tr_{j,t})$ are key to shaping inequality.

## Production and Trade Network Structure

- Each country $j$ produces output $Y_{j,t}$ using:
  - Labor $L_{j,t}$
  - A CES composite of intermediate goods from all countries $X_{j,t}$
- Final output technology is Cobb-Douglas:

$$Y_{j,t} = \xi_j Z_{j,t} d(T_{j,t}) L_{j,t}^{\beta_j} X_{j,t}^{1-\beta_j}$$

- $\xi_j$ is a country-specific normalization constant.
- Estimated damage functions are country-specific.

## TRADE IN INTERMEDIATE INPUTS

- Countries are linked through a CES import structure:

$$X_{j,t} = \left( \sum_{i=1}^{N} \gamma_{ji}^{m\,1/\sigma_j} X_{ji,t}^{\frac{\sigma_j - 1}{\sigma_j}} \right)^{\frac{\sigma_j}{\sigma_j - 1}}$$

- $X_{ji,t}$: quantity of inputs from country $i$ used in country $j$
- $\gamma_{ji}^{m}$: trade shares; $\sigma_j$: elasticity of substitution
- This structure defines the **EU-world trade network** as a weighted, directed graph of input flows.

## Emissions and Abatement

- Firms face a carbon tax and choose the abatement level $\mu_{j,t} \in [0, 1]$
- Abatement costs:

$$Z_{j,t} = \theta_{1,j} \mu_{j,t}^{\theta_{2,j}}, \quad \theta_{2,j} > 1$$

- Emissions:

$$E_{j,t} = (1 - \mu_{j,t}) \varphi_j Y_{j,t}$$

- $\varphi_j$ is the country-specific carbon intensity that allows us to match emissions to output ratio in each country.

## Firm Optimization and Factor Demand

- Firms choose $L_{j,t}$, $\{X_{ji,t}\}$, $\mu_{j,t}$ to maximize:

$$\Pi_{j,t} = P_{j,t}Y_{j,t} - w_{j,t}L_{j,t} - \sum_i P_{i,t}X_{ji,t} - Z_{j,t}Y_{j,t} - \tau^E_{j,t}E_{j,t}$$

- First-order conditions yield:

$$\begin{aligned} X_{ji,t} &= \text{Intermediate input demand from country } i \\ w_{j,t} &= \text{Marginal productivity of labor} \\ \mu_{j,t} &= \text{Optimal abatement level given the carbon tax } \tau^E_{j,t} \end{aligned}$$

- Trade elasticities, prices, and abatement jointly determine input sourcing and emissions.

## The Climate Block

- **Cumulative emissions:** Atmospheric carbon stock $M_t$ increases with emissions from all countries: $\dot{M}_t = \sum_{j=1}^{N} E_{j,t}$.
- **Temperature dynamics:** Global temperature $T_t$ responds to cumulative emissions: $\dot{T}_t = \phi_1(\phi_2 M_t - T_t)$.
- **Country-specific temperature:** Local temperatures evolve with: $T_{j,t} = T_j^* + \gamma_j^T T_t$.
- **Damages from climate change:** Output losses are governed by a convex damage function: $d(T_{j,t}) = \exp\left(\sum_{k=0}^{2} b_{j,k} T_{j,t}^k\right)$.

*Our climate dynamics follow Matthews et al. (2009), Allen et al. (2009), and recent improvements in damage calibration (e.g., Miftakhova et al., 2019; Dietz et al., 2021). We also consider an alternative representation as in Folini, Friedl, Kubler and Scheidegger (2024) or Dietz, van der Ploeg, Rezai, Venmans (2021).*

## Government Budget and Market Clearing

**Government Budget Constraint:**

$$\dot{B}^G_{j,t} + G_{j,t} + Tr_{j,t} = \tau^w_j w_{j,t} L_{j,t} + \tau^E_{j,t} E_{j,t} + r_{j,t} B^H_{j,t}$$

