The Cost of Going It Alone: Deglobalization's Carbon Consequences via clean Trade and FDI

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Abstract

We study how globalization—and its reversal—shapes global decarbonization through clean trade and clean FDI. Trade diffuses Chinese clean equipment that is low-cost due to high productivity, while expanded market access stimulates production and learning-by-experience that further reduces prices over time, accelerating global clean-energy-generation (CEE) capital accumulation; clean FDI—tilted by policy incentives—directly installs CEE capital in host countries. To quantify these channels, we develop a multi-region, multi-sector dynamic general equilibrium model featuring clean–dirty energy substitution, emissions accounting through roundabout production linkages (input–output), learning-by-experience in clean-equipment manufacturing, and cross-border CEE-capital flows subject to investment frictions and policy wedges. We then calibrate the model to match globalization-era trends in clean-equipment trade, clean FDI, and learning-by-experience, and run counterfactuals that raise trade and investment frictions to reflect recent policy shifts. Main findings TBA...

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1. Introduction

2. Motivating facts

3. Model

3.1. Production

In each country n and date t, sector-j output is a continuum of varieties $\omega \in [0,1]$ produced with Cobb–Douglas technologies in the spirit of Eaton and Kortum (2002). Variety-level efficiency is the product of a sector–country component $A_{n,j,t}$ and an idiosyncratic draw $z_{n,j}(\omega)$ that is independently Fréchet distributed with unit mean. Production in every sector combines a set of sector-specific primary inputs with intermediates sourced from all sectors, with roundabout input–output structure as in Caliendo and Parro (2015).

3.1.1. Sectors

The economy has four production sectors, $\mathcal{K} \equiv \{m, r, e, o\}$. Sector m produces fossil fuels (coal, natural gas, and crude oil) that generate emissions when used. Sector r produces clean-energy equipment that is used intensively in clean investment, and the resulting installed stock of clean-energy-generation capital is a key input in clean-energy production. Sector e produces energy as a composite of clean and dirty energy, with substitution between the two at the lower nest. Sector o produces goods that are not included in the mining, clean-energy equipment, or energy sectors.

Mining ($j = m$). Mining varieties use natural resource deposits $M_{n,m,t}$, labor $L_{n,m,t}$, generic production capital $K^p_{n,m,t}$, and intermediate inputs:

$$Y_{n,m,t}(\omega) = z_{n,m}(\omega)\, A_{n,m,t} \left(M_{n,m,t}(\omega)\right)^{\gamma^M_{n,m}} \left(K^p_{n,m,t}(\omega)\right)^{\gamma^{K^p}_{n,m}} \left(L_{n,m,t}(\omega)\right)^{\gamma^L_{n,m}} \prod_{k\in\mathcal{K}} \left(X_{n,mk,t}(\omega)\right)^{\gamma^X_{n,mk}},$$
$$\gamma^M_{n,m} + \gamma^{K^p}_{n,m} + \gamma^L_{n,m} + \sum_{k\in\mathcal{K}} \gamma^X_{n,mk} = 1. \tag{1}$$

Mining output, like goods from other sectors, is used for both final demand and as intermediate inputs throughout the production network. Its distinctive feature is that, when used as fossil fuels, it generates emissions and serves as a key variable input in dirty-energy production.

Clean-energy equipment (CEE) ($j = r$). CEE varieties use labor $L_{n,r,t}$, generic production capital $K^p_{n,r,t}$, and intermediate inputs:

$$Y_{n,r,t}(\omega) = z_{n,r,t}(\omega)\, A_{n,r,t} \left(K^p_{n,r,t}(\omega)\right)^{\gamma^{K^p}_{n,r}} \left(L_{n,r,t}(\omega)\right)^{\gamma^L_{n,r}} \prod_{k\in\mathcal{K}} \left(X_{n,rk,t}(\omega)\right)^{\gamma^X_{n,rk}}, \qquad (2)$$
$$\gamma^{K^p}_{n,r} + \gamma^L_{n,r} + \sum_{k\in\mathcal{K}} \gamma^X_{n,rk} = 1.$$

CEE output is a core component of clean investment (for example, $I^c_{n,t}$) and thereby accumulates the installed stock of clean-energy-generation capital used in clean-energy production. We interpret sector r as producing the main equipment used to install solar photovoltaic and wind power capacity, as well as related storage systems, such as photovoltaic modules, wind-turbine components, grid-scale batteries, and power-conversion systems.

Energy ($j = e \equiv ce \cup de$). Sector e produces an energy composite that combines clean energy (ce) and dirty energy (de). These two types are imperfect substitutes, and the resulting composite energy can be used either for final demand or as an intermediate input in production across all sectors.

Clean-energy production relies on renewable natural endowments, $R_{n,t}$, such as solar irradiance, wind, as well as the installed stock of clean-energy-generation assets (clean capital) $K^c_{n,t}$ accumulated through past clean investment. In contrast, dirty-energy production relies on generic production capital $K^p_{n,t}$ and uses fossil fuels obtained from the mining sector as intermediate inputs.

For each variety $\omega \in [0, 1]$, the production function follows a Cobb–Douglas specification with Ricardian heterogeneity:

$$Y_{n,de,t}(\omega) = z_{n,de}(\omega)\, A_{n,de,t} \left(K^p_{n,t}(\omega)\right)^{\gamma^{K^p}_{n,de}} \left(L_{n,de,t}(\omega)\right)^{\gamma^L_{n,de}} \prod_{k\in\mathcal{K}} \left(X_{n,de\,k,t}(\omega)\right)^{\gamma^X_{n,de\,k}}, \qquad (3)$$
$$\gamma^{K^p}_{n,de} + \gamma^L_{n,de} + \sum_{k\in\mathcal{K}} \gamma^X_{n,de\,k} = 1,$$

$$(4)$$

$$Y_{n,ce,t}(\omega) = z_{n,ce}(\omega)\, A_{n,ce,t} \left(R_{n,t}(\omega)\right)^{\gamma^R_{n,ce}} \left(K^c_{n,t}(\omega)\right)^{\gamma^{K^c}_{n,ce}} \left(L_{n,ce,t}(\omega)\right)^{\gamma^L_{n,ce}} \prod_{k\in\mathcal{K}} \left(X_{n,ce\,k,t}(\omega)\right)^{\gamma^X_{n,ce\,k}}, \qquad (5)$$
$$\gamma^R_{n,ce} + \gamma^{K^c}_{n,ce} + \gamma^L_{n,ce} + \sum_{k\in\mathcal{K}} \gamma^X_{n,ce\,k} = 1.$$

The sector-e composite is then formed by aggregating the sector-ce (clean energy) and sector-de (dirty energy) composites through a CES function:

$$Q^{e}_{n,t} = \left[\phi^{e} \big(Q_{n,ce,t}\big)^{\frac{\sigma^{e}-1}{\sigma^{e}}} + (1-\phi^{e}) \big(Q_{n,de,t}\big)^{\frac{\sigma^{e}-1}{\sigma^{e}}} \right]^{\frac{\sigma^{e}}{\sigma^{e}-1}}, \qquad \phi^{e} \in (0,1). \tag{6}$$

In the model, we interpret ce as the main clean-energy technologies—such as solar and wind generation—that are central to driving decarbonization during the study period. These technologies are supported by installed clean-energy facilities, which represent the primary margin of decarbonization in the model. [1]

Other sectors ($j = o$). Sector o produces goods from all sectors not classified under the mining, clean-energy equipment, or energy categories. Production in this sector relies on a diverse mix of inputs, including capital (K^{p}), labor (L), energy (E), and intermediate inputs sourced from all sectors.For each variety $\omega \in [0,1]$, the production process follows:

$$\begin{gathered} Y_{n,o,t}(\omega) = z_{n,o,t}(\omega)\, A_{n,o,t} \left(K^{p}_{n,o,t}(\omega)\right)^{\gamma^{K^p}_{n,o}} \left(L_{n,o,t}(\omega)\right)^{\gamma^{L}_{n,o}} \left(E_{n,t}(\omega)\right)^{\gamma^{E}_{n,o}} \prod_{k\in\{m,r,e,o\}} \left(X_{n,ok,t}(\omega)\right)^{\gamma^{X}_{n,ok}}, \\ \gamma^{K^p}_{n,o} + \gamma^{L}_{n,o} + \gamma^{E}_{n,o} + \sum_{k\in\{m,r,e,o\}} \gamma^{X}_{n,ok} = 1. \end{gathered} \tag{7}$$

3.1.2. Productivity terms and learning by doing

Sector-country productivity $A_{n,j,t}$ captures time-varying, sector-specific productivity and enters multiplicatively with $z_{n,j,t}(\omega)$ to determine effective productivity for each variety. For most sectors, we set $A_{n,j,t} = \bar{A}_{n,j,t}$, which is exogenous over time. However, for the clean-energy equipment sector r, we incorporate learning by doing, allowing sectoral productivity to depend on past output:

$$A_{n,r,t} = \bar{A}_{n,r,t} \cdot E^{lbd}_{n,r,t}, \tag{8}$$

where $E^{lbd}_{n,r,t}$ represents experience-driven efficiency improvements.

Experience depends on past clean-energy equipment production, with the learning process governed by the following equation:

$$E^{lbd}_{n,r,t} = \Gamma_{n} \left(\sum_{i=1}^{\infty} \delta_{E}^{i-1} Y_{n,r,t-i} \right)^{\rho}, \qquad \Gamma_{n} > 0, \quad \rho \geq 0, \quad \delta_{E} \in (0,1). \tag{9}$$

1. While hydropower also qualifies as a clean energy source, it is not included within ce in our model. Instead, we treat it in the other-goods sector, reflecting its secondary role in the decarbonization process, as wind and solar energy are the dominant sources of decarbonization during the timeframe considered in our experiments.

Here, δ_E is the experience depreciation factor, ρ is the learning elasticity, and Γ_n is a scale parameter normalized so that $E^{lbd}_{n,r,t_0} = 1$ in the base year t_0.

This learning-by-doing mechanism reflects the accumulation of knowledge and efficiency gains in the clean-energy equipment sector as it produces more over time.

3.1.3. Sectoral composite intermediate good

Sectoral output in country n aggregates a continuum of tradable varieties $q_{n,j,t}(\omega)$, $\omega \in [0,1]$, using a CES aggregator:

$$Q_{n,j,t} = \left[\int_0^1 \left(q_{n,j,t}(\omega) \right)^{\frac{\sigma-1}{\sigma}} d\omega \right]^{\frac{\sigma}{\sigma-1}}, \tag{10}$$

where $\sigma > 1$ is the elasticity of substitution across varieties.

Sectoral goods usage The composite good is allocated to final consumption, investment, and intermediate use as:

$$Q_{n,j,t} = C_{n,j,t} + \sum_{\tau \in \{c,p\}} I^{\tau}_{n,j,t} + \sum_{k \in \mathcal{K}} \int_0^1 X_{n,jk,t}(\omega)\, d\omega. \tag{11}$$

Here, $P_{n,j,t}$ denotes the price index for sector-j goods, and total expenditure in country n is:

$$Z_{n,j,t} \equiv P_{n,j,t} \cdot Q_{n,j,t}. \tag{12}$$

Consumption and investment bundle Total final demand consists of aggregate consumption $C_{n,t}$ and investment bundles for both clean and generic production capital, $\{I^c_{n,t}, I^p_{n,t}\}$, which feed into the laws of motion for clean capital and generic production capital. Consumption is a Cobb–Douglas composite over sectoral goods:

$$C_{n,t} = \prod_{j \in \{m,r,e,o\}} \left(C_{n,j,t} \right)^{\beta^C_{n,j}}, \qquad \sum_{j \in \{m,r,e,o\}} \beta^C_{n,j} = 1, \tag{13}$$

where $C_{n,j,t}$ represents consumption of sector-j goods.[2]

Investment bundles $I^{\tau}_{n,t}$, for $\tau \in \{c,p\}$, are also defined as CES composites of clean and

2. Energy consumption follows a CES composite of clean and dirty energy:

$$C_{n,e,t} = \left[\phi^e \left(C_{n,ce,t} \right)^{\frac{\sigma^e-1}{\sigma^e}} + (1-\phi^e)\left(C_{n,de,t} \right)^{\frac{\sigma^e-1}{\sigma^e}} \right]^{\frac{\sigma^e}{\sigma^e-1}}, \text{with } P_{n,e,t} = \left[\phi^e \left(P_{n,ce,t} \right)^{1-\sigma^e} + (1-\phi^e)\left(P_{n,de,t} \right)^{1-\sigma^e} \right]^{\frac{1}{1-\sigma^e}}.$$

.

dirty energy inputs:

$$I^{\tau}_{n,t} = \prod_{j\in\{m,r,e,o\}} \left(I^{\tau}_{n,j,t}\right)^{\beta^{I,\tau}_{n,j}}, \qquad \sum_{j\in\{m,r,e,o\}} \beta^{I,\tau}_{n,j} = 1.$$

Here, $\beta^{C}_{n,j}$ and $\beta^{I,\tau}_{n,j}$ represent expenditure shares on sector-j goods in consumption and investment, respectively.

