Carbon Pricing, Green Growth, and the Energy Transition

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Pricing Carbon

If you had to put a price on one ton of CO_2, what would it be?
And who should pay: companies, consumers, or governments?

The Externality: Why Carbon Needs a Price

- GHG emissions cause negative externalities unaccounted for in markets.
- Social cost of carbon estimated between \$40–150/ton CO.
- Pigouvian tax corrects market failure by internalizing social costs.

Sources: IPCC AR6, Pigou (1920), Stern Review

Pigovian Taxes and Optimal Price

- Optimal carbon price equals marginal social damage from emissions.
- Gradually increasing price needed to guide investments.
- Reflects intergenerational equity considerations.

Sources: Tol, R.S.J. Social cost of carbon estimates have increased over time. Nat. Clim. Chang. 13, 532–536 (2023).
Sources: Rickels, W., Meier, F. Quaas, M. The historical social cost of fossil and industrial CO_2 emissions. Nat. Clim. Chang. 13, 742–747 (2023).

Why This Matters

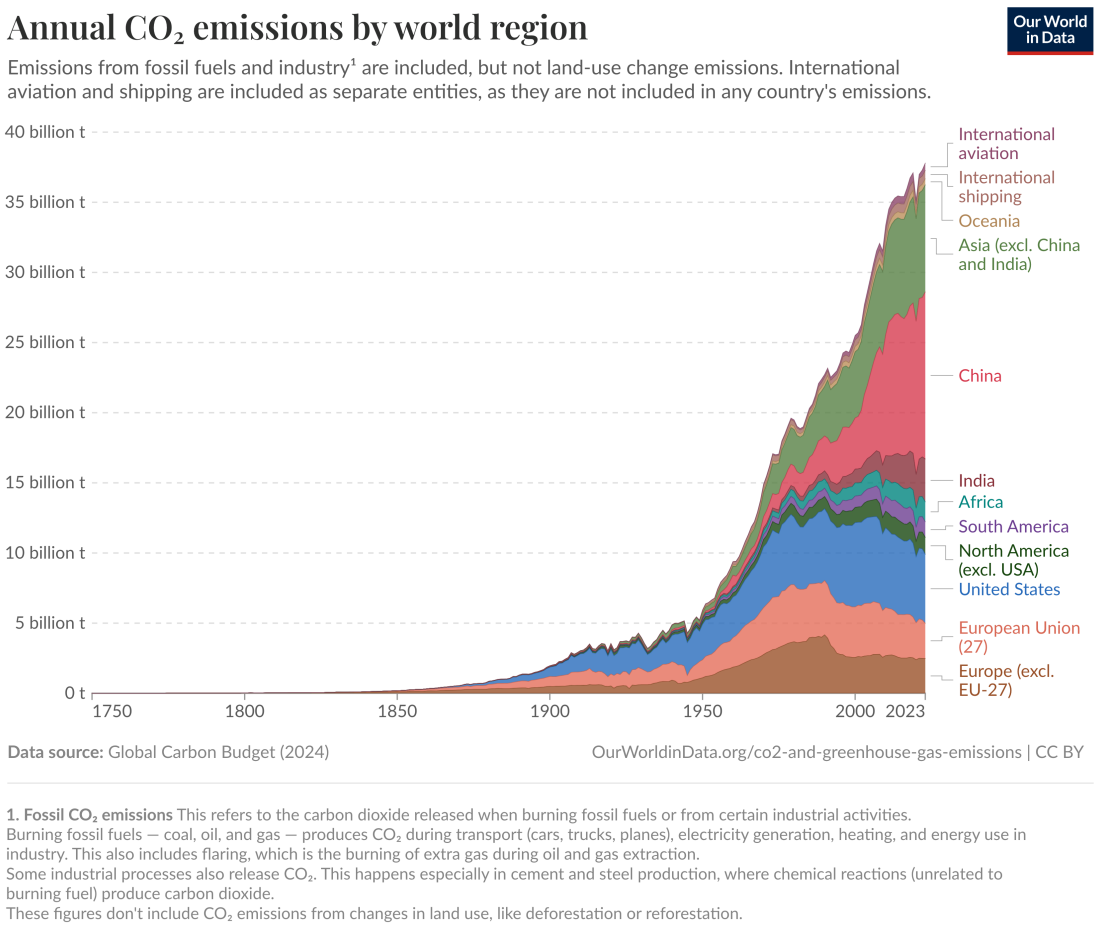


Figure: Global CO_2 emissions 100 million tons per day, mostly unpriced. Data source: Global Carbon Budget (2024)