**Public Spending Rule:**

$$G_{j,t} = \bar{G}_j Y_{j,t}$$

**Market Clearing Conditions:**

$$\text{Capital Market:} \quad \int_{\underline{b}}^{+\infty} \int_z g_j(b,z,t) b_{j,t} \, \mathrm{d}z \, \mathrm{d}b = B^H_{j,t},$$

$$\text{Goods Market:} \quad Y_{j,t} = \sum_i M_{ij,t} + C_{j,t} + G_{j,t} + Z_{j,t} Y_{j,t}$$

$$\text{Labor Market:} \quad \int_{\underline{b}}^{+\infty} \int_z g_j(b,z,t) \, \mathrm{d}z \, \mathrm{d}b = \bar{L}_j, \ \forall j,t$$

# Estimation Strategy

# Estimation: General Overview

- Our estimation strategy builds on Benmir, Maso, Mori, Roman & Tarsia (2025), which analyzes how temperature shocks propagate through international trade linkages (BMMRT hereafter).
- We combine economic and climate data to estimate the key structural parameters of the model.
- In what follows, we outline the estimation procedures and results for:
  - CES consumption and production parameters,
  - Climate damage functions, and
  - Income process dynamics.

## Economic Data

- The main dataset for the analysis is the World Input–Output Database (WIOD) by Timmer et al. (2015).
- We combine WIOD 2013 and 2016 to cover 20 years of data from 1995 to 2014.
- In BMMRT, we focus on 41 countries (40 + RoW) and 30 sectors, classified according to ISIC Rev. 3 as in Baqaee and Fahri (2024). For this paper, we consider EA19 + RoW and aggregate sectors at the country level.

# Input-Output Tables (I)

- IO tables are matrices that map the flow of goods and services across countries and sectors in a given time interval.
- Each column details the production process for a specific country-sector. The output of a given country-sector equals the sum of goods supplied by all other sectors, the sector's own resources and the value added by labor and capital.
- Consequently, the distribution of the output of country-industries over user categories is indicated in the rows of the table.

# INPUT-OUTPUT TABLES (II)

| | | | Use by country-industries | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Country 1 | | | … | Country M | | |
| | | | Industry 1 | … | Industry N | … | Industry 1 | … | Industry N |
| **Supply from country-industries** | Country 1 | Industry 1 | | | | | | | |
| | | … | | | | | | | |
| | | Industry N | | | | | | | |
| | …… | | | | | | | | |
| | Country M | Industry 1 | | | | | | | |
| | | … | | | | | | | |
| | | Industry N | | | | | | | |
| **Value added by labour and capital** | | | | | | | | | |
| **Gross output** | | | | | | | | | |

Outline of a WIOT (Timmer et al. 2015)

## Socio Economic Account

- In addition to the IO tables, Timmer et al. (2015) provide aggregate country-industry data on employment and capital, along with price and volume indices for gross output, intermediate input and value added.
- We use the price indices to deflate the IO table figures into real values.
- The remaining series are used to estimate the parameters for the nested CES framework.

# Climate Data

- We develop a new methodology to compute country-sector temperature measures.
- We leverage on sectoral economic activity data (proxied by emissions) available at the geographic coordinate level and sourced from Climate TRACE.
- We use economic activity as weights to aggregate local temperature data obtain from Copernicus into country-sector measures.

## Country-Sector Temperature

$$T_{i,t} = \sum_{k=1}^{K} w_{k,t}\, T_{k,t}$$

Where:

- $T_{i,t}$ is the aggregate temperature at time $t$ for country-sector $i$.
- $K$ is the number of coordinates available at time $t$ for country-sector $i$.
- $w_{k,t}$ is the weight for the temperature recorded in coordinate $k$ such that:

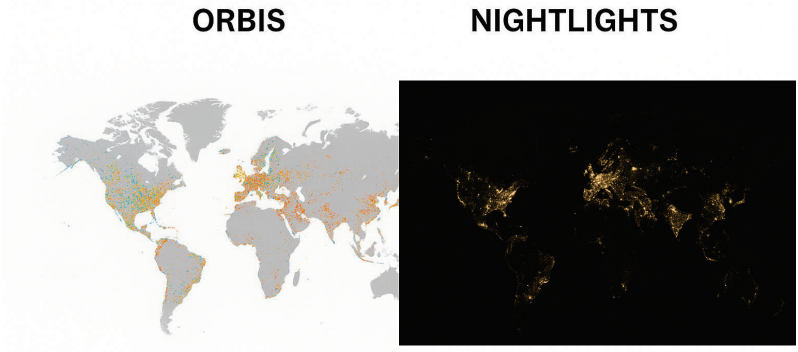
$$w_{k,t} = \frac{\text{Emissions}_{k,t}}{\sum_{k=1}^{K} \text{Emissions}_{k,t}}$$

- $T_{k,t}$ is the temperature recorded at coordinate $k$ at time $t$.