The price indices for aggregate consumption and investment are thus given by:

$$P^{C}_{n,t} = \prod_{j\in\{m,r,e,o\}} \left(\frac{P_{n,j,t}}{\beta^{C}_{n,j}}\right)^{\beta^{C}_{n,j}}, P^{I,\tau}_{n,t} = \prod_{j\in\{m,r,e,o\}} \left(\frac{P_{n,j,t}}{\beta^{I,\tau}_{n,j}}\right)^{\beta^{I,\tau}_{n,j}}, \quad \tau \in \{c,p\}. \tag{14}$$

3.2. Trade

Following Eaton and Kortum (2002), trade is subject to iceberg trade costs. One unit of a tradable variety $\omega \in [0,1]$ in sector j, shipped from export country i to import country n at time t, requires $\kappa_{ni,j,t} \geq 1$ units at origin, with $\kappa_{nn,j,t} = 1$. Therefore, the delivered price satisfies:

$$p_{ni,j,t}(\omega) = p_{i,j,t}(\omega)\,\kappa_{ni,j,t}.$$

3.2.1. Unit cost

Sectors $j \in \{m, r, ce, de, o\}$ may use different subsets of inputs. For simplicity, we define a unified "full" unit-cost function that accommodates all potential inputs.][3]

Thus, the unit cost of producing a bundle of inputs in sector j and country n is:

$$c_{n,j,t} = B_{n,j}\left(V^{M}_{n,t}\right)^{\gamma^{M}_{n,j}}\left(V^{R}_{n,t}\right)^{\gamma^{R}_{n,j}}\left(V^{p}_{n,t}\right)^{\gamma^{K^p}_{n,j}}\left(V^{c}_{n,t}\right)^{\gamma^{K^c}_{n,j}}\left(w_{n,t}\right)^{\gamma^{L}_{n,j}} \prod_{k\in\{m,r,e,o\}}\left(P_{n,k,t}\right)^{\gamma^{X}_{n,jk}}, \quad \forall j \in \{m,r,ce,de,o\}, \tag{15}$$

where the cost shares satisfy:

$$\gamma^{M}_{n,j} + \gamma^{R}_{n,j} + \gamma^{K^p}_{n,j} + \gamma^{K^c}_{n,j} + \gamma^{L}_{n,j} + \sum_{k\in\{m,r,e,o\}} \gamma^{X}_{n,jk} = 1.$$

The constant $B_{n,j}$ is:

$$B_{n,j} = \left(\gamma^{M}_{n,j}\right)^{-\gamma^{M}_{n,j}}\left(\gamma^{R}_{n,j}\right)^{-\gamma^{R}_{n,j}}\left(\gamma^{K^p}_{n,j}\right)^{-\gamma^{K^p}_{n,j}}\left(\gamma^{K^c}_{n,j}\right)^{-\gamma^{K^c}_{n,j}}\left(\gamma^{L}_{n,j}\right)^{-\gamma^{L}_{n,j}} \prod_{k\in\{m,r,e,o\}}\left(\gamma^{X}_{n,jk}\right)^{-\gamma^{X}_{n,jk}}. \tag{16}$$

3. For inputs not used in a given sector, we set the corresponding cost share to zero, i.e., $\gamma^{\cdot}_{n,j} = 0$ (and $\gamma^{X}_{n,jk} = 0$ for the relevant intermediate input).

Here, $P_{n,k,t}$ denotes the composite price index of sector-k goods faced by producers in country n, $w_{n,t}$ is the wage, and $V^p_{n,t}$ and $V^c_{n,t}$ are the rental rates of generic production capital K^p and clean capital K^c, respectively. For mining, $V^M_{n,t}$ represents the shadow rental price of the natural-resource input, and for renewables, $V^R_{n,t}$ denotes the shadow price of renewable natural endowments.

3.2.2. Trade share

Let $p_{ni,j,t}(\omega)$ denote the delivered unit price in country n for variety $\omega \in [0,1]$ produced in country i and sector j at time t. Firms in country n choose the lowest-cost supplier for each variety, so the probability that country i is the lowest-cost supplier to n for a randomly drawn variety in sector j is given by:

$$\Pr\left\{p_{ni,j,t}(\omega) = \min_m p_{nm,j,t}(\omega)\right\}. \tag{17}$$

By the law of large numbers, this probability coincides with the expenditure share, and one can derive that:

$$\pi_{ni,j,t} = \frac{\left(A_{i,j,t}\right)^{\theta_j}\left(\kappa_{ni,j,t}c_{i,j,t}\right)^{-\theta_j}}{\sum_{m=1}^{N}\left(A_{m,j,t}\right)^{\theta_j}\left(\kappa_{nm,j,t}c_{m,j,t}\right)^{-\theta_j}}. \tag{18}$$

Alternatively, define $Z_{ni,j,t}$ as country n's expenditure on sector-j goods from country i, so $Z_{n,j,t} = \sum Z_{ni,j,t}$ is total sector-j expenditure in country n, In each country n at time t, the representative household chooses sequences of consumption $\{C_{n,t}\}_{t\geq 0}$ and investment in each capital type $\{I^c_{n,t}, I^p_{n,t}\}_{t\geq 0}$ to maximize

$$\sum_{t=1}^{\infty} \beta^{t-1}\,\psi_{n,t}L_{n,t}\,\ln\left(\frac{C_{n,t}}{L_{n,t}}\right), \tag{19}$$

subject to the budget constraint

$$\begin{aligned} P^C_{n,t}\,C_{n,t} \;+\; \sum_{\tau\in\{c,p\}}(1-\omega^\tau_{n,t})\,P^{I,\tau}_{n,t}\,I^\tau_{n,t} \;=\; &\sum_{\tau\in\{c,p\}} V^\tau_{n,t}\,K^\tau_{n,t} \;+\; w_{n,t}\,L_{n,t} \;+\; V^R_{n,t}\,R_{n,t} \\ &+\; V^M_{n,t}\,M_{n,t} \;+\; T^c_{n,t} \;+\; T^D_{n,t}. \end{aligned} \tag{20}$$

where $\beta \in (0,1)$ is the subjective discount factor and $\psi_{n,t} > 0$ is a discount-factor shock that captures external forces affecting saving dynamics. Labor is supplied inelastically. The household owns the domestic stocks of clean capital $K^c_{n,t}$ and generic production capital $K^p_{n,t}$, and it holds the property rights to natural-resource deposits $M_{n,t}$ and renewable natural endowments $R_{n,t}$. We model trade imbalances as transfers between economies, following Caliendo, Parro, Rossi-Hansberg, and Sarte (2018). A fixed share of GDP, $\phi_{n,t}$, is allocated to a global portfolio, which distributes per-capita lump-sum transfers to each country.[4] The net transfer (trade deficit) is given by

$$T_{n,t}^{D} = -\phi_{n,t} IN_{n,t} + L_{n,t} \frac{\sum_n IN_{n,t}}{\sum_n L_{n,t}}, \tag{21}$$

with $IN_{n,t} \equiv \sum_{\tau \in \{c,p\}} V_{n,t}^{\tau} K_{n,t}^{\tau} + w_{n,t} L_{n,t} + V_{n,t}^{R} R_{n,t} + V_{n,t}^{M} M_{n,t}$. Net transfers are distributed equally across households within each economy.

Investment wedge The wedge $\omega_{n,t}^{\tau}$ reflects the government's tilt toward (or away from) investment in capital type τ by altering the effective purchase cost of investment in period t. Specifically, the government may offer a subsidy for clean capital, represented by a non-zero wedge $\omega_{n,t}^{c}$, while we normalize the generic capital wedge to zero, i.e., $\omega_{n,t}^{p} \equiv 0$. Thus, the total subsidy provided by the government is captured by $T_{n,t}^{c} \equiv -\omega_{n,t}^{c} P_{n,t}^{I,c} I_{n,t}^{c}$, which is financed by lump-sum taxes levied on households. This wedge captures the government's policy stance on promoting clean capital investment, which influences the relative attractiveness of investing in different types of capital.

3.2.3. Capital accumulations and Euler equation

Investment $\{I_{n,t}^{c}, I_{n,t}^{p}\}$ augments the corresponding stocks subject to type-specific depreciation and installation efficiency.

Capital accumulation Type–τ capital evolves according to

$$K_{n,t+1}^{\tau} = (1-\delta^{\tau}) K_{n,t}^{\tau} + \chi_{n,t}^{\tau} I_{n,t}^{\tau}, \qquad \tau \in \{c, p\}, \tag{22}$$

where $\delta^{\tau} \in (0,1]$ is the depreciation rate and $\chi_{n,t}^{\tau} \in (0,1)$ is an installation-efficiency term. A higher $\chi_{n,t}^{\tau}$ implies lower installation frictions, so a given unit of investment yields more installed capital.

Combining (20) and (22) yields an equivalent formulation in terms of next-period capital:

$$\begin{aligned} P_{n,t}^{C} C_{n,t} + \sum_{\tau \in \{c,p\}} (1-\omega_{n,t}^{\tau}) \frac{P_{n,t}^{I,\tau}}{\chi_{n,t}^{\tau}} K_{n,t+1}^{\tau} = \sum_{\tau \in \{c,p\}} \left[(1-\omega_{n,t}^{\tau}) \frac{P_{n,t}^{I,\tau}}{\chi_{n,t}^{\tau}} (1-\delta^{\tau}) + V_{n,t}^{\tau} \right] K_{n,t}^{\tau} \\ + w_{n,t} L_{n,t} + V_{n,t}^{R} R_{n,t} + V_{n,t}^{M} M_{n,t} + T_{n,t}^{c} + T_{n,t}^{D}. \end{aligned} \tag{23}$$

4. The share of GDP sent to the global portfolio is exogenous, while the proceeds are endogenous to clear the global market.

Euler equation The Euler condition for type–$\tau \in \{c, p\}$ investment is thus

$$\frac{C_{n,t+1}/L_{n,t+1}}{C_{n,t}/L_{n,t}} = \beta \cdot \frac{\psi_{n,t+1}}{\psi_{n,t}} \cdot R^{\tau}_{n,t+1}, \tag{24}$$

where

$$R^{\tau}_{n,t+1} \equiv \left(\frac{\left((1-\omega^{\tau}_{n,t+1}) \, P^{I,\tau}_{n,t+1}/\chi^{\tau}_{n,t+1} \right)/P^{C}_{n,t+1}}{\left((1-\omega^{\tau}_{n,t}) \, P^{I,\tau}_{n,t}/\chi^{\tau}_{n,t} \right)/P^{C}_{n,t}} \right) \cdot \left((1-\delta^{\tau}) + \frac{V^{\tau}_{n,t+1}}{(1-\omega^{\tau}_{n,t+1}) \, P^{I,\tau}_{n,t+1}/\chi^{\tau}_{n,t+1}} \right) \tag{25}$$

is defined as the wedge-adjusted gross return on period-t type-τ wealth.