Why This Matters

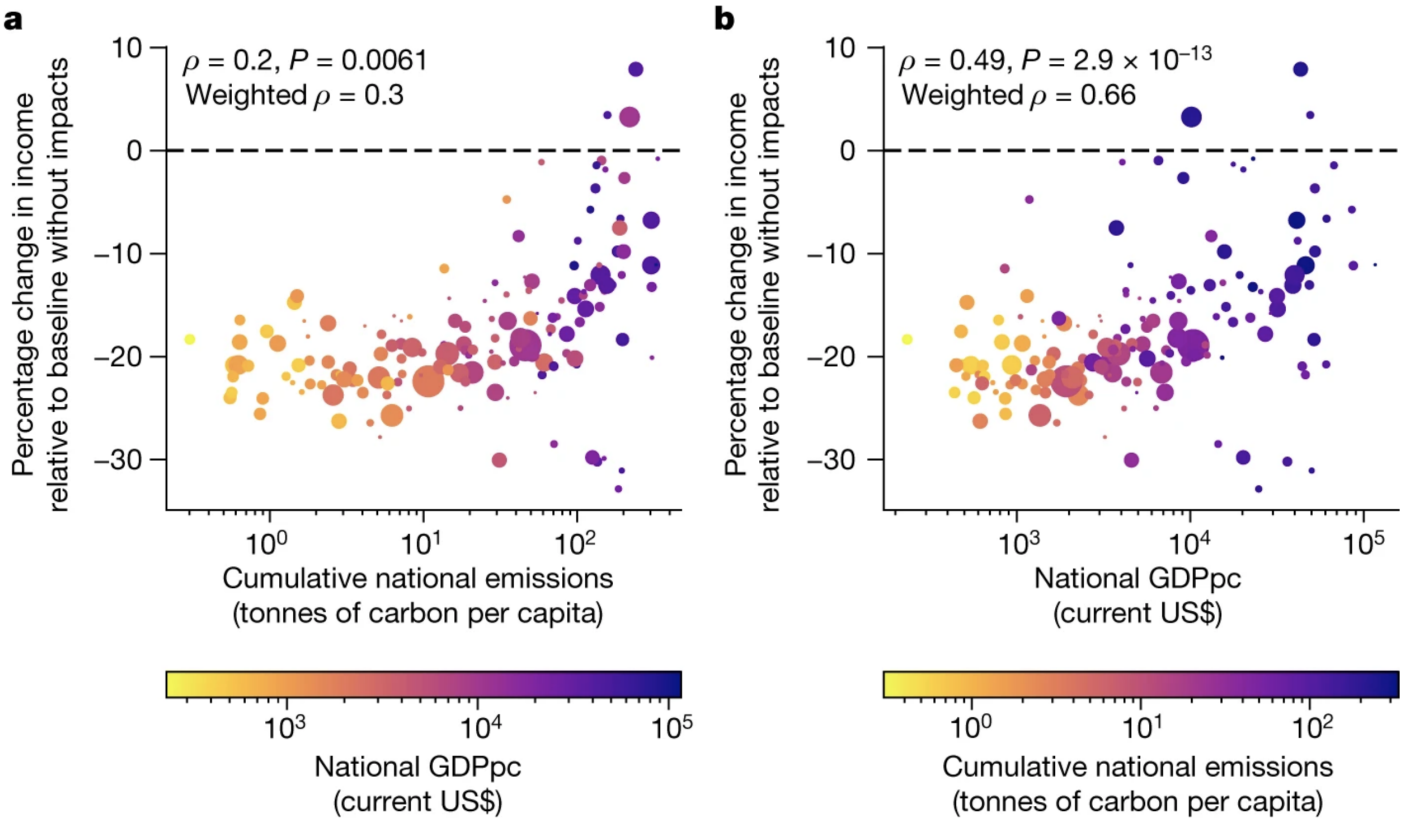


Figure: Kotz, M., Levermann, A. Wenz, L. The economic commitment of climate change. Nature 628, 551–557 (2024).

Distributional Impacts

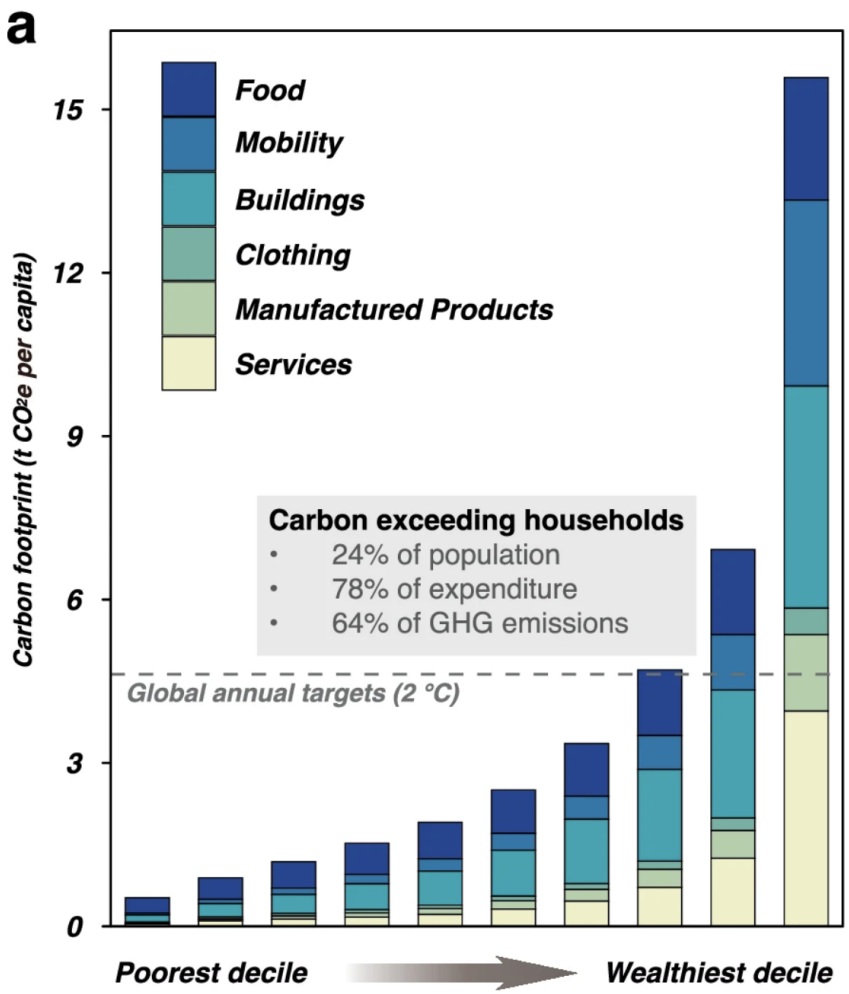


Figure: Guan, Y., Shan, Y., Hang, Y. et al. Unlocking global carbon reduction potential by embracing low-carbon lifestyles. Nat Commun 16, 4599 (2025).