# Climate Trace (I)

- Climate TRACE is a global initiative that tracks GHG emissions using satellite and sensor data.
- The dataset includes emissions data for over 50 subsectors and more than 350 million assets worldwide.
- We convert the subsectors provided by TRACE into the ISIC Rev. 3 classification to match the IO table industries.

# ORBIS Database and Nightlight Dataset




Climate TRACE interface

## Some (Key) Technicalities

- Emission-based weights are available only for 2015–2022. To estimate their values for earlier years, we calculate the average yearly emissions growth for each geographic coordinate available and apply backward interpolation.
- For the sectors that do not have coordinate-level data, we use country-temperature weighted by population from Gortan et al. (2023).
- RoW aggregate temperatures are computed as the GDP-weighted average of each country's population-weighted temperature.

# Climate Damages (Temperature Polynomial)

$$\Delta y_{i,j,t} = \beta_0 + \sum_{\ell \geq 0}^{2} \beta f(\Delta T_{i,j,t-\ell}) + \sum_{\ell \geq 0}^{2} \gamma g(\Delta P_{i,j,t-\ell}) + \delta_i + \psi_{j,t} + \varepsilon_{i,j,t}$$

Where:

- $\Delta y_{i,j,t}$ log input (in FD), for industry $i$ in country of origin $j$
- $f(\Delta T_{i,t})$ flexible polynomial in yearly average temperature (in FD) for industry $i$ in country of origin $j$
- $g(\Delta P_{i,t})$ flexible polynomial in yearly total precipitation (in FD) for industry $i$ in country of origin $j$
- $\delta_i$ industry of origin fixed effect
- $\psi_{j,t}$ country of origin-year fixed effect
- $\varepsilon_{i,j,t}$ idiosyncratic errors clustered at the country of origin level

# Climate Damages - Rationale

- **First Difference:**
  - Rules out nonstationarity (Newell et al., 2021; Klenow et al., 2023)
  - More conservative pure levels effect assumption (Kotz et al., 2024)

- **Polynomial Order:**
  - $f(\cdot)$ and $g(\cdot)$ allowed to vary across each country-industry of destination pair regressions. Optimal order identified through 10-fold Cross Validation

# Climate Damages (Temperature Polynomial)

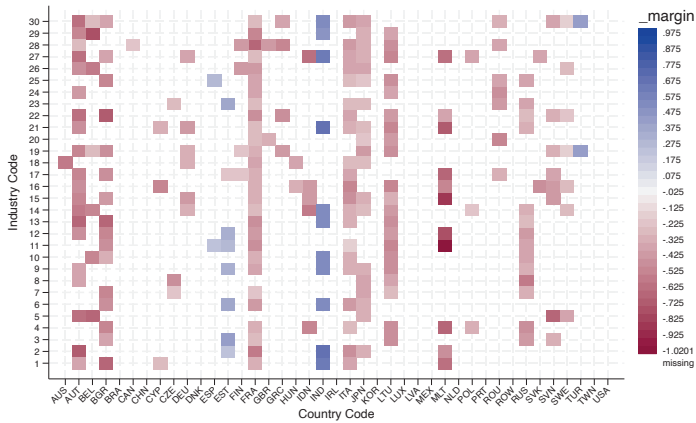



Figure: Cumulative marginal effect of an additional 1°C on intermediate inputs for each destination country-industry pairs.