This condition implies that both capital types deliver the same risk-adjusted return, which is also known as the no-arbitrage condition:

$$R^{c}_{n,t+1} = R^{p}_{n,t+1} \qquad \text{if } K^{c}_{n,t+1} > 0 \text{ and } K^{p}_{n,t+1} > 0. \tag{26}$$

A higher ω^{τ} reduces the effective unit cost of installing type-τ capital, which increases the effective marginal return to investing in that capital, thereby strengthening investment incentives. Investment continues until the returns from both types of capital converge, making the two types of investment indifferent.

3.3. Capital Allocation

At the beginning of period t, investment returns are realized and depreciation occurs. The representative agent then chooses (i) the consumption–saving decision, as discussed in the previous section, and (ii) the allocation of wealth across producer countries, subject to bilateral capital-market frictions and idiosyncratic return shocks.

3.3.1. Returns Maximization

The investor in country n allocates type-τ capital (or wealth) across producer countries to maximize returns, taking into account idiosyncratic efficiency shocks and bilateral frictions . Following Kleinman, Liu, Redding, and Yogo (2023), the realized return from investing one unit of wealth in producer i is:

$$\frac{e^{\tau}_{ni,t}(q) r^{\tau}_{i,t}}{\nu^{\tau}_{ni,t}},$$

where $r^{\tau}_{i,t}$ represents the rental rate per efficiency unit of type-τ capital.

The idiosyncratic efficiency shocks, $e^{\tau}_{ni,t}(q)$, follow a Fréchet distribution:

$$\Pr\left(\vec{e}^{\tau}(q) \leq \vec{e}^{\tau}\right) = \exp\left\{-\sum_{i\in\mathcal{N}}\left(\frac{e_i^{\tau}}{E_i^{\tau}}\Gamma(1-\varepsilon^{-1})\right)^{-\varepsilon}\right\},$$

where E_i^{τ} represents the capital-use efficiency in producer i. These shocks influence the average return on type-τ capital, and the dispersion parameter ε governs the sensitivity of portfolio shares to differences in returns across opportunities. These efficiency shocks are tied to factors like producer-country institutions and technological characteristics specific to each capital type.

Bilateral capital-market frictions, denoted by $\nu_{ni,t}^{\tau}$, distort returns based on the investor-producer pair and capital type. For domestic investments ($n = i$), we normalize $\nu_{nn,t}^{\tau} = 1$. For foreign investments ($n \neq i$), $\nu_{ni,t}^{\tau} > 1$. These frictions account for additional costs of foreign portfolio and direct investment, including trading, information asymmetries, and policy-related barriers.

Capital share The investor allocates wealth to the destination that delivers the highest return:

$$\frac{e_{ni,t}^{\tau}(q) r_{i,t}^{\tau}}{\nu_{ni,t}^{\tau}} = \max_{h\in\mathcal{N}}\left\{\frac{e_{nh,t}^{\tau}(q) r_{h,t}^{\tau}}{\nu_{nh,t}^{\tau}}\right\}.$$

The probability that investor n allocates a unit of type-τ wealth to producer i at time t is given by the portfolio share:

$$\lambda_{ni,t}^{\tau} = \frac{K_{ni,t}^{\tau}}{K_{n,t}^{\tau}} = \frac{\left(E_{i,t}^{\tau} r_{i,t}^{\tau}/\nu_{ni,t}^{\tau}\right)^{\varepsilon}}{\sum_{h=1}^{N}\left(E_{h,t}^{\tau} r_{h,t}^{\tau}/\nu_{nh,t}^{\tau}\right)^{\varepsilon}}.$$

3.3.2. Expected returns and efficiency units

Define the expected return per unit of type–τ wealth invested by investor n in producer i as $V_{ni,t}^{\tau}$, thus

$$V_{ni,t}^{\tau} = \mathbb{E}\left[\frac{e_{ni,t}^{\tau}(q)\, r_{i,t}^{\tau}}{\nu_{ni,t}^{\tau}}\right] = \mathbb{E}\left[\max_{h\in\mathcal{N}}\left\{\frac{e_{nh,t}^{\tau}(q)\, r_{h,t}^{\tau}}{\nu_{nh,t}^{\tau}}\right\}\right]. \tag{27}$$

One can derive

$$V_{ni,t}^{\tau} = \left(\sum_{h=1}^{N}\left(\frac{E_{h,t}^{\tau}\, r_{h,t}^{\tau}}{\nu_{nh,t}^{\tau}}\right)^{\varepsilon}\right)^{\frac{1}{\varepsilon}}. \tag{28}$$

A key implication of the Fréchet structure is that, within each capital type τ, all producer countries deliver the same mean capital income rate to a given investor n. As a result, the mean return can be written as $V_{n,t}^{\tau} \equiv V_{ni,t}^{\tau}$. One can also delivers the mean efficiency units of type–τ capital supplied by investor n to producer i as

$$\overline{e}^{\tau}_{ni,t} = E^{\tau}_{i,t} \left(\lambda^{\tau}_{ni,t}\right)^{-1/\varepsilon}. \tag{29}$$

Thus, the capital income flowing from investor n to producer i can be expressed as:

$$V^{\tau}_{n,t}\, K^{\tau}_{ni,t} = r^{\tau}_{i,t}\, \frac{\overline{e}^{\tau}_{ni,t}}{\nu_{ni,t}}\, K^{\tau}_{ni,t}.$$

We define $\mathcal{K}^{\tau,\text{eff}}_{ni,t} \equiv \dfrac{\overline{e}^{\tau}_{ni,t}}{\nu_{ni,t}}\, K^{\tau}_{ni,t}$ as the efficiency-adjusted capital allocated by investor n in country i. Aggregating across all investors, the total efficiency-adjusted capital of type-τ available to producer i is:

$$\mathcal{K}^{\tau,\text{eff}}_{i,t} = \sum_{n=1}^{N} \frac{\overline{e}^{\tau}_{ni,t}}{\nu_{ni,t}}\, K^{\tau}_{ni,t}. \tag{30}$$

Finally, market clearing for type–τ capital used by producer i therefore requires that total payments to capital from the production side equal total capital income received by all investors:

$$r^{\tau}_{i,t}\, \mathcal{K}^{\tau,\text{eff}}_{i,t} = \sum_{n=1}^{N} V^{\tau}_{n,t}\, K^{\tau}_{ni,t} = \sum_{n=1}^{N} V^{\tau}_{n,t}\, \lambda^{\tau}_{ni,t}\, K^{\tau}_{n,t}, \qquad \tau \in \{c, p\}. \tag{31}$$

3.4. Market equilibrium

Sectoral output Sectoral output in country n is the sum of deliveries to all destination markets:

$$Y_{n,j,t} = \sum_{i=1}^{N} Z_{in,j,t}, \qquad j \in \{m, r, ce, de, o\}. \tag{32}$$

where $Z_{in,j,t}$ denotes expenditure by country i on sector-j goods produced in country n.

Goods market clearing Total output must equal total absorption, which consists of final consumption, investment, and intermediate input use:

$$Q_{n,j,t} = C_{n,j,t} + \sum_{\tau\in\{c,p\}} I^{\tau}_{n,j,t} + \sum_{k\in\{m,r,ce,de,o\}} \int_0^1 X_{n,jk,t}(\omega)\, d\omega. \tag{33}$$

Factor supply Aggregate factor supplies equal total factor demands summed across all sectors and varieties:

$$
\begin{aligned}
L_{n,t} &= \sum_{j\in\{m,r,ce,de,o\}} \int_0^1 L_{n,j,t}(\omega)\, d\omega, \quad M_{n,t} = \sum_{j\in\{m,r,ce,de,o\}} \int_0^1 M_{n,j,t}(\omega)\, d\omega, \\
R_{n,t} &= \sum_{j\in\{m,r,ce,de,o\}} \int_0^1 R_{n,j,t}(\omega)\, d\omega, \quad \mathcal{K}^{\tau,\mathrm{eff}}_{n,t} = \sum_{j\in\{m,r,ce,de,o\}} \int_0^1 \mathcal{K}^{\tau,\mathrm{eff}}_{n,j,t}(\omega)\, d\omega, \quad \tau \in \{c,p\}.
\end{aligned} \tag{34}
$$

Factor demand Factor payments exhaust sectoral output. Aggregate payments to each factor equal the sum of sectoral factor shares times sectoral output:

$$
\begin{aligned}
L_{n,t} &= w_{n,t}^{-1} \sum_{j\in\{m,r,ce,de,o\}} \gamma^L_{n,j}\, Y_{n,j,t}, \qquad M_{n,t} = V^{M\,-1}_{n,t} \sum_{j\in\{m,r,ce,de,o\}} \gamma^M_{n,j}\, Y_{n,j,t}, \\
R_{n,t} &= V^{R\,-1}_{n,t} \sum_{j\in\{m,r,ce,de,o\}} \gamma^R_{n,j}\, Y_{n,j,t}, \quad \mathcal{K}^{\tau,\mathrm{eff}}_{n,t} = r^{\tau\;-1}_{n,t} \sum_{j\in\{m,r,ce,de,o\}} \gamma^{K^\tau}_{n,j}\, Y_{n,j,t}, \quad \tau \in \{c,p\}.
\end{aligned} \tag{35}
$$

Sectoral Expenditure Total expenditure by country n on sector j combines final consumption, investment, and intermediate input demand:

$$
Z_{n,j,t} = \beta^C_{n,j}\, P^C_{n,t} C_{n,t} + \sum_{\tau\in\{c,p\}} \beta^{I,\tau}_{n,j}\, P^\tau_{n,t} I^\tau_{n,t} + \sum_{k\in\{m,r,ce,de,o\}} \gamma^X_{n,jk} \left(\sum_{i=1}^N Z_{in,k,t} \right). \tag{36}
$$

Trade balance The trade balance (or deficit) of country n is the difference between total imports (adjusted for the portion of imports whose value belongs to domestic owners) and total exports (adjusted for the portion of exports whose value belongs to foreign owners) across all sectors. This is expressed as:

$$
\sum_{j\in\{m,r,ce,de,o\}} \sum_{i=1}^N (Z_{ni,j,t} - Z_{in,j,t}) = \sum_{\tau\in\{c,p\}} V^\tau_{n,t} K^\tau_{n,t} - \sum_{\tau\in\{c,p\}} r^\tau_{n,t} K^{\mathrm{eff},\tau}_{n,t} + T^D_{n,t}. \tag{37}
$$

Equilibrium definition The model is characterized by time-invariant parameters governing preferences, technologies, substitution elasticities, capital depreciation, experience accumulation, and destination-specific capital allocation; by time-varying exogenous processes for sectoral productivities and trade costs; and by policy wedges, installation efficiencies, factor endowments, transfer rules, and initial capital stocks $\{K^c_{n,0}, K^p_{n,0}\}$.

We define a competitive equilibrium below, with the associated conditions summarized in Table A.2. A sequential equilibrium consists of sequences of allocations

$$
\{C_{n,t}, I^c_{n,t}, I^p_{n,t}, K^c_{n,t+1}, K^p_{n,t+1}, \pi_{ni,j,t}, \lambda^\tau_{ni,t}\}
$$

and sequences of prices

$$\{P_{n,t}^{C}, P_{n,t}^{I,c}, P_{n,t}^{I,p}, P_{n,j,t}, w_{n,t}, V_{n,t}^{c}, V_{n,t}^{p}, V_{n,t}^{M}, V_{n,t}^{R}\},$$

such that (i) the representative household optimizes given prices, wedges, transfers, and capital laws of motion; (ii) firms minimize costs and price competitively under constant-returns technologies and iceberg trade costs; and (iii) all goods, factor, and capital-service markets clear.