Global burden of disease

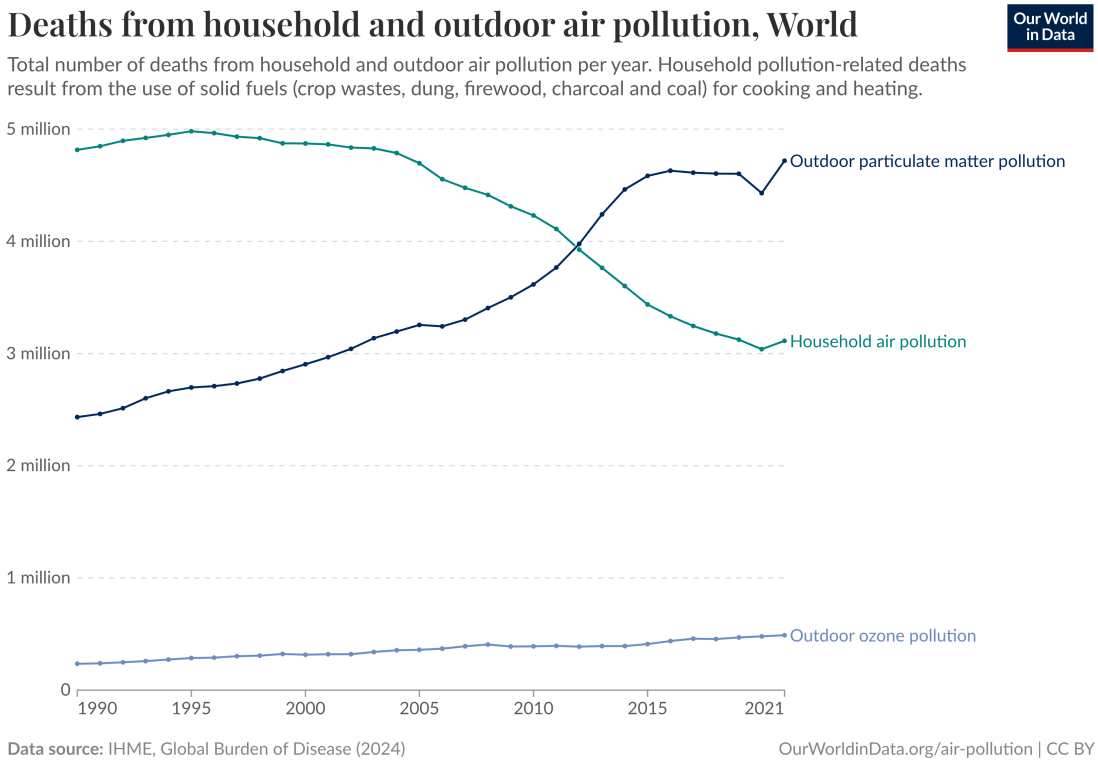


Figure: Data source: IHME, Global Burden of Disease (2024)

The Energy Transition Challenge

- Urgent shift needed from fossil fuels to net-zero by 2050.
- Requires large-scale infrastructure, investment, and lifestyle changes.
- Carbon budget consistent with $\leq 1.5°C$ warming is limited.

Source: DNV Energy Transition Outlook (2023)

Carbon Pricing in the Policy Mix

- Market-based, cost-effective instrument to reduce emissions.
- Complements regulations, subsidies, RD, infrastructure investment.
- Aligns private incentives with social cost of carbon emissions.

Sources: World Bank, OECD reports

Global Carbon Pricing Coverage

- Over 70 carbon pricing schemes worldwide covering 23% of global emissions.
- Examples include EU ETS, China national ETS, Canada's carbon tax.

Source: World Bank Carbon Pricing Dashboard (2025)