## CES EstimationMethods

- Allen-Uzawa Elasticities (AES) calculated using cross-price derivatives (Baqaee and Farhi (2024)). Assumes perfect competition. Shares fixed as Cobb-Douglas.
- Cost minimisation method. The coefficient of logs of the ratio of input prices is the elasticity. Shares are derived from the constant.
- Cost minimisation requires exogenous price shifters. Unobserved productivity changes may impact demand for and prices of inputs.
- Instruments: Atalay (2017) - military spending. Jo and Miftakhova (2024) - national price trend. Appropriate instrument unclear here - too global.
- Instead we do Non-Linear Least Squares (NLS)

# CES - NLS METHOD

- Normal EOS bounds: $\sigma \geq 0 \Rightarrow \rho \in (-1, \infty)$ since $\sigma = \frac{1}{1+\rho}$
- To avoid EOS bounds: $\rho = \exp(\lambda) - 1 \Rightarrow \lambda \in (-\infty, \infty)$
- Shares $\theta_j \in [0, 1]$ for some input j and must add to 1. To ensure this without explicitly constrain, we use softmax function:

$$\theta_j = \frac{e^{\mu_j}}{\sum_k e^{\mu_k}}$$

$$\sum_k \theta_k = \frac{\sum_j e^{\mu_j}}{\sum_k e^{\mu_k}} = 1$$

- We estimate $\lambda$ and $\mu_j$ instead of $\rho$ and $\theta_j$:

$$\min_{\lambda,\mu} \text{SSR}_{i,t} = \min_{\lambda,\mu} \sum_{t=1}^{T} (Y_{i,t} - f(\mathbf{X}_{i,t}, \lambda, \mu_1, ..., \mu_k))^2$$

## CES Next Steps

- NLS results are those of association not causality (Papageorgiou et al. (2017))
- A shock series to break the usual connection between demand and unobserved productivity
- Variation in input and output is driven by exogenous shocks
- By simulating a model to match the data arising from these shocks, SMM can filter out the omitted variable bias.

## Income Processes

- We use income data from the World Inequality Database for each country.
- RoW is computed as a weighted average of all non-EA countries in the WID.
- We fit this data on a log-normal distribution that we can directly feed to our model.

# Some Simulation Results

## Steady State Calibration

We calibrate some parameters at the steady state to match the following value:

- Relative size of each country
- Debt-to-GDP ratios
- Labor taxes
- Emission intensity

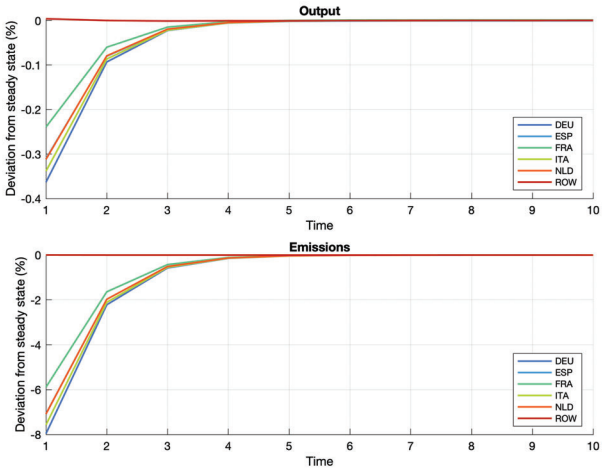
In addition, we solve for the country-specific discount factor $\rho_j$ to match the interest rate in each country.

## Initial Wealth Inequalities

| Country | Gini (Data) | Gini (Model) |
|---|---|---|
| Germany | 0.68 | 0.76 |
| France | 0.59 | 0.65 |
| Italy | 0.57 | 0.60 |
| Spain | 0.57 | 0.63 |
| Netherlands | 0.64 | 0.68 |
| Rest of World | – | 0.66 |

Table: Comparison of Wealth Gini Coefficients: Data vs. Model Estimates. Wealth Gini data are from the UBS Global Wealth Report 2024.

# Response to Carbon Price Shock



## Distributional Impact of Carbon Pricing

We compute the change in the Gini coefficient following a carbon price shock for major EU economies and the Rest of the World. Results highlight heterogeneous distributional effects across countries.

| Country | Change in GINI (pp) |
|---|---|
| Germany | + 0.30 |
| France | - 0.01 |
| Italy | - 0.02 |
| Spain | + 0.04 |
| Netherlands | + 0.10 |
| Rest of World | + 0.04 |

Positive values indicate rising inequality. Units are percentage points (pp).

# Thank You!