3.5. Discussion

This section uses numerical experiments to illustrate the model's core mechanisms and to discipline the interpretation of the quantitative counterfactuals that follow. The experiments are conducted in a symmetric two-country environment and summarized in Table 1. In all cases, we use world GDP as the numeraire and normalize it to 100. The key methodological choice is to work with a static (exogenous-investment-rate) version of the model to make channels transparent. Concretely, We hold predetermined capital stocks fixed when studying shocks to trade costs, cross-border capital-market frictions, and other exogenous wedges; otherwise, in a full steady-state comparison, those shocks would also shift the endogenous long-run capital stock and the saving (investment) rate, obscuring the partial-equilibrium logic. Importantly, fixing the *investment rate in value terms* does not fix the *quantity* of investment: whenever investment prices move, the same nominal investment share translates into different real quantities of investment goods and, hence, different next-period capital stocks. This is precisely why the static experiments are informative for the dynamic model: the dynamic economy can be viewed as a sequence of within-period equilibria linked by capital accumulation and experience accumulation. Today's investment quantities determine tomorrow's installed capital stocks, while learning-by-doing operates through past CEE production—higher CEE output builds experience and raises future CEE productivity.

Energy block and emissions. The production side features four sectors: fossil fuels, clean-energy equipment (CEE), energy, and an other-goods sector. Energy is non-tradable and is produced as a CES aggregate of clean and dirty energy, with an elasticity of substitution set to 3.08 following Jo (2025). Dirty energy uses fossil fuels as a key intermediate input. Fossil-fuel use generates emissions. We normalize the emissions factor so that one unit of fossil-fuel use produces one unit of emissions. CEE output does not directly generate clean energy; instead, it is an essential component of clean investment, which accumulates the stock of clean-energy-generation capital that enters clean-energy production. Throughout the experiments, we track (i) real income per capita, (ii) total emissions, (iii) emissions intensity (emissions per unit of real income), (iv) the clean-energy expenditure share, and (v) real quantities of CEE output and investment in each capital type, which govern next-period clean-capital accumulation and future learning.

TABLE 1
NUMERICAL EXPERIMENTS

	Baseline	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11
Fixed variables											
A. Capital market firctions											
Type I : generic	5	5	5	5	5	**1**	**1**	5	5	5	5
Type II : clean	5	**1**	5	5	5	5	**1**	5	5	5	5
B. Productivity parameter											
CEE sector	1	1	1	**5**	1	1	1	1	1	1	1
All other sector	1	1	1	1	1	1	1	1	1	1	1
C. Trade Cost											
CEE sector	5	5	5	5	5	5	5	**1**	**1**	5	5
All other sector	5	5	5	5	5	5	5	**1**	5	**1**	5
D. Capital Supply											
Type I : generic	10	10	10	10	**50**	10	10	10	10	10	10
Type II : clean	10	10	**50**	10	10	10	10	10	10	10	10
E. Investment rate											
Type I : generic	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Type II : clean	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	**0.5**
Endogenous variables											
Clean energy expenditure share	0.76	0.78	0.92	0.76	0.58	0.74	0.76	0.74	0.76	0.74	0.74
Emission quantity	3.45	3.39	2.97	3.45	6.22	3.68	3.62	4.15	3.45	4.15	3.29
Real income per capita	0.33	0.34	0.45	0.33	0.64	0.35	0.36	0.41	0.33	0.41	0.33
Emission / Real inc.p.c.	10.46	9.98	6.58	10.46	9.67	10.41	9.94	10.17	10.46	10.17	9.95
CEE quantity	1.29	1.33	1.79	6.75	2.58	1.39	1.43	1.60	1.54	1.34	2.15
Investment I quantity	0.99	1.02	1.35	0.99	1.93	1.06	1.09	1.23	0.99	1.23	0.99
Investment II quantity	0.89	0.92	1.28	3.35	1.73	0.95	0.99	1.09	1.03	0.95	1.48

Notes: In all cases, we use world GDP as the numeraire and normalize it to 100.

Case 2 (lower clean-capital market frictions). Case 2 lowers cross-border frictions for clean capital (Type II) while holding all else at the baseline. The main effect is a decline in the effective user cost of deploying clean capital internationally, which expands the set of profitable clean-capital placements and raises the effective supply of clean-capital services where they are most valuable. This reduces the unit cost of clean energy relative to dirty energy, triggering a composition shift toward clean energy. Consistent with this mechanism, the clean-energy expenditure share rises (from 0.76 to 0.78) and emissions decline (from 3.45 to 3.39), while real income per capita increases slightly (0.33 to 0.34). The emissions-intensity improvement (10.46 to 9.98) reflects both the cleaner energy mix and a modest efficiency gain from better capital allocation.

Case 3 (higher clean-capital supply). Case 3 increases the supply of clean capital (Type II) directly. This shock operates through a first-order energy-price channel: more installed clean capital lowers the marginal cost of producing clean energy, which reallocates energy production away from the dirty technology and reduces fossil-fuel demand. In general equilibrium, cheaper energy also lowers production costs in downstream sectors, raising real income and amplifying the substitution away from dirty energy. The quantitative pattern matches this logic: the clean-energy expenditure share jumps markedly (0.76 to 0.92), emissions fall (3.45 to 2.97), and real income per capita rises strongly (0.33 to 0.45), producing a large decline in emissions intensity (10.46 to 6.58). The increases in investment quantities and CEE output in this case reflect the scale effect: higher real income raises aggregate absorption, and with investment shares fixed in value terms, higher GDP translates into more investment spending and thus larger real quantities.

Case 4 (higher CEE productivity). Case 4 raises productivity in the CEE sector. Because CEE goods are a core input into clean investment, higher CEE productivity primarily lowers the price of the clean-investment bundle and therefore increases the real quantity of clean investment purchased for a given nominal investment share. This is exactly what Table 1 shows: CEE quantity rises sharply (1.29 to 6.75) and the clean-investment quantity increases (0.89 to 3.35), even though contemporaneous real income, emissions, and the clean-energy expenditure share remain essentially unchanged. The reason is that the within-period energy mix is pinned down by the predetermined clean-capital stock; the immediate effect of cheaper CEE is thus not a contemporaneous decarbonization effect but an *intertemporal* one: higher clean investment today implies a larger clean-capital stock tomorrow, and higher CEE output today accelerates learning-by-doing, both of which amplify future clean-energy expansion and future emissions reductions.

Case 5 (higher generic-capital supply). Case 5 increases the supply of generic production capital (Type I). This shock lowers production costs broadly and generates a strong scale effect, raising real income per capita (0.33 to 0.64). At the same time, it changes relative energy costs: dirty energy relies more directly on generic capital than clean energy does in this calibration, so the relative price of dirty energy falls. The composition effect therefore works against decarbonization: the clean-energy expenditure share declines sharply (0.76 to 0.58) and emissions rise substantially (3.45 to 6.22). Emissions intensity nevertheless declines slightly (10.46 to 9.67) because output and real income expand even more than emissions; in other words, the economy becomes dirtier in levels but not proportionally as dirty in emissions per unit of real activity.

Case 6 (lower generic-capital market frictions). Case 6 lowers cross-border frictions for generic capital (Type I). Mechanically, this improves the international allocation of generic capital and lowers its effective user cost where marginal products are high. The general-equilibrium implications resemble a smaller version of Case 5: cheaper generic capital reduces costs economy-wide and especially in the dirty-energy technology, which induces a modest shift toward dirty energy and raises emissions (3.45 to 3.68), while real income rises (0.33 to 0.35). The clean-energy expenditure share falls slightly (0.76 to 0.74), consistent with a relative-price channel operating through the dirty-energy cost advantage.

Case 7 (lower frictions for both capital types). Case 7 lowers frictions for both generic and clean capital and can be interpreted as the overlap of Cases 2 and 6. Relative-price effects partially offset: cheaper clean capital pushes the mix toward clean, while cheaper generic capital pushes toward dirty. As a result, the clean-energy expenditure share remains close to the baseline (0.76), but the scale/efficiency effects remain: improved capital allocation raises real income (0.33 to 0.36). Emissions rise modestly (3.45 to 3.62) because higher activity increases energy demand, while emissions intensity falls (10.46 to 9.94) because the allocation gains and the partial clean-capital channel prevent emissions from rising one-for-one with income.

Case 8 (lower trade costs in all tradable sectors). Case 8 reduces iceberg trade costs across sectors. This shock increases specialization and lowers the cost of traded intermediates, which propagates through input–output linkages to reduce unit costs in downstream production. The dominant effect is a scale and productivity effect: real income per capita rises (0.33 to 0.41). Emissions increase (3.45 to 4.15) because higher output raises energy demand and, with imperfect substitutability between clean and dirty energy, part of the additional energy demand is met by the dirty technology. The clean-energy expenditure share declines slightly (0.76 to 0.74), consistent with a relative-price mechanism in which the cost reductions benefit dirty-energy production more (via its traded-input intensity), even as the overall economy becomes richer. Emissions intensity falls (10.46 to 10.17), reflecting that trade integration raises real income more than proportionally.

Case 9 (lower trade costs in the CEE sector only). Case 9 reduces trade costs only for CEE goods. This shock acts much like a sector-specific improvement in CEE productivity from the perspective of CEE users: the delivered price of CEE falls, increasing the real quantity of CEE absorbed in clean investment. Consistent with this interpretation, CEE quantity rises (1.29 to 1.54) and clean-investment quantity increases (0.89 to 1.03), while contemporaneous real income, emissions, and the clean-energy expenditure share remain essentially unchanged. As in Case 4, the key implication is intertemporal: cheaper (and more abundant) CEE today implies faster clean-capital accumulation tomorrow and, through the learning channel, lower future CEE prices—both of which magnify future decarbonization.

Case 10 (lower trade costs in non-CEE sectors only). Case 10 lowers trade costs in all other tradable sectors but leaves CEE trade costs unchanged. The shock still generates a strong input-cost and specialization channel, raising real income per capita (0.33 to 0.41) and increasing emissions (3.45 to 4.15) through a scale effect, similar to Case 8. However, because CEE goods do not become cheaper in this case, the clean-investment response is weaker (clean-investment quantity rises only to 0.95 versus 1.09 in Case 8), and the economy does not receive the additional dynamic push from cheaper CEE. Moreover, cheaper traded intermediates reduce dirty-energy costs substantially through its input structure, which contributes to the decline in the clean-energy expenditure share (0.76 to 0.74). Put differently, Case 10 delivers the classic efficiency gains from broader trade integration but without the targeted "clean-equipment" channel that would accelerate clean-capital deepening.

Case 11 (higher clean-investment rate). Case 11 raises the nominal investment share devoted to clean capital (Type II). This experiment isolates the role of investment composition. Holding technologies and frictions fixed, shifting expenditure toward clean investment increases demand for CEE, raising CEE output (1.29 to 2.15) and the real quantity of clean investment (0.89 to 1.48). In the within-period equilibrium, emissions decline (3.45 to 3.29) and emissions intensity falls (10.46 to 9.95), indicating that the spending reallocation reduces fossil-fuel demand in the current allocation (for example, because the clean-investment bundle is less fossil-fuel intensive than the displaced uses of resources). The more important implication is dynamic: higher clean investment today mechanically raises tomorrow's clean-capital stock, which further lowers the cost of clean energy and amplifies future emissions reductions.

Takeaways. Across these experiments, three forces organize the results. First, shocks that directly reduce the relative cost of clean energy (more clean capital, cheaper clean-capital deployment) raise the clean-energy share and reduce emissions through a composition effect. Second, shocks that lower economy-wide production costs (more generic capital, cheaper generic-capital deployment, broad trade integration) raise real income and often increase emissions through a scale effect, even when emissions intensity improves. Third, shocks that specifically reduce the price of CEE (higher CEE productivity or lower CEE trade costs) primarily work through an intertemporal amplification mechanism. While the static experiments highlight the immediate increase in CEE output and clean-investment quantities, the forthcoming dynamic model endogenizes the propagation: higher clean investment raises next period's clean-capital stock, and higher CEE production strengthens learning-by-doing, raising future CEE productivity and magnifying the long-run impact.