Trends in Prices and Revenues

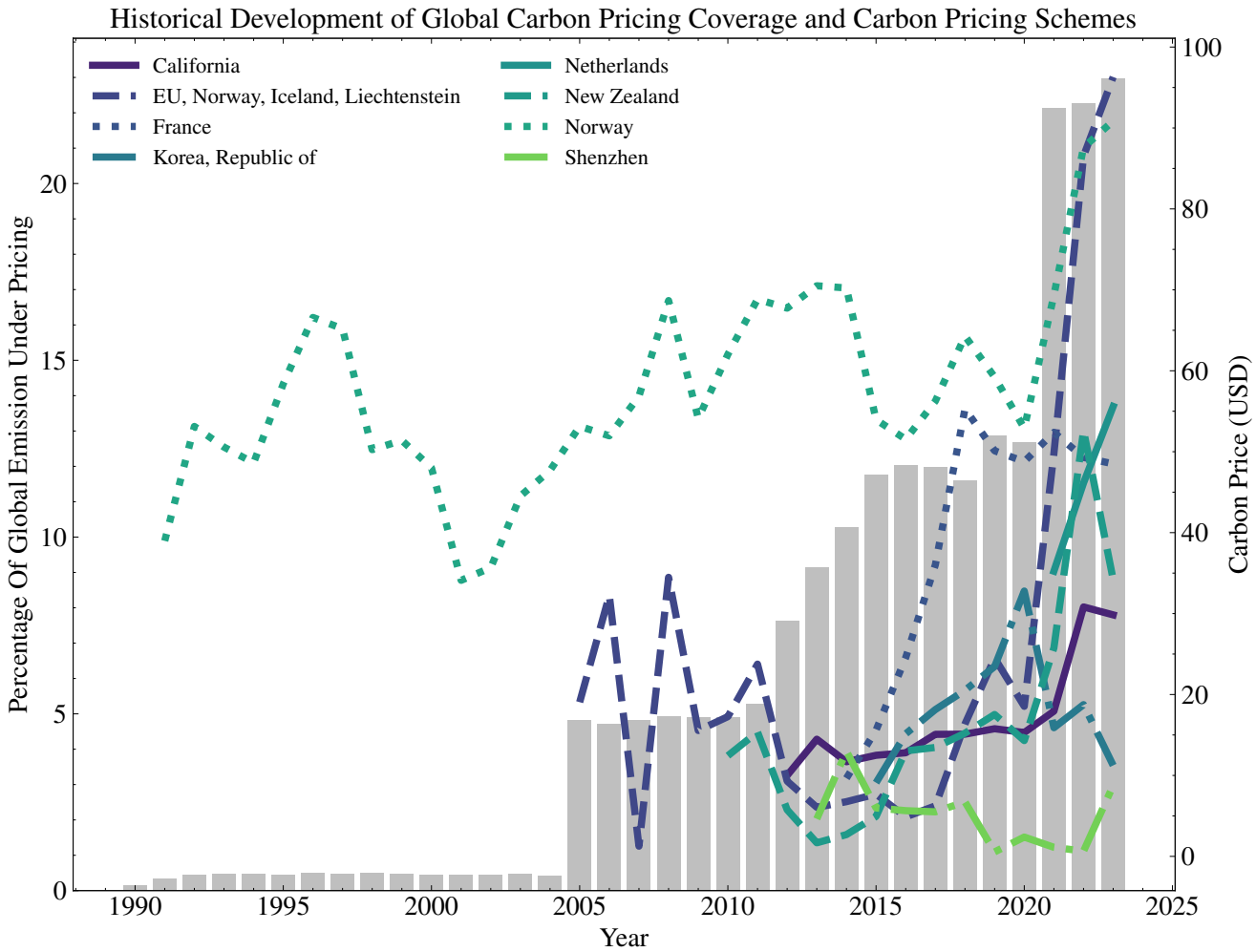


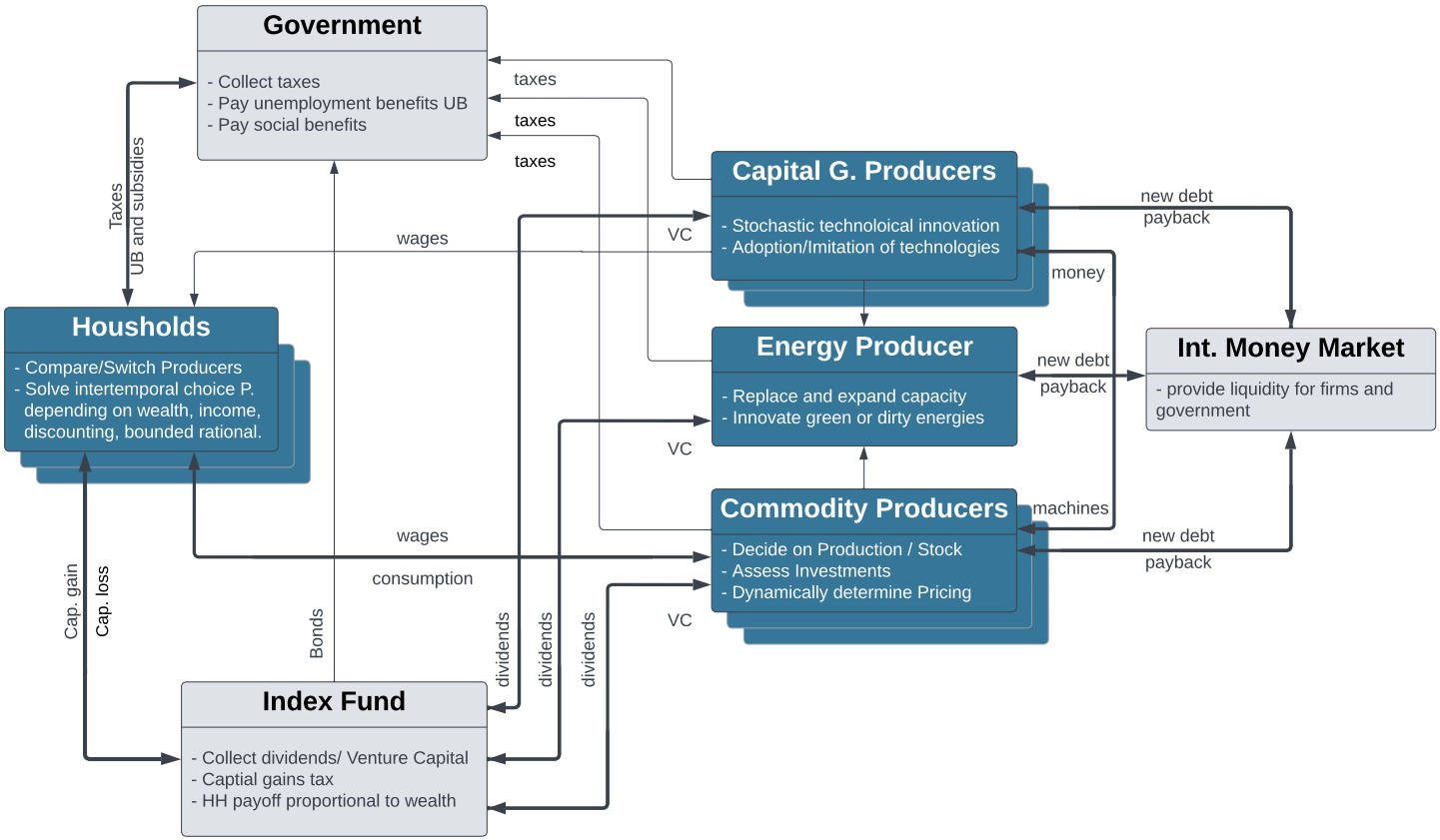
Figure: Mengesha, I., Roy, D. Carbon pricing drives critical transition to green growth. Nat Commun 16, 1321 (2025).

Trends in Prices and Revenues

- Prices mostly range \$15–60 per ton CO_2; many still below social cost.
- Global revenue exceeds \$50 billion per year.
- Revenues fund climate finance, rebates, and general budget needs.

Sources: IMF, OECD, World Bank conference data

Macroeconomic model



Mengesha, I., Roy, D. Carbon pricing drives critical transition to green growth. Nat Commun 16, 1321 (2025).
Dosi, G., Fagiolo, G. Roventini, A. Schumpeter meeting keynes: a policy-friendly model of endogenous growth and business cycles. J. Econ. Dyn. Control 34, 1748–1767 (2010).

Household Agent Equations 1/2

Utility Maximization:

$$U_t^h = \sum_{s=t}^{t+T} \frac{1}{(1+\rho)^{s-t}} u(c_s^h)$$

where U_t^h is household h's utility, ρ discount rate, and c_s^h consumption at time s.

Budget Constraint:

$$w_t^h + r_t^h + \text{transfers}_t^h = c_t^h + \Delta a_t^h$$

where w_t^h is labor income, r_t^h capital income, transfers_t^h tax redistributions, and Δa_t^h change in assets.

Household Agent Equations 2/2

Consumption Decision:

$$c_t^h = \arg\max_c U_t^h \quad \text{s.t. budget constraints and preferences}$$

Labor Market Interaction:

Households supply labor N_t^h and seek wage w_t^h maximizing income

Capital Income:

$$r_t^h = \text{returns from index fund holdings and other assets}$$

Consumer Good Producer Agent Equations 1/2

Profit Maximization:

$$\max_{N_t^i, K_t^i} \ \pi_t^i = p_t^i y_t^i - w_t N_t^i - r_t K_t^i - \tau_E E_t^i - \tau_C C_t^i$$

where

$$y_t^i = A_t^i (K_t^i)^{\alpha} (N_t^i)^{1-\alpha}$$

is the Cobb-Douglas production function with technology A_t^i, capital K_t^i, and labor N_t^i.

Consumer Good Producer Agent Equations 2/2

Technology Evolution (Innovation & Imitation):

$$A_{t+1}^i = A_t^i(1 + \phi_{\text{R\&D}}) + \phi_{\text{policy}}(\tau_C)$$

capturing both RD progress and policy-induced technological change.

Energy and Carbon Costs:

$$\tau_E E_t^i \quad \text{and} \quad \tau_C C_t^i$$

represent the energy tax and carbon tax paid on energy use and emissions.

