Green Development

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15th Energy & Climate Economics Conference, Toulouse

June 2026

The views expressed herein are those of the authors and not necessarily those of the Federal Reserve Bank of New York or any other person affiliated with the Federal Reserve System. Bruno Conte acknowledges funding from the EU's Horizon Europe programme under the Marie Sklodowska-Curie grant agreement No 101146979-SPEED, and the project PID2024-161155NB-I00, funded by MICIU/AEI/10.13039/501100011033 and FEDER, UE.

Introduction

- The decline in the cost of renewable energy has promoted a shift toward cleaner sources
- Fossil fuels and green energy yield different emissions, but also have distinct
  - **Geography of endowments**
  - **Transport costs**
- The relative evolution of the technology to produce each type of energy can affect
  - The locations where energy is produced
  - The geography of economic activity in the world

Introduction

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  - **Geography of endowments**
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- The relative evolution of the technology to produce each type of energy can affect
  - The locations where energy is produced
  - The geography of economic activity in the world
- **Can green energy lead to faster growth in parts of the developing world?**

What We Do

- Develop a quantitative spatial model of the world economy with an explicit energy sector:
  - Suitability of renewables and the evolution of local fossil fuel stocks
  - Costly energy trade
  - Local investments in green and fossil technology
- Quantify using data on
  - The geography of renewable capabilities, fossil fuel reserves and their extraction costs
  - Realistic energy and goods transportation network (roads, pipelines, powerlines)
- Simulations to assess if renewable technology can be a local development opportunity
  - Current results say **no** – least productive places lag behind in terms of innovation

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Remaining of this talk: ~~Literature.~~ + model + quantification + (preliminary) results + next steps

Model

Preferences & Mobility

- Household chooses consumption good $c_t^h(r)$ and **residential energy $\mathbf{e_t^h(r)}$** to maximize

$$u_t(r) = \bar{u}\bar{\varphi}\left(b_t(r)c_t^h(r)^{\varphi}e_t^h(r)^{1-\varphi}\right)$$

  - Residential energy is a CES composite between fossil fuels and clean sources

$$e_t^h(r) = \left(\varpi^{f,h}(r)^{\frac{1}{\epsilon^h}}e_t^{f,h}(r)^{\frac{\epsilon^h-1}{\epsilon^h}} + \varpi^{c,h}(r)^{\frac{1}{\epsilon^h}}e_t^{c,h}(r)^{\frac{\epsilon^h-1}{\epsilon^h}}\right)^{\frac{\epsilon^h}{\epsilon^h-1}}$$

  - Consider taxes and subsidies specific to each location r and energy source j, $\tau_t^{j,h}(r)$
  - $b_t(r) = \bar{b}_t(r)L_t(r)^{-\lambda}$ are local amenities evolving as $\bar{b}_t(r) = \left(1 + \Lambda^b(\Delta T_t(r), T_{t-1}(r))\right)\bar{b}_{t-1}(r)$

- Household spatial sorting as in Desmet et al. (2021) and Cruz and Rossi-Hansberg (2024)

Consumption Good Technology

- Production function of consumption goods

$$q_t(r) = z_t^q(r) a_t^q(r)^{\frac{1}{\theta^q}} L_t^{\text{prod},q}(r)^{\iota} L_t^{\text{innov},q}(r)^{\gamma} h_t^q(r)^{\mu} e_t^q(r)^{1-\iota-\mu-\gamma}$$

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  - Innovation costs expressed in terms of labor and given by $\nu^q w_t(r)$
  - Consider taxes and subsidies specific to each location r and energy source j, $\tau_t^{j,q}(r)$
  - $z_t^q(r)$ is a productivity draw from an iid Fréchet with shape $\theta^q \rightarrow$ gravity in goods

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- **Endogenous growth:** $a_t^q(r) = \bar{a}_t^q(r) L_t^q(r)^{\alpha^q}$ is good-specific productivity, evolving as

$$\bar{a}_t^q(r) = \left(1 + \Lambda^a(\Delta T_t(r), T_{t-1}(r))\right) \left(L_{t-1}^{\text{innov},q}(r)\right)^{\gamma} \left(\bar{a}_{t-1}^q(r)\right)^{\xi^q} \left(\int_{v\in S} D^q(v,r)\bar{a}_{t-1}^q(v)\, dv\right)^{1-\xi^q}$$