4. Calibration

In this section, we calibrate the model. We begin by describing the data sources used in the calibration. Next, we identify the exogenous, time-invariant parameters. We then explain how the time-varying shocks are calibrated. Finally, we present the solution method and feed these shocks into the model to assess the fit of the calibrated model.

4.1. Data description

The calibration relies on several data sources. Our main sources are the BACI Trade Database, GTAP v11, the World Bank database, the databases of the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA), the United Nations Conference on Trade and Development (UNCTAD), the China Global Investment Tracker (CGIT), and the fDi Markets.

The sample is organized around four country groups: China, the United States, the European Union (treated as a single aggregate), and the rest of the world (ROW). The sample period runs from 2006 to 2019. The ROW is constructed residually as the world aggregate net of the selected countries or country groups. Unless otherwise noted, all series used in the calibration are harmonized to this common country aggregation and sample window.

4.2. Time-invariant parameters

TABLE 2
TIME-INVARIANT OBJECTS AND FIXED INITIAL CONDITIONS

Object	**Description**	**Calibration method**
Production and sectoral-demand block		
θ_j	Trade elasticity (Fréchet dispersion) for sector j	Empirical estimation
σ_j	Elasticity of substitution across varieties in sector j	Literature
$\gamma^F_{n,j}$, $\gamma^X_{n,jk}$	Factor cost shares ($F \in \{L, M, R, K^c, K^p\}$) and intermediate-input shares	Direct data matching
σ^e	Elasticity of substitution between clean and dirty energy	Literature
ϕ^e	Share parameter in the CES aggregation of clean and dirty energy	Direct data matching
$\beta^C_{n,j}$, $\beta^{I,\tau}_{n,j}$	Sectoral expenditure shares in consumption and investment bundles	Direct data matching
Household block		
β	Subjective discount factor	Literature
Capital accumulation and allocation block		
δ^τ	Depreciation rate for capital type $\tau \in \{c, p\}$	Literature and direct data matching
ε	Fréchet dispersion parameter in bilateral capital allocation	Empirical estimation
Learning-by-doing block		
ρ	Learning-by-doing elasticity in the CEE sector	Literature / empirical estimation
δ_E	Depreciation rate of accumulated experience	Literature
Γ_n	Country-specific scale parameter in the learning block	Normalization ($E^{lbd}_{n,r,t_0} = 1$)
Initial-condition block		
$K^c_{n,0}$, $K^p_{n,0}$	Initial stocks of clean capital and generic production capital	Initial-condition matching

In this subsection, we calibrate the time-invariant parameters reported in Table 2. For objects directly matched from annual data, we first construct country- and sector-specific series over 2006–2019 and then take time averages to obtain the corresponding time-invariant model inputs. To simplify the exposition, we omit time subscripts whenever no confusion arises.

Production and sectoral-demand block. We begin with the trade elasticity θ_j. Following Simonovska and Waugh (2014), we set $\theta_j = 4$ in the benchmark calibration. In the current draft, this benchmark is imposed uniformly across sectors; allowing for sector-specific values is left for future refinement. Next, the elasticity of substitution across varieties, σ_j, is set to a common benchmark value of 2, in line with Broda and Weinstein (2006). The production-share parameters $\gamma^F_{n,j}$ and $\gamma^X_{n,jk}$ are directly matched to the benchmark input–output data. Let $Y_{n,j,t}$ denote gross output in country n, sector j, and year t; let $VA^F_{n,j,t}$

denote payments to factor $F \in \{L, M, R, K^c, K^p\}$ in that country-sector-year; and let $Z^X_{n,kj,t}$ denote expenditure on intermediate inputs from sector k used by sector j. We then construct

$$\gamma^F_{n,j,t} = \frac{VA^F_{n,j,t}}{Y_{n,j,t}}, \qquad \gamma^X_{n,kj,t} = \frac{Z^X_{n,kj,t}}{Y_{n,j,t}},$$

and define the time-invariant objects $\gamma^F_{n,j}$ and $\gamma^X_{n,jk}$ as the corresponding averages over 2006–2019. By construction, these shares satisfy the adding-up restriction

$$\sum_{F\in\{L,M,R,K^c,K^p\}} \gamma^F_{n,j} + \sum_{k\in\{m,r,e,o\}} \gamma^X_{n,jk} = 1.$$

The elasticity of substitution between clean and dirty energy, σ^e, is set to 3.08 following Jo (2025). The CES weight ϕ^e_n is calibrated using the observed expenditure share of clean energy in the aggregate energy composite. Using data on total values and quantities, we infer prices as unit values, $P = PQ/Q$.[5] Formally, for each region n, ϕ^e_n is obtained by minimizing the distance between the model-implied and data-implied expenditure shares across all years in the sample:

$$\phi^e_n = \arg\min_{\phi} \sum_t \left| \frac{P_{n,ce,t}Q_{n,ce,t}}{P_{n,e,t}Q_{n,e,t}} - \phi \left(\frac{P_{n,ce,t}}{P_{n,e,t}}\right)^{1-\sigma^e} \right|.$$

The sectoral expenditure shares in consumption and investment, $\beta^C_{n,j}$ and $\beta^{I,\tau}_{n,j}$, are constructed from observed expenditure shares. For consumption, we define

$$\beta^C_{n,j,t} = \frac{P_{n,j,t}C_{n,j,t}}{\sum_{k\in\{m,r,e,o\}} P_{n,k,t}C_{n,k,t}},$$

and obtain the time-invariant object $\beta^C_{n,j}$ by averaging across years. For investment, we define

$$\beta^{I,\tau}_{n,j,t} = \frac{P_{n,j,t}I^\tau_{n,j,t}}{\sum_{k\in\{m,r,e,o\}} P_{n,k,t}I^\tau_{n,k,t}}, \qquad \tau \in \{c, p\},$$

and then take time averages.

Household block. The subjective discount factor is set to $\beta = 0.96$ at the annual frequency.

5. Specifically, ϕ^e_n is chosen so that the model-implied clean-energy expenditure share, $\phi^e_n \left(\frac{P_{n,ce,t}}{P_{n,e,t}}\right)^{1-\sigma^e}$, matches its empirical counterpart, $\frac{P_{n,ce,t}Q_{n,ce,t}}{P_{n,e,t}Q_{n,e,t}}$.

Capital accumulation and allocation block. The depreciation rate for capital type $\tau \in \{c, p\}$, denoted by δ^τ, is set to annual values of $\delta^c = 0.04$ and $\delta^p = 0.05$.[6] The Fréchet dispersion parameter governing bilateral capital allocation, ε, is set to 8, following Koijen and Yogo (2020).

Learning-by-doing block. The learning-by-doing elasticity in the clean-energy equipment sector, ρ,

The depreciation rate of accumulated experience, δ_E,

The country-specific scale parameter Γ_n is pinned down by the normalization $E^{lbd}_{n,r,t_0} = 1$ in the base year t_0.

Initial-condition block. Finally, the initial stocks of clean capital and generic production capital, $K^c_{n,0}$ and $K^p_{n,0}$, are matched to base-year observations. The exact construction of $K^c_{n,0}$ from installed clean-energy-generation capital and of $K^p_{n,0}$ from benchmark productive-capital data is TBA.

6. We set $\delta^c = 0.04$ because the depreciation rate of renewable generation capital is typically calibrated in the range of 0.03–0.04, while that of battery storage is often set around 0.05 (Arkolakis and Walsh, 2023; Baldwin, Cai, and Kuralbayeva, 2020). Since our green capital stock combines solar, wind, and storage assets, 0.04 is a natural intermediate value. We set $\delta^p = 0.05$ because the depreciation rate of conventional capital is commonly calibrated in the range of 0.05–0.06 (Baldwin, Cai and Kuralbayeva, 2020; Caselli and Feyrer, 2007; Buera and Shin, 2017), although some related climate-economy studies assume a higher value of 0.10 (Kotlikoff, Kubler, Polbin, and Scheidegger, 2024).

4.3. Time-Varing Variables

TABLE 3
TIME-VARYING EXOGENOUS OBJECTS

Object	Description	Calibration method
Production block		
$A_{n,j,t}$	Fundamental Sectoral productivity	Model inversion
Trade block		
$\kappa_{ni,j,t}$	Bilateral iceberg trade costs	Model inversion
Household and policy block		
$\psi_{n,t}$	Exogenous discount-factor shock	Model inversion
$\omega^{\tau}_{n,t}$	Government investment wedge/subsidy for capital type τ (with $\omega^{p}_{n,t} = 0$ by normalization)	Model inversion / policy matching
$\phi_{n,t}$	Exogenous share of national income allocated to the global portfolio, governing trade-imbalance transfers	Direct data matching
Capital accumulation block		
$\chi^{\tau}_{n,t}$	Installation-efficiency term for capital type τ	Model inversion
Capital allocation block		
$\nu^{\tau}_{ni,t}$	Bilateral capital-market frictions for capital type τ (FDI / portfolio barriers)	Model inversion
$E^{\tau}_{i,t}$	Capital-use efficiency scale parameter in producer i for capital type τ	Normalization / model fit
Endowment block		
$L_{n,t}$	Labor endowment (or inelastic labor supply)	Direct data matching
$M_{n,t}$	Natural-resource endowment used in mining	Direct data matching / constructed series
$R_{n,t}$	Renewable natural endowment used in clean-energy production	Direct data matching / constructed series

In this subsection, we calibrate the time-varying exogenous objects listed in Table 3. All series are constructed at an annual frequency over 2006–2019 and aggregated to the model's four regions: China, the United States, the European Union, and the rest of the world.

Production and trade block.

Capital accumulation block.

Endowment block.