Input Choices: - Labor N_t^i and capital K_t^i chosen to maximize profits in response to factor prices w_t and r_t.

Producer Markup:

$$p_t^i = m_t^i \cdot \text{marginal cost}$$

where m_t^i is the markup factor.

Energy Good Producer Agent Equations 1/2

Profit Maximization:

$$\max_{N_t^e, K_t^e} \pi_t^e = p_t^e y_t^e - w_t N_t^e - r_t K_t^e - \tau_E E_t^e - \tau_C C_t^e$$

where production output:

$$y_t^e = A_t^e (K_t^e)^{\alpha} (N_t^e)^{1-\alpha}$$

Fuel-Switching and Technology Adoption:

$$A_{t+1}^e = A_t^e (1 + \phi_{\text{R\&D}}) + \phi_{\text{policy}}(\tau_C)$$

reflecting innovation and policy-driven shifts toward greener energy.

Energy and Carbon Tax:

$$\tau_E E_t^e, \quad \tau_C C_t^e$$

represent energy usage fees and carbon emission fees incorporated into production costs.

Energy Good Producer Agent Equations 2/2

Investment Decision Dynamics: Based on expected returns and cost of capital, incorporating green capacity constraints.

Price Setting:

$$p_t^e = m_t^e \times \text{marginal cost}$$

where m_t^e is the markup applied by energy producers.

Key Taxation Parameters in the Model

- τ_L: Labor income tax — tax households pay on their labor income.
- τ_K: Capital tax — tax households pay on capital income received from the index fund (IF).
- τ_Π: Profit tax — levied on positive profits made by producers.
- τ_E: Energy tax — additional fee producers pay per unit of energy used in production.
- τ_C: Carbon tax — additional fee producers pay per unit of carbon emitted during production.

Critical Transition

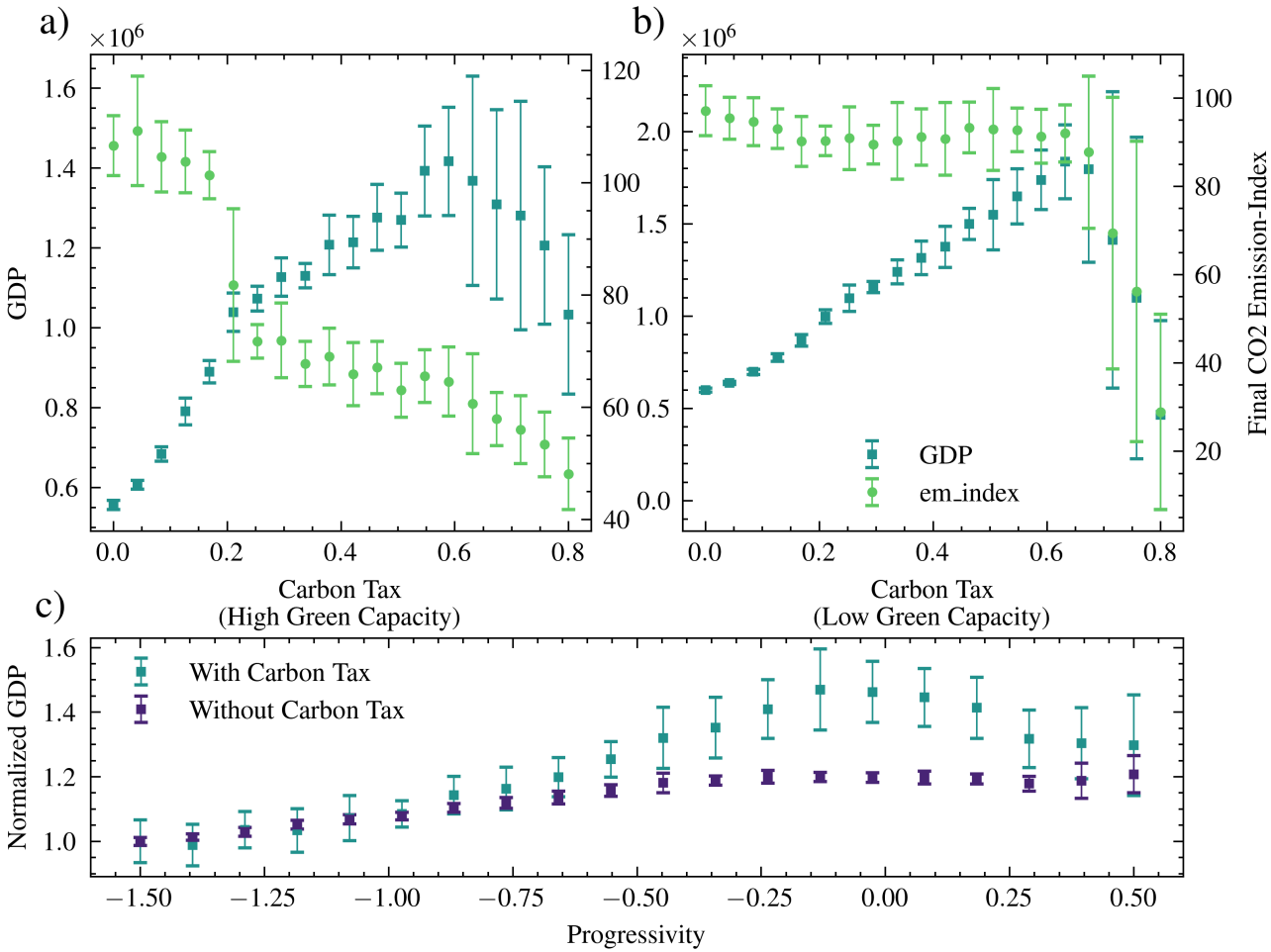


Figure: Mengesha, I., Roy, D. Carbon pricing drives critical transition to green growth. Nat Commun 16, 1321 (2025).

Green Growth Concept

- Decoupling economic growth from carbon emissions.
- Relative and absolute decoupling explained.
- Examples of partial decoupling progress.