4.4. *Solution method and model fit*

5. Quantitative analysis

6. Conclusion

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Appendix

A. Equilibrium condition and algorithm

TABLE A.1
Steady state equilibrium

(F1)	$E^{lbd}_{n,r,T} = 1,\ Y_{n,r,T} = \bar{Y},\ \Gamma_n = (\frac{\bar{Y}}{1-\delta_E})^{-\rho}\ ,\rho \geq 0, \delta_E \in (0,1).$	$\forall(n,T)$
(F2)	$P_{n,j,T}Q_{n,j,T} \equiv Z_{n,j,T} \equiv \sum_{i=1}^{N} Z_{ni,j,T}, \qquad Y_{n,j,T} \equiv \sum_{i=1}^{N} Z_{in,j,T}$	$\forall(n,i,T)$
(F3)	$B_{n,j} \equiv \left(\gamma^M_{n,j}\right)^{-\gamma^M_{n,j}} \left(\gamma^R_{n,j}\right)^{-\gamma^R_{n,j}} \left(\gamma^{K^p}_{n,j}\right)^{-\gamma^{K^p}_{n,j}} \left(\gamma^{K^c}_{n,j}\right)^{-\gamma^{K^c}_{n,j}} \left(\gamma^L_{n,j}\right)^{-\gamma^L_{n,j}} \prod_{k\in\{m,r,e,o\}} \left(\gamma^X_{n,jk}\right)^{-\gamma^X_{n,jk}}.$	$\forall(n,i,T)$
(F4)	$c_{n,j,T} = B_{n,j} \left(V^M_{n,T}\right)^{\gamma^M_{n,j}} \left(V^{Res}_{n,T}\right)^{\gamma^R_{n,j}} \left(r^p_{n,T}\right)^{\gamma^{K^p}_{n,j}} \left(r^c_{n,T}\right)^{\gamma^{K^c}_{n,j}} \left(w_{n,T}\right)^{\gamma^L_{n,j}} \prod_{k\in\{m,r,e,o\}} \left(P_{n,k,T}\right)^{\gamma^X_{n,jk}}.$	$\forall(n,j,T)$
(F5)	$w_{n,T}L_{n,T} = \sum_{j\in\{m,r,ce,de,o\}} \gamma^L_{n,j}\, Y_{n,j,T}, \qquad V^M_{n,T}M_{n,T} = \sum_{j\in\{m,r,ce,de,o\}} \gamma^M_{n,j}\, Y_{n,j,T}, \qquad V^{Res}_{n,T}\, R_{n,T} = \sum_{j\in\{m,r,ce,de,o\}} \gamma^R_{n,j}\, Y_{n,j,T}.$	$\forall(n,T)$
(F6)	$r^\tau_{n,T}\, \mathcal{K}^{\tau,\text{eff}}_{n,T} = \sum_{j\in\{m,r,ce,de,o\}} \gamma^{K^\tau}_{n,j}\, Y_{n,j,T}, \quad \tau \in \{c,p\}.$	$\forall(n,T)$
(H1)	$C_{n,T} = \prod_{j\in\{m,r,e,o\}} (C_{n,j,T})^{\beta^C_{n,j}}, \qquad I^\tau_{n,T} = \prod_{j\in\{m,r,e,o\}} (I^\tau_{n,j,T})^{\beta^{I,\tau}_{n,j}},\ \tau \in \{c,p\}$	$\forall(n,T)$
(H2)	$P^C_{n,T} = \prod_{j\in\{m,r,e,o\}} \left(\frac{P_{n,j,T}}{\beta^C_{n,j}}\right)^{\beta^C_{n,j}}, \qquad P^{I,\tau}_{n,T} = \prod_{j\in\{m,r,e,o\}} \left(\frac{P_{n,j,T}}{\beta^{I,\tau}_{n,j}}\right)^{\beta^{I,\tau}_{n,j}},\ \tau \in \{c,p\}$	$\forall(n,T)$
(H3)	$C_{n,e,T} = \left[(\phi^e)^{1/\sigma_e}(C_{n,ce,T})^{\frac{\sigma^e-1}{\sigma^e}} + (1-\phi^e)^{1/\sigma_e}(C_{n,de,T})^{\frac{\sigma^e-1}{\sigma^e}}\right]^{\frac{\sigma^e}{\sigma^e-1}},\ P_{n,e,T} = \left[\phi^e(P_{n,ce,T})^{1-\sigma^e} + (1-\phi^e)(P_{n,de,T})^{1-\sigma^e}\right]^{\frac{1}{1-\sigma^e}}$	$\forall(n,T)$
(H3')	$\frac{P_{n,ce,T}C_{n,ce,T}}{P_{n,e,T}C_{n,e,T}} = \phi^e(\frac{P_{n,ce,T}}{P_{n,e,T}})^{1-\sigma^e}$	$\forall(n,T)$
(H4)	$R^\tau_{n,T}\ \equiv\ (1-\delta^\tau) + \frac{V^\tau_{n,T}}{(1-\omega^\tau_{n,T})\, P^{I,\tau}_{n,T}/\chi^\tau_{n,T}}$	$\forall(n,T)$
(H5)	$1 = \beta \cdot R^\tau_{n,T}, \qquad \forall\tau \in \{c,p\}, \qquad V^c_{n,T} = \frac{(1-\omega^c_{n,T})\, P^{I,c}_{n,T}}{\chi^c_{n,T}} \left[(\delta^c - \delta^p) + \frac{\chi^p_{n,T}\, V^p_{n,T}}{(1-\omega^p_{n,T})\, P^{I,p}_{n,T}}\right]$	$\forall(n,T)$
(H6)	$\lambda^\tau_{ni,T} = \frac{K^\tau_{ni,T}}{K^\tau_{n,T}} = \frac{\left(E^\tau_{i,T}\, r^\tau_{i,T}/\nu^\tau_{ni,T}\right)^\varepsilon}{\sum_{h=1}^N \left(E^\tau_{h,T}\, r^\tau_{h,T}/\nu^\tau_{nh,T}\right)^\varepsilon}, \qquad \overline{e}^\tau_{ni,T} = \Gamma(1-1/\varepsilon)E^\tau_{i,T}\left(\lambda^\tau_{ni,T}\right)^{-1/\varepsilon} = \Gamma(1-1/\varepsilon)\frac{\nu^\tau_{ni,T}}{r^\tau_{i,T}} \left(\sum_{h=1}^N \left(E^\tau_{h,T}\, r^\tau_{h,T}/\nu^\tau_{nh,T}\right)^\varepsilon\right)^{1/\varepsilon}.$	$\forall(n,i,T)$
(H7)	$V^\tau_{ni,T} \equiv V^\tau_{n,T} = \Gamma(1-1/\varepsilon)\left(\sum_{h=1}^N \left(\frac{E^\tau_{h,T}\, r^\tau_{h,T}}{\nu^\tau_{nh,T}}\right)^\varepsilon\right)^{\frac{1}{\varepsilon}} = \frac{r^\tau_{i,T}\, \overline{e}^\tau_{ni,T}}{\nu^\tau_{ni,T}}, \qquad V^\tau_{ni,T}\, K^\tau_{ni,T} = \frac{r^\tau_{i,T}\, \overline{e}^\tau_{ni,T}}{\nu^\tau_{ni,T}}\, K^\tau_{ni,T}.$	$\forall(n,i,T)$
(H8)	$\mathcal{K}^{\tau,\text{eff}}_{n,T} = \sum_{i=1}^N \frac{\overline{e}^\tau_{in,T}}{\nu_{in,T}}\, K^\tau_{in,T} \equiv \sum_{i=1}^N \mathcal{K}^{\tau,\text{eff}}_{in,T}, \qquad \mathcal{K}^{\tau,\text{eff}}_{in,T} \equiv \frac{\overline{e}^\tau_{in,T}}{\nu_{in,T}}\, K^\tau_{in,T}.$	$\forall(n,T)$
(H8')	$r^\tau_{n,T}\, \mathcal{K}^{\tau,\text{eff}}_{n,T} = \sum_{i=1}^N V^\tau_{i,T}\, K^\tau_{in,T} = \sum_{i=1}^N V^\tau_{i,T}\, \lambda^\tau_{in,T}\, K^\tau_{i,T}.$	$\forall(n,T)$
(H9)	$\delta^\tau K^\tau_{n,T} = \chi^\tau_{n,T} I^\tau_{n,T},\ \tau \in \{c,p\}$	$\forall(n,T)$
(T1)	$P_{n,j,T} = \mathcal{A}_j(\Phi_{n,j,T})^{-1/\theta_j}, \qquad \Phi_{n,j,T} \equiv \sum_{i=1}^N (A_{i,j,T})^{\theta_j}[\kappa_{ni,j,T} \cdot c_{i,j,T}]^{-\theta_j}, \qquad \mathcal{A}_j = \left[\Gamma\left(\frac{1+\theta_j-\sigma_j}{\theta_j}\right)\right]^{1/(1-\sigma_j)}$	$\forall(n,j,T)$
(T2)	$\pi_{ni,j,T} \equiv \frac{Z_{ni,j,T}}{Z_{n,j,T}} = \frac{(A_{i,j,T})^{\theta_j}[\kappa_{ni,j,T} \cdot c_{i,j,T}]^{-\theta_j}}{\sum_{m=1}^N (A_{m,j,T})^{\theta_j}[\kappa_{nm,j,T} \cdot c_{m,j,T}]^{-\theta_j}} = (A_{i,j,T})^{\theta_j} \left(\frac{\mathcal{A}_j \kappa_{ni,j,T} \cdot c_{i,j,T}}{P_{n,j,T}}\right)^{-\theta_j}$	$\forall(n,i,j,T)$
(T3)	$Z_{n,j,T} = \beta^C_{n,j}P^C_{n,T}C_{n,T} + \sum_\tau \beta^{I,\tau}_{n,j}P^\tau_{n,T}I^{I,\tau}_{n,T} + \sum_{k\in\{m,r,ce,de,o\}} \gamma^X_{n,kj} \left(\sum_{i=1}^N Z_{in,k,T}\right)$	$\forall(n,j,T)$
(T4)	$P^C_{n,T}C_{n,T} + \sum_\tau P^{I,\tau}_{n,T}\ I_{n,T} = INC_{n,T} \equiv IN_{n,T} + T^D_{n,t}, \qquad IN_{n,T} \equiv \sum_{\tau\in\{c,p\}} V^\tau_{n,T}K^\tau_{n,T} + w_{n,T}L_{n,T} + V^R_{n,T}R_{n,T} + V^M_{n,T}M_{n,T}$	$\forall(n,T)$
(T5)	$P^C_{n,T}\, C_{n,T}\ +\ \sum_{\tau\in\{c,p\}} (1-\omega^\tau_{n,T})\, P^{I,\tau}_{n,T}\, I^\tau_{n,T}\ =\ IN_{n,T}\ +\ \sum_{\tau\in\{c,p\}} T^\tau_{n,T}\ +\ T^D_{n,t}, \qquad T^\tau_{n,T} \equiv -\omega^\tau_{n,T}\, P^{I,\tau}_{n,T}\, I^\tau_{n,T}$	$\forall(n,T)$
(T6)	$\sum_{j\in\{m,r,ce,de,o\}} \sum_{i=1}^N \left(Z_{ni,j,T} - Z_{in,j,T}\right) \equiv \sum_{\tau\in\{c,p\}} V^\tau_{n,T}K^\tau_{n,T} - \sum_{\tau\in\{c,p\}} r^\tau_{n,T}K^{\text{eff},\tau}_{n,T} + T^D_{n,t},\ T^D_{n,t} \equiv -\phi_{n,T}IN_{n,T} + \frac{L_{n,T}}{\sum_{m=1}^N L_{m,T}} \sum_{i=1}^N \phi_{i,T}IN_{n,T}$	$\forall(n,T)$

Algorithm 1 Steady-State Equilibrium at T

1: Guess $\{K^p_{n,T}\}_{n\in\mathcal{N}}$, repeat the following until $\max_n \left|R^p_{n,T} - 1/\beta\right| < \varepsilon$:

- (a) $\{K^p_{n,T}\} \xrightarrow{\text{H9}} \{I^p_{n,T}\}$.
- (b) Guess $\{K^c_{n,T}\}_{n\in\mathcal{N}}$, repeat the following until $\max_n \left|R^c_{n,T} - R^p_{n,T}\right| < \varepsilon \cdot 1e-1$:
  - (b.1) $\{K^c_{n,T}\} \xrightarrow{\text{H9}} \{I^c_{n,T}\}$.
  - (b.2) Guess $\{w_{n,T}, V^M_{n,T}, V^R_{n,T}, r^\tau_{n,T}\}$, repeat the following until $\max_n \left|SN_{n,T}\right| < \varepsilon \cdot 1e-2$:
    - (b.2.a) $\{r^\tau_{n,T}\} \xrightarrow{\text{H6 H8}} \{\lambda^\tau_{ni,j,T}, \overline{e}^\tau_{ni,T}, \mathcal{K}^{\tau,\text{eff}}_{in,T}, \mathcal{K}^{\tau,\text{eff}}_{n,T}, V^\tau_{n,T}\}$.
    - (b.2.b) $\xrightarrow{\text{F3-F4, H2-H3, T1-T2}} \{P_{n,k,T}, c_{n,j,T}, \pi_{ni,j,T}, P^C_{n,T}, P^{I,\tau}_{n,T}\}$.
    - (b.2.c) $\xrightarrow{\text{T3}\sim\text{T6}} \{Z_{n,j,T}, C_{n,T}, T^D_{n,t}\}$.
    - (b.2.d) $\xrightarrow{\text{F5-F6}} \left\{Dist^L_{n,T},\ Dist^M_{n,T},\ Dist^R_{n,T},\ Dist^{\mathcal{K}^{\tau,\text{eff}}}_{n,T}\right\}$.
    - (b.2.e) Update: $Dist^L_{n,T} \equiv \sum_j \gamma^L_{n,j} Y_{n,j,T} - w_{n,T} L_{n,T}$,