Early Warning Indicators

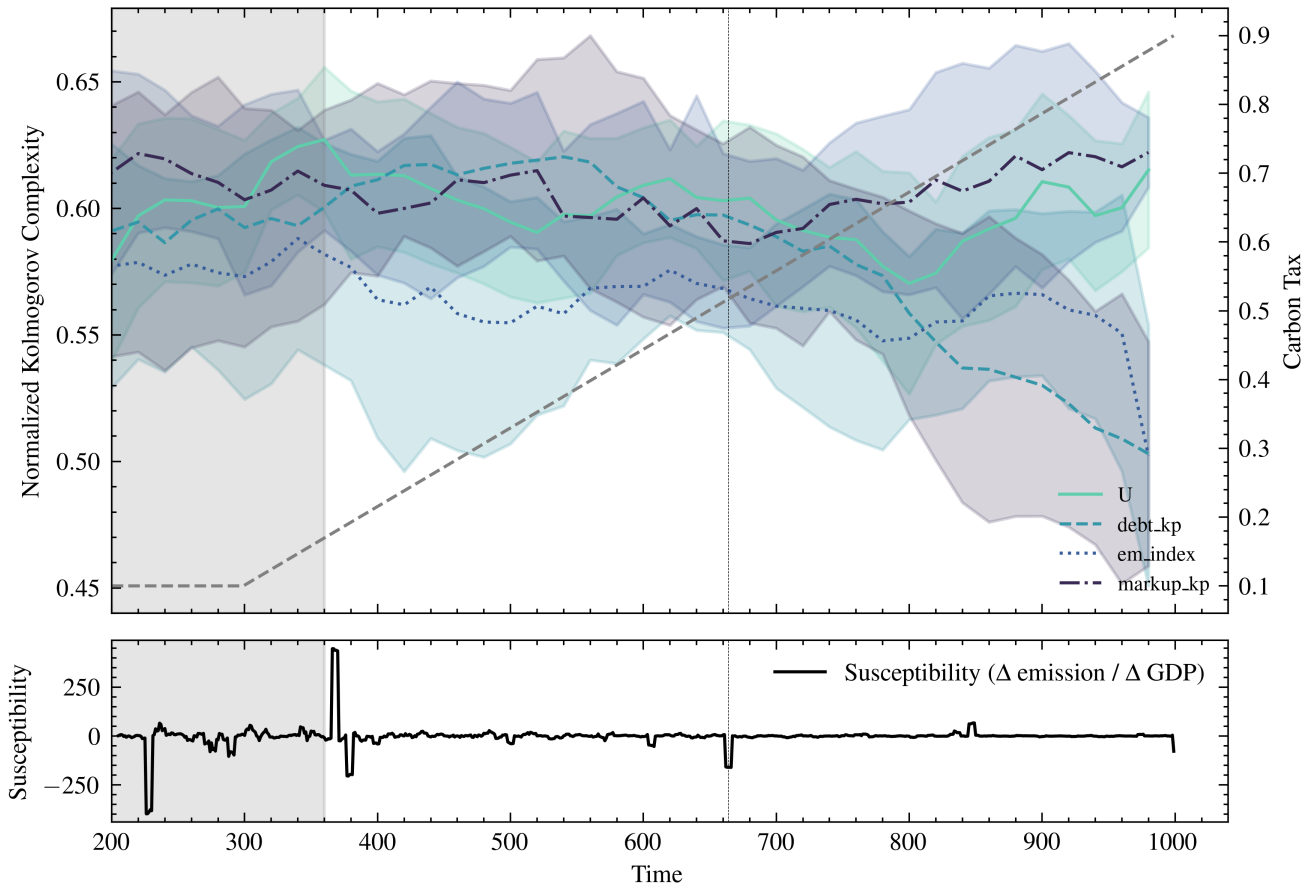


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Distributional Impacts

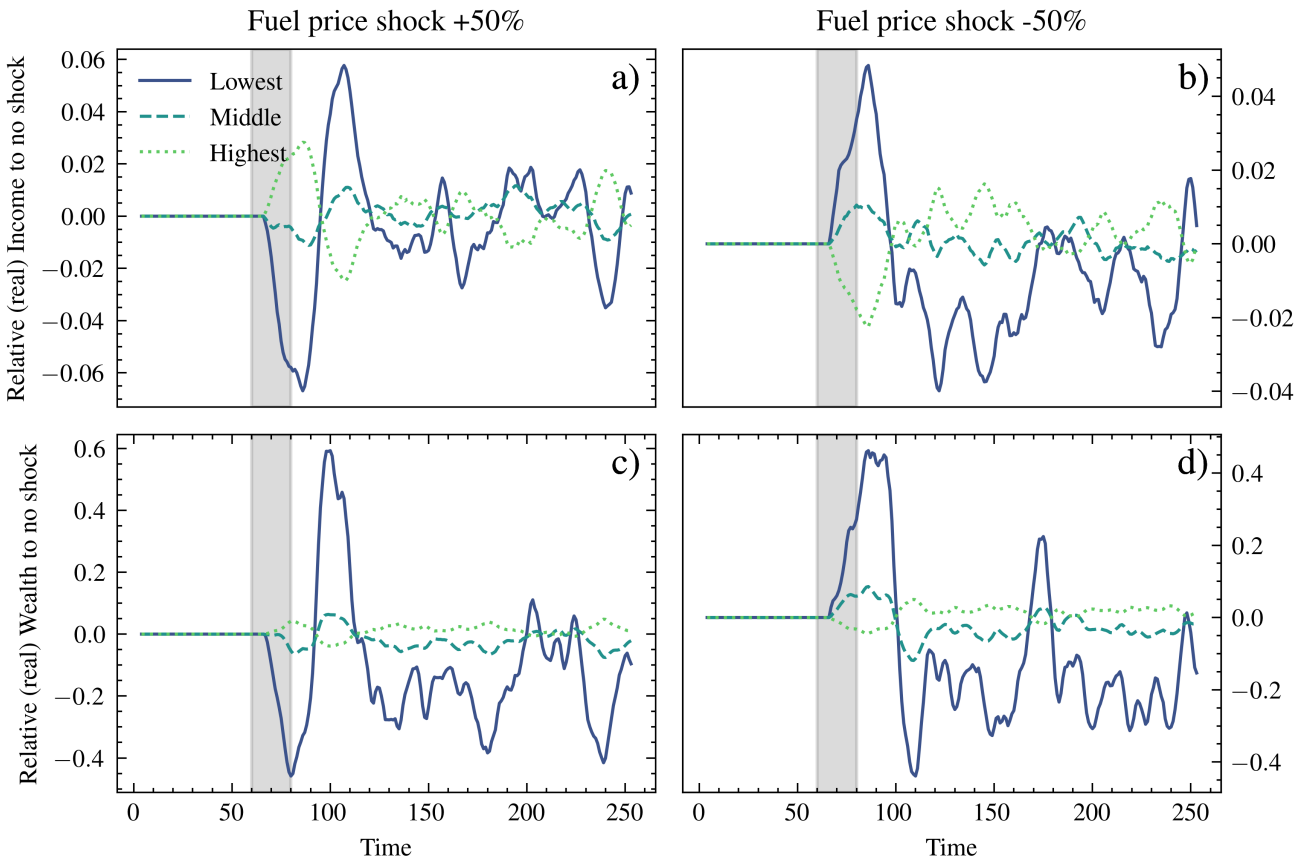


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Distributional Impacts

- Carbon pricing burden varies by income, region and industry.
- Equity addressed via rebates, dividends, and targeted relief.

Sources: Mengesha, I., Roy, D. Carbon pricing drives critical transition to green growth. Nat Commun 16, 1321 (2025).

Endogenizing Political Capital & Carbon Tax (1/2)

Concept: Carbon tax evolves dynamically based on *political capital* as a proxy for public sentiment.

Political Capital Definition:

$$P_t = \frac{1}{N} \sum_{i=1}^{N} \text{opinion}_t^i, \quad \text{where} \quad \text{opinion}_t^i \in [-1, 1]$$

- Aggregated from agent opinions on increasing/decreasing carbon tax. - Opinions are **updated endogenously** based on current simulation data.

Generative Agents (LLMs):

- Receive context: carbon tax level, emission reductions, wage, unemployment, redistribution.
- Use prompts to evaluate support for carbon tax change.
- Output continuous opinion scores reflecting self-interest climate outcomes.

Endogenizing Political Capital & Carbon Tax (2/2)

Aggregation and Policy Feedback:

$$\text{Political Capital } P_t \rightarrow \text{Policy Decision} \rightarrow \tau_c(t+1)$$

- Carbon tax τ_c adjusted up/down if P_t crosses thresholds (e.g., P_{raise}, P_{lower}).
- Changes are smoothed to avoid abrupt jumps and reflect political inertia.
- Dynamic feedback loop:
  1. Simulate economic and emissions outcomes.
  2. Agents update opinions via generative model with new data.
  3. Aggregate opinions to update political capital.
  4. Policy adjusts carbon tax accordingly.

Extensions: misinformation effects, lobbying, media influence, peer effects.

Why is criticality important?

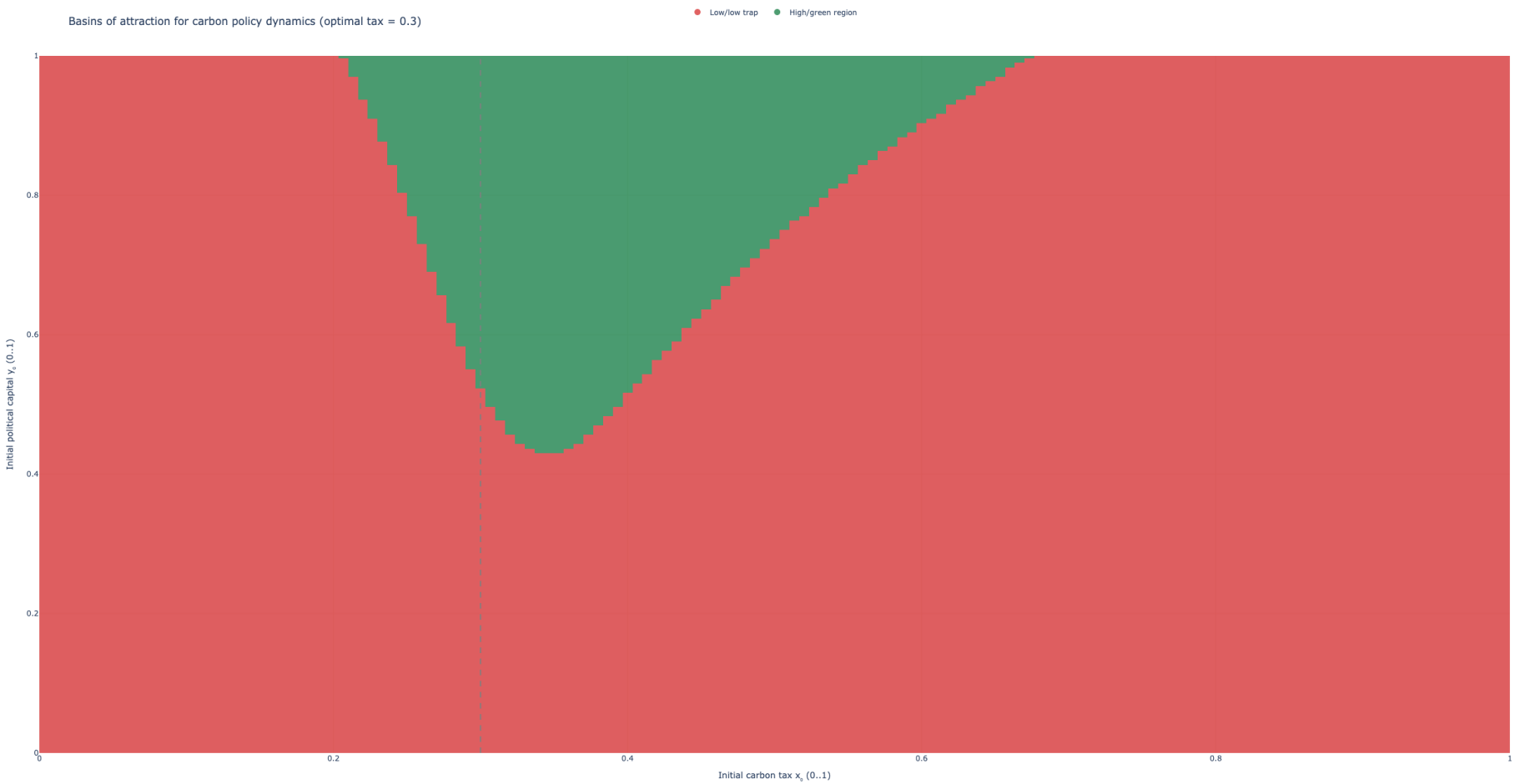


Figure: Roy, D. Path-Dependent Carbon Transitions: Political Capital and Carbon Tax Traps. (*In Review*).