      $w'_{n,T} = w_{n,T} + \lambda^w_t \cdot Dist^L_{n,T}/L_{n,T}, \quad V^{M\prime}_{n,T} = V^M_{n,T} + \lambda^M_t \cdot Dist^M_{n,T}/M_{n,T}$,

      $V^{R\prime}_{n,T} = V^R_{n,T} + \lambda^R_t \cdot Dist^R_{n,T}/R_{n,T}, \quad r^{\tau\prime}_{n,T} = r^\tau_{n,T} + \lambda^\tau_t \cdot Dist^{\mathcal{K}^{\tau,\text{eff}}}_{n,T}/\mathcal{K}^{\tau,\text{eff}}_{n,T}$.
    - (b.2.f) $\rightarrow \left\{SN_{n,T} \equiv EX_{n,T} - IM_{n,T} + T^D_{n,t} \equiv Dist^L_{n,T} + Dist^M_{n,T} + Dist^R_{n,T} + Dist^{\mathcal{K}^{\tau,\text{eff}}}_{n,T}\right\}$.
    - (b.2.g) Set $\{w_{n,T}, V^M_{n,T}, V^R_{n,T}, r^\tau_{n,T}\} \leftarrow \{w'_{n,T}, V^{M\prime}_{n,T}, V^{R\prime}_{n,T}, r^{\tau\prime}_{n,T}\}$ and repeat.
  - (b.3) $\xrightarrow{\text{H4}} \{R^p_{n,T}, R^c_{n,T}\}$, and $V^c_{n,T}{}' = \dfrac{(1-\omega^c_{n,T})\,P^{I,c}_{n,T}}{\chi^c_{n,T}} \left[(\delta^c - \delta^p) + \dfrac{\chi^p_{n,T}\,V^p_{n,T}}{(1-\omega^p_{n,T})\,P^{I,p}_{n,T}}\right]$.
  - (b.4) $\rightarrow$ Update $K^c_{n,T}{}'$ with $K^c_{n,T}{}' = K^c_{n,T} \cdot \left[1 + \lambda_{K^c} \cdot \dfrac{V^c_{n,T}{}' - V^c_{n,T}}{V^c_{n,T}}\right]$ or $K^c_{n,T}{}' = K^c_{n,T} \cdot \left(\dfrac{V^c_{n,T}{}'}{V^c_{n,T}}\right)^{\lambda_{K^c}}$,

    or $K^c_{n,T}{}' = K^c_{n,T} \cdot \left[1 + \lambda_{K^c} \cdot \dfrac{R^p_{n,T} - R^c_{n,T}}{R^c_{n,T}}\right]$ or $K^c_{n,T}{}' = K^c_{n,T} \cdot \left(\dfrac{R^p_{n,T}}{R^c_{n,T}}\right)^{\lambda_{K^c}}$.
  - (b.5) Set $\{K^c_{n,T}\} \leftarrow \{K^{c\prime}_{n,T}\}$ and repeat.
- (c) $\xrightarrow{\text{H5}}$ Update $K^p_{n,T}{}'$ with $K^p_{n,T}{}' = K^p_{n,T} \cdot \left[1 + \lambda_{K^p} \cdot \dfrac{1/\beta - R^p_{n,T}}{R^p_{n,T}}\right]$ or $K^p_{n,T}{}' = K^p_{n,T} \cdot \left(\dfrac{1/\beta}{R^p_{n,T}}\right)^{\lambda_{K^p}}$.
- (d) Set $\{K^p_{n,T}\} \leftarrow \{K^{p\prime}_{n,T}\}$ and repeat.

2: Return $\{K^p_{n,T}, K^c_{n,T}\}_{n\in\mathcal{N}}$ and stop.

TABLE A.2

Dynamic equilibrium

(F1)	$E^{lbd}_{n,r,T} = \Gamma_n \left(\sum_{i=1}^{\infty} \delta_E^{i-1} Y_{n,r,t-i} \right)^{\rho}, \qquad \Gamma_n > 0, \quad \rho \geq 0, \quad \delta_E \in (0,1)., \ \Gamma_n\text{:}\ E_{n,j,t_0} = 1\ .$	$\forall (n,t)$
(F2)	$P_{n,j,t} Q_{n,j,t} \equiv Z_{n,j,t} \equiv \sum_{i=1}^{N} Z_{ni,j,t}, \qquad Y_{n,j,t} \equiv \sum_{i=1}^{N} Z_{in,j,t}$	$\forall (n,i,t)$
(F3)	$B_{n,j} \equiv \left(\gamma^M_{n,j}\right)^{-\gamma^M_{n,j}} \left(\gamma^R_{n,j}\right)^{-\gamma^R_{n,j}} \left(\gamma^{K^p}_{n,j}\right)^{-\gamma^{K^p}_{n,j}} \left(\gamma^{K^c}_{n,j}\right)^{-\gamma^{K^c}_{n,j}} \left(\gamma^L_{n,j}\right)^{-\gamma^L_{n,j}} \prod_{k \in \{m,r,e,o\}} \left(\gamma^X_{n,jk}\right)^{-\gamma^X_{n,jk}}.$	$\forall (n,i,t)$
(F4)	$c_{n,j,t} = B_{n,j} \left(V^M_{n,t}\right)^{\gamma^M_{n,j}} \left(V^{Res}_{n,T}\right)^{\gamma^R_{n,j}} \left(r^p_{n,t}\right)^{\gamma^{K^p}_{n,j}} \left(r^c_{n,t}\right)^{\gamma^{K^c}_{n,j}} \left(w_{n,t}\right)^{\gamma^L_{n,j}} \prod_{k \in \{m,r,e,o\}} \left(P_{n,k,t}\right)^{\gamma^X_{n,jk}}.$	$\forall (n,j,t)$
(F5)	$w_{n,t} L_{n,t} = \sum_{j \in \{m,r,ce,de,o\}} \gamma^L_{n,j} Y_{n,j,t}, \qquad V^M_{n,t} M_{n,t} = \sum_{j \in \{m,r,ce,de,o\}} \gamma^M_{n,j} Y_{n,j,t}, \qquad V^{Res}_{n,T} R_{n,t} = \sum_{j \in \{m,r,ce,de,o\}} \gamma^R_{n,j} Y_{n,j,t}.$	$\forall (n,t)$
(F6)	$r^\tau_{n,t} \mathcal{K}^{\tau,\text{eff}}_{n,t} = \sum_{j \in \{m,r,ce,de,o\}} \gamma^{K^\tau}_{n,j} Y_{n,j,t}, \quad \tau \in \{c,p\}.$	$\forall (n,t)$
(H1)	$C_{n,t} = \prod_{j \in \{m,r,e,o\}} (C_{n,j,t})^{\beta^C_{n,j}}, \qquad I^\tau_{n,t} = \prod_{j \in \{m,r,e,o\}} (I^\tau_{n,j,t})^{\beta^{I,\tau}_{n,j}},\ \tau \in \{c,p\}$	$\forall (n,t)$
(H2)	$P^C_{n,t} = \prod_{j \in \{m,r,e,o\}} \left(\frac{P_{n,j,t}}{\beta^C_{n,j}}\right)^{\beta^C_{n,j}}, \qquad P^{I,\tau}_{n,t} = \prod_{j \in \{m,r,e,o\}} \left(\frac{P_{n,j,t}}{\beta^{I,\tau}_{n,j}}\right)^{\beta^{I,\tau}_{n,j}},\ \tau \in \{c,p\}$	$\forall (n,t)$
(H3)	$C_{n,e,t} = \left[(\phi^e)^{1/\sigma_e} (C_{n,ce,t})^{\frac{\sigma^e - 1}{\sigma^e}} + (1-\phi^e)^{1/\sigma_e} (C_{n,de,t})^{\frac{\sigma^e-1}{\sigma^e}}\right]^{\frac{\sigma^e}{\sigma^e - 1}},\ P_{n,e,t} = \left[\phi^e (P_{n,ce,t})^{1-\sigma^e} + (1-\phi^e)(P_{n,de,t})^{1-\sigma^e}\right]^{\frac{1}{1-\sigma^e}}$	$\forall (n,t)$
(H3')	$\frac{P_{n,ce,t} C_{n,ce,t}}{P_{n,e,t} C_{n,e,t}} = \phi^e (\frac{P_{n,ce,t}}{P_{n,e,t}})^{1-\sigma^e}$	$\forall (n,t)$
(H4)	$R^\tau_{n,t+1} \ \equiv\ (1-\delta^\tau) + \frac{V^\tau_{n,t+1}}{(1-\omega^\tau_{n,t+1})\, P^{I,\tau}_{n,t+1} / \chi^\tau_{n,t+1}}$	$\forall (n,t)$
(H5)	$\frac{C_{n,t+1}/L_{n,t+1}}{C_{n,t}/L_{n,t}} = \beta \cdot \frac{\psi_{n,t+1}}{\psi_{n,t}} \cdot \left(\frac{\left((1-\omega^\tau_{n,t+1})\, P^{I,\tau}_{n,t+1}/\chi^\tau_{n,t+1}\right)/P^C_{n,t+1}}{\left((1-\omega^\tau_{n,t})\, P^{I,\tau}_{n,t}/\chi^\tau_{n,t}\right)/P^C_{n,t}} \right) \cdot \left[R^\tau_{n,t+1}\right], \qquad \forall \tau \in \{c,p\}.$	$\forall (n,t)$
(H6)	$\lambda^\tau_{ni,t} = \frac{K^\tau_{ni,t}}{K^\tau_{n,t}} = \frac{\left(E^\tau_{i,t}\, r^\tau_{i,t}/\nu^\tau_{ni,t}\right)^\varepsilon}{\sum_{h=1}^N \left(E^\tau_{h,t}\, r^\tau_{h,t}/\nu^\tau_{nh,t}\right)^\varepsilon}, \qquad \overline{e}^\tau_{ni,t} = \Gamma(1-1/\varepsilon) E^\tau_{i,t} \left(\lambda^\tau_{ni,t}\right)^{-1/\varepsilon} = \Gamma(1-1/\varepsilon) \frac{\nu^\tau_{ni,t}}{r^\tau_{i,t}} \left(\sum_{h=1}^N \left(E^\tau_{h,t}\, r^\tau_{h,t}/\nu^\tau_{nh,t}\right)^\varepsilon \right)^{1/\varepsilon}.$	$\forall (n,i,t)$
(H7)	$V^\tau_{ni,t} \equiv V^\tau_{n,t} = \Gamma(1-1/\varepsilon) \left(\sum_{h=1}^N \left(\frac{E^\tau_{h,t}\, r^\tau_{h,t}}{\nu^\tau_{nh,t}} \right)^\varepsilon \right)^{\frac{1}{\varepsilon}} = \frac{r^\tau_{i,t}\, \overline{e}^\tau_{ni,t}}{\nu^\tau_{ni,t}}, \qquad V^\tau_{ni,t}\, K^\tau_{ni,t} = \frac{r^\tau_{i,t}\, \overline{e}^\tau_{ni,t}}{\nu^\tau_{ni,t}}\, K^\tau_{ni,t}.$	$\forall (n,i,t)$
(H8)	$\mathcal{K}^{\tau,\text{eff}}_{n,t} = \sum_{i=1}^N \frac{\overline{e}^\tau_{in,t}}{\nu_{in,t}}\, K^\tau_{in,t} \equiv \sum_{i=1}^N \mathcal{K}^{\tau,\text{eff}}_{in,t}, \qquad \mathcal{K}^{\tau,\text{eff}}_{in,t} \equiv \frac{\overline{e}^\tau_{in,t}}{\nu_{in,t}}\, K^\tau_{in,t}.$	$\forall (n,t)$
(H8')	$r^\tau_{n,t}\, \mathcal{K}^{\tau,\text{eff}}_{n,t} = \sum_{i=1}^N V^\tau_{i,t}\, K^\tau_{in,t} = \sum_{i=1}^N V^\tau_{i,t}\, \lambda^\tau_{in,t}\, K^\tau_{i,t}.$	$\forall (n,t)$
(H9)	$K^\tau_{n,t+1} = (1-\delta^\tau) K^\tau_{n,t} + \chi^\tau_{n,t} I^\tau_{n,t},\ \tau \in \{c,p\}$	$\forall (n,t)$
(T1)	$P_{n,j,t} = \mathcal{A}_j (\Phi_{n,j,t})^{-1/\theta_j}, \qquad \Phi_{n,j,t} \equiv \sum_{i=1}^N (A_{i,j,t})^{\theta_j} [\kappa_{ni,j,t} \cdot c_{i,j,t}]^{-\theta_j}, \qquad \mathcal{A}_j = \left[\Gamma\left(\frac{1+\theta_j-\sigma_j}{\theta_j}\right)\right]^{1/(1-\sigma_j)}$	$\forall (n,j,t)$
(T2)	$\pi_{ni,j,t} \equiv \frac{Z_{ni,j,t}}{Z_{n,j,t}} = \frac{(A_{i,j,t})^{\theta_j} [\kappa_{ni,j,t} \cdot c_{i,j,t}]^{-\theta_j}}{\sum_{m=1}^N (A_{m,j,t})^{\theta_j} [\kappa_{nm,j,t} \cdot c_{m,j,t}]^{-\theta_j}} = (A_{i,j,t})^{\theta_j} \left(\frac{\mathcal{A}_j \kappa_{ni,j,t} \cdot c_{i,j,t}}{P_{n,j,t}} \right)^{-\theta_j}$	$\forall (n,i,j,t)$
(T3)	$Z_{n,j,T} = \beta^C_{n,j} P^C_{n,t} C_{n,t} + \sum_\tau \beta^{I,\tau}_{n,j} P^\tau_{n,t} I^{I,\tau}_{n,t} + \sum_{k \in \{m,r,ce,de,o\}} \gamma^X_{n,kj} \left(\sum_{i=1}^N Z_{in,k,t} \right)$	$\forall (n,j,t)$
(T4)	$P^C_{n,t} C_{n,t} + \sum_\tau P^{I,\tau}_{n,t}\ I_{n,t} = INC_{n,t} \equiv IN_{n,t} + T^D_{n,t}, \qquad IN_{n,t} \equiv \sum_{\tau \in \{c,p\}} V^\tau_{n,t} K^\tau_{n,t} + w_{n,t} L_{n,t} + V^R_{n,t} R_{n,t} + V^M_{n,t} M_{n,t}$	$\forall (n,t)$
(T5)	$P^C_{n,t}\, C_{n,t} \ +\ \sum_{\tau \in \{c,p\}} (1-\omega^\tau_{n,t})\, P^{I,\tau}_{n,t}\, I^\tau_{n,t} \ =\ IN_{n,t} \ +\ \sum_{\tau \in \{c,p\}} T^\tau_{n,t} \ +\ T^D_{n,t}, \qquad T^\tau_{n,t} \equiv -\omega^\tau_{n,t}\, P^{I,\tau}_{n,t}\, I^\tau_{n,t}$	$\forall (n,t)$
(T5')	$P^C_{n,t}\, C_{n,t} \ +\ \sum_{\tau \in \{c,p\}} (1-\omega^\tau_{n,t})\, \frac{P^{I,\tau}_{n,t}}{\chi^\tau_{n,t}}\, K^\tau_{n,t+1} \ =$	
	$\sum_{\tau \in \{c,p\}} \left[(1-\omega^\tau_{n,t})\, \frac{P^{I,\tau}_{n,t}}{\chi^\tau_{n,t}} (1-\delta^\tau) + V^\tau_{n,t} \right] K^\tau_{n,t} +\ w_{n,t}\, L_{n,t} \ +\ V^R_{n,t}\, R_{n,t} \ +\ V^M_{n,t}\, M_{n,t} \ +\ T^c_{n,t} \ +\ T^D_{n,t}.$	$\forall (n,j,t)$
(T6)	$\sum_{j \in \{m,r,ce,de,o\}} \sum_{i=1}^N \left(Z_{ni,j,t} - Z_{in,j,t}\right) \equiv \sum_{\tau \in \{c,p\}} V^\tau_{n,t} K^\tau_{n,t} - \sum_{\tau \in \{c,p\}} r^\tau_{n,t} K^{\text{eff},\tau}_{n,t} + T^D_{n,t}, T^D_{n,t} \equiv -\phi_{n,t} IN_{n,t} + \frac{L_{n,t}}{\sum_{m=1}^N L_{m,t}} \sum_{i=1}^N \phi_{i,t} IN_{n,t}$	$\forall (n,t)$