Innovation Effects of Carbon Pricing

- Carbon pricing linked to 25–40% increase in clean tech patents and R&D.
- Strongest effects observed in renewables and industrial sectors.

Source: Nature Communications, 2025

Stimulating Innovation

- Predictable, rising carbon prices spur long-term clean tech investment.
- Empirical evidence shows increased innovation activity post-pricing.

Source: Nature Communications, OECD

Renewable Energy Trends

- Renewables accounted for 51% of new electricity capacity (2017-2022).
- Rapid cost declines enable expanded adoption.

Source: Eurostat, IEA, DNV

Model Overview

- **Agents:** Individual farmers with heterogeneous land sizes.
- **Strategies:** Adopt solar-powered tube wells vs remain on diesel/grid power.
- **Decisions:** Irrigation frequency (stochastic, constrained by policy) and crop choice (rice vs maize).
- **Payoffs:** Economic returns from crop yields minus energy costs and groundwater depletion penalties.
- **Interactions:** Collective groundwater extraction lowers water table, impacting subsequent payoffs.
- **Environment:** Groundwater level evolves with extractions, natural recharge, and policy-driven aquifer recharge.
- **Market Dynamics:** Stochastic rice and maize prices influence farmer choices.
- **Policy Interventions:**
  - Irrigation usage cap limits extraction per farmer.
  - Aquifer recharge increases groundwater supply.

Model Dynamics and Outputs

- Model tracks over time:
  - Groundwater table depth.
  - Average farmer payoff.
  - Fraction of solar adopters.
  - Proportion of rice cultivation.
  - Average irrigation frequency.
  - Stochastic market prices for rice and maize.
- Enables exploration of sustainability, economic viability, and policy effectiveness in water-stressed agriculture.

Tragedy of Commons?

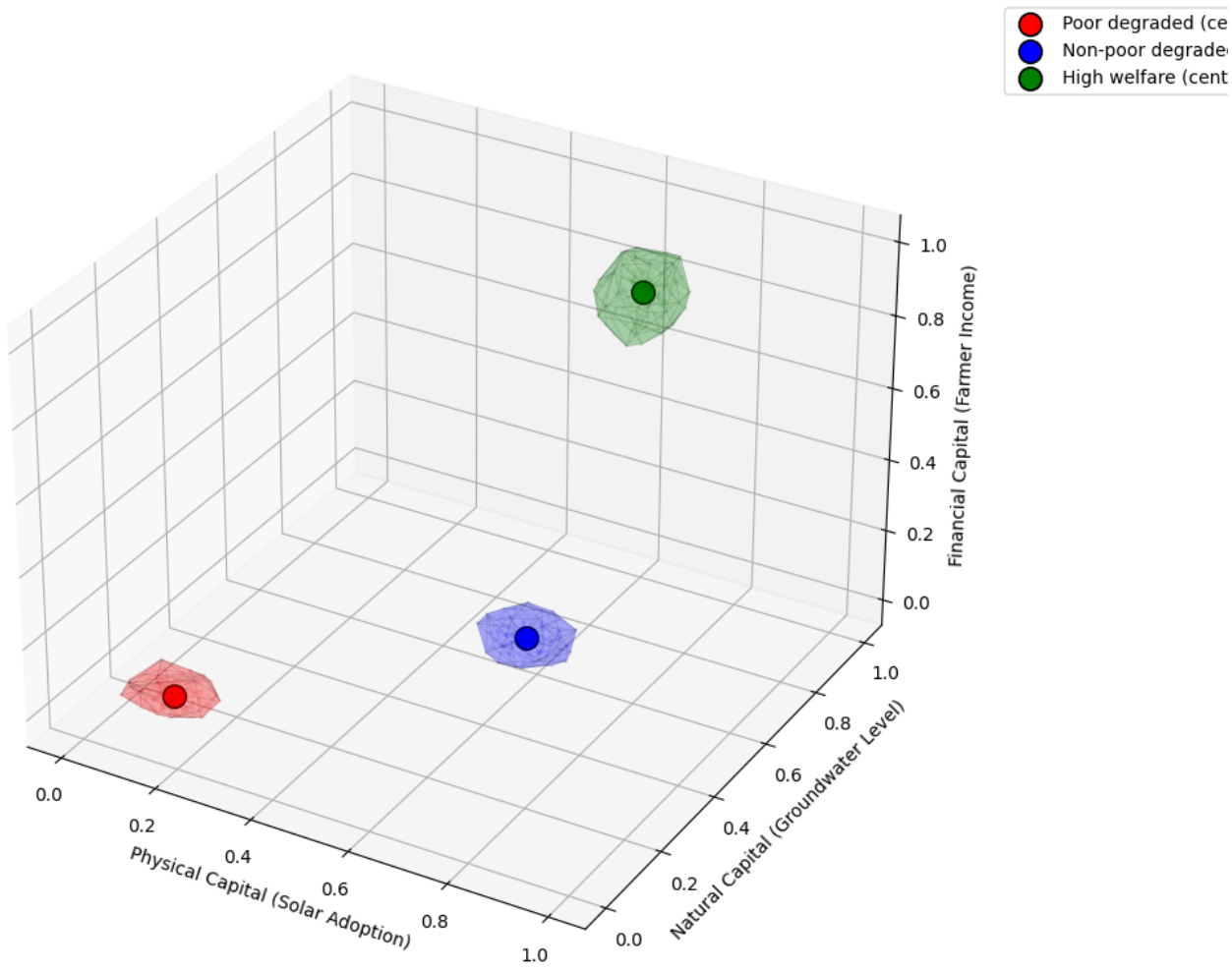


Figure: Two stable traps + 1 degraded unstable trap (Work in progress)

Inefficient Transition?

- Lack of coordinated, collective action can create an inefficient and vulnerable transition
- Grid upgrades, battery storage, hydrogen infrastructure essential.
- Investment needs rise to trillions annually.

International Coordination

- Carbon leakage and competitiveness concerns.
- Border Carbon Adjustments as emerging solution.

Source: WTO, Climate policy research

Equity and the Global South

- Balancing growth, development, and decarbonization.
- Need for capacity-building and climate finance.

Frontiers and Outlook

- Increasing price ambition aligned with net-zero targets.
- Integration with negative emissions and economy-wide coverage.

Conclusions and Open Questions

- Optimal carbon pricing reduces emissions - but traps can emerge.
- Success depends on design, fairness, and political capital.
- Important research questions remain on long-term impacts and global coordination.