Algorithm 2 Dynamic Equilibrium

1: Guess $\{K^p_{n,t}\}_{n\in\mathcal{N},t=2,\cdots,T-1}$, repeat the following until

$$\max_{n,t}\Big|\frac{C_{n,t+1}/L_{n,t+1}}{C_{n,t}/L_{n,t}}\beta\cdot\frac{\psi_{n,t+1}}{\psi_{n,t}}\cdot\left(\frac{\big((1-\omega^\tau_{n,t+1})\,P^{I,\tau}_{n,t+1}/\chi^\tau_{n,t+1}\big)/P^C_{n,t+1}}{\big((1-\omega^\tau_{n,t})\,P^{I,\tau}_{n,t}/\chi^\tau_{n,t}\big)/P^C_{n,t}}\right)\cdot R^\tau_{n,t+1}\Big|<\varepsilon$$

.

(a) $\{K^p_{n,t}\}\xrightarrow{\text{H9}}\{I^p_{n,t}\}$.

(b) Guess $\{K^c_{n,t}\}_{n\in\mathcal{N},t=2,\cdots,T-1}$, repeat the following until $\max_{n,t}\big|R^c_{n,t+1}-R^p_{n,t+1}\big|<\varepsilon\cdot 1e-1$:

(b.1) $\{K^c_{n,t}\}\xrightarrow{\text{H9}}\{I^c_{n,t}\}$.

(b.2) Guess $\{w_{n,t},V^M_{n,t},V^R_{n,t},r^\tau_{n,t}\}$, repeat the following until $\max_{n,t}\big|SN_{n,t}\big|<\varepsilon\cdot 1e-2$:

(b.2.a) $\{r^\tau_{n,t}\}\xrightarrow{\text{H6 H8}}\{\lambda^\tau_{ni,j,t},\overline{e}^\tau_{ni,t},\mathcal{K}^{\tau,\text{eff}}_{in,t},\mathcal{K}^{\tau,\text{eff}}_{n,t},V^\tau_{n,t}\}$.

(b.2.b) $\xrightarrow{\text{F3-F4, H2-H3, T1-T2}}\{P_{n,k,t},c_{n,j,t},\pi_{ni,j,t},P^C_{n,t},P^{I,\tau}_{n,t}\}$.

(b.2.c) $\xrightarrow{\text{T3}\sim\text{T6}}\{Z_{n,j,t},C_{n,t},D_{n,t}\}$.

(b.2.d) $\xrightarrow{\text{F5-F6}}\Big\{Dist^L_{n,t},\ Dist^M_{n,t},\ Dist^R_{n,t},\ Dist^{\mathcal{K}^{\tau,\text{eff}}}_{n,t}\Big\}$.

(b.2.e) Update: $Dist^L_{n,t}\equiv\sum_j\gamma^L_{n,j}Y_{n,j,t}-w_{n,t}L_{n,t}$,

$$w'_{n,t}=w_{n,t}+\lambda^w_t\cdot Dist^L_{n,t}/L_{n,t},\quad V^{M\prime}_{n,t}=V^M_{n,t}+\lambda^M_t\cdot Dist^M_{n,t}/M_{n,t},$$
$$V^{R\prime}_{n,t}=V^R_{n,t}+\lambda^R_t\cdot Dist^R_{n,t}/R_{n,t},\quad r^{\tau\prime}_{n,t}=r^\tau_{n,t}+\lambda^\tau_t\cdot Dist^{\mathcal{K}^{\tau,\text{eff}}}_{n,t}/\mathcal{K}^{\tau,\text{eff}}_{n,t}.$$

(b.2.f) $\to\Big\{SN_{n,t}\equiv EX_{n,t}-IM_{n,t}+D_{n,t}\equiv Dist^L_{n,t}+Dist^M_{n,t}+Dist^R_{n,t}+Dist^{\mathcal{K}^{\tau,\text{eff}}}_{n,t}\Big\}$.

(b.2.g) Set $\{w_{n,t},V^M_{n,t},V^R_{n,t},r^\tau_{n,t}\}\leftarrow\{w'_{n,t},V^{M\prime}_{n,t},V^{R\prime}_{n,t},r^{\tau\prime}_{n,t}\}$ and repeat.

(b.3) $\xrightarrow{\text{H4}}\{R^p_{n,t+1},R^c_{n,t+1}\}$, and $V^c_{n,t+1}{}'=\dfrac{(1-\omega^c_{n,t+1})\,P^{I,c}_{n,t+1}}{\chi^c_{n,t+1}}\left[(\delta^c-\delta^p)+\dfrac{\chi^p_{n,t+1}\,V^p_{n,t+1}}{(1-\omega^p_{n,t+1})\,P^{I,p}_{n,t+1}}\right]$.

(b.4) $\to$ Update $K^c_{n,t+1}{}'$ with

$$K^c_{n,t+1}{}'=K^c_{n,t+1}\cdot\left[1+\lambda_{K^c}\cdot\frac{V^c_{n,t+1}{}'-V^c_{n,t+1}}{V^c_{n,t+1}}\right]\text{ or }K^c_{n,t+1}{}'=K^c_{n,t+1}\cdot\left(\frac{V^c_{n,t+1}{}'}{V^c_{n,t+1}}\right)^{\lambda_{K^c}},$$
$$\text{or }K^c_{n,t+1}{}'=K^c_{n,t+1}\cdot\left[1+\lambda_{K^c}\cdot\frac{R^p_{n,t+1}-R^c_{n,t+1}}{R^c_{n,t+1}}\right]\text{ or }K^c_{n,t+1}{}'=K^c_{n,t+1}\cdot\left(\frac{R^p_{n,t+1}}{R^c_{n,t+1}}\right)^{\lambda_{K^c}}.$$

(b.5) Set $\{K^c_{n,t}\}\leftarrow\{K^{c\prime}_{n,t}\}$ and repeat.

(c) $\xrightarrow{\text{H5}}R^p_{n,t+1}{}'=\dfrac{u'(C_{n,t})}{u'(C_{n,t+1})}\Big[\beta\left(\dfrac{(1-\omega^p_{n,t+1})P^{I,p}_{n,t+1}/\chi^p_{n,t+1}}{(1-\omega^p_{n,t})P^{I,p}_{n,t}/\chi^p_{n,t}}\right)\Big]^{-1}$ .Update $K^p_{n,t+1}{}'$, with

$$K^p_{n,t+1}{}'=K^p_{n,t+1}\cdot\left[1+\lambda_{K^p}\cdot\frac{R^p_{n,t+1}{}'-R^p_{n,t+1}}{R^p_{n,t+1}}\right]\text{ or }K^p_{n,t+1}{}'=K^p_{n,t+1}\cdot\left(\frac{R^p_{n,t+1}{}'}{R^p_{n,t+1}}\right)^{\lambda_{K^p}}$$

(d) Set $\{K^p_{n,t}\}\leftarrow\{K^{p\prime}_{n,t}\}$ and repeat.

2: Return $\{K^p_{n,t},K^c_{n,t}\}_{n\in\mathcal{N},t=2,\cdots,T-1}$ and stop.