Energy Production Technology

- Production function of energy type $j \in \{f, c\}$ is a CES composite of different sources
  - Clean energy ($j = c$) bundle aggregates solar, wind and hydro ($k \in K_c$)

$$\eta_t^j(r) = \left(\sum_{k \in K_j} \eta_t^{j,k}(r)^{\frac{\vartheta^j - 1}{\vartheta^j}} \right)^{\frac{\vartheta^j}{\vartheta^j - 1}}$$

$$\eta_t^{j,k}(r) = z_t^{j,k}(r) \left(a_t^{j,k}(r) / \kappa_t^{j,k}(r) \right)^{\frac{1}{\theta^j}} L_t^{\text{prod},j,k}(r)^{\iota} L_t^{\text{innov},j,k}(r)^{\gamma} h_t^{j,k}(r)^{\mu} c_t^{j,k}(r)^{1-\iota-\gamma-\mu}$$

  - $c_t^{j,k}(r)$ are intermediate inputs (e.g., solar panels)
  - $a_t^{j,k}(r) = \bar{a}_t^{j,k}(r) \left(\sum_{k \in K_j} L_t^{j,k}(r) \right)^{\alpha^j}$ is energy-specific productivity, evolving as before
  - $\boldsymbol{\kappa_t^{j,k}(r) = f^{j,k} \left(\Upsilon_t^{j,k}(r) H(r) \right)}$ is an **extraction friction** (increasing with scarcity for $j = f$)

Gravity in Energy, Trade Balance, and Market Clearing

- Iceberg trade costs lead to gravity equation for bilateral trade flows in energy

$$\pi_t^j(s,r) = \frac{a_t^j(r) mc_t^j(r)^{-\theta^j} \varsigma^j(r,s)^{-\theta^j}}{\int a_t^j(v) mc_t^j(v)^{-\theta^j} \varsigma^j(v,s)^{-\theta^j}\, \mathrm{d}v}$$

  - where $mc_t^j(r)$ is marginal cost and $\varsigma^j(r,s)$ are energy transport costs
  - Trade in fossil fuels: via transportation infrastructure (e.g., ships and pipes)
  - Trade in clean energy: via power grid networks (s. to congestion)
- Trade is balanced in each location
  - but deficits or surpluses at the sector and location level are endogenously determined

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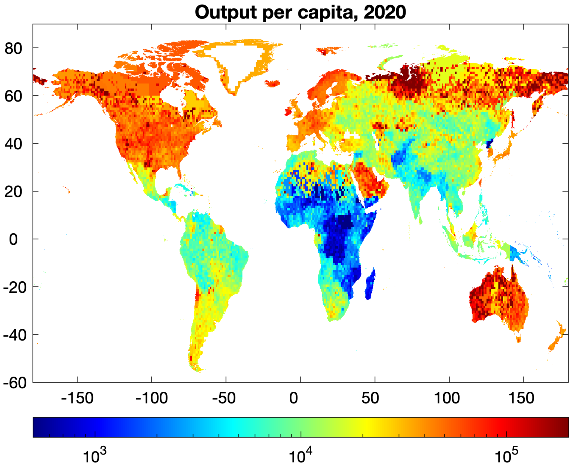
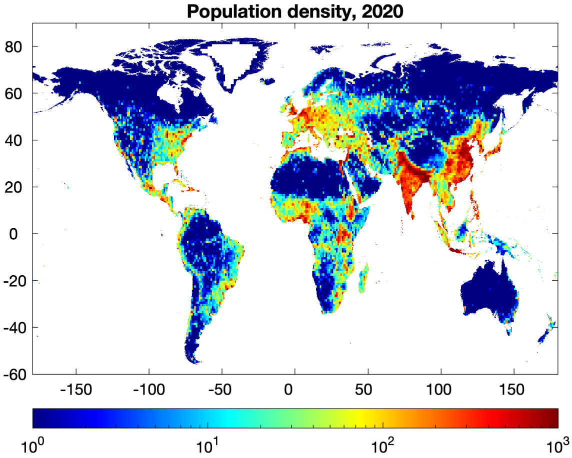
- Trade is balanced in each location
  - but deficits or surpluses at the sector and location level are endogenously determined
- **Equilibrium:** markets for labor, land, goods, and energy clear
  - Subject to tax revenue rebates and the climate feedback loop

Quantification

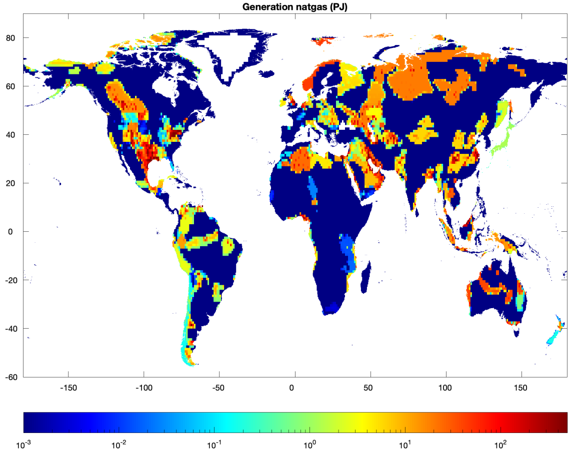
GCP and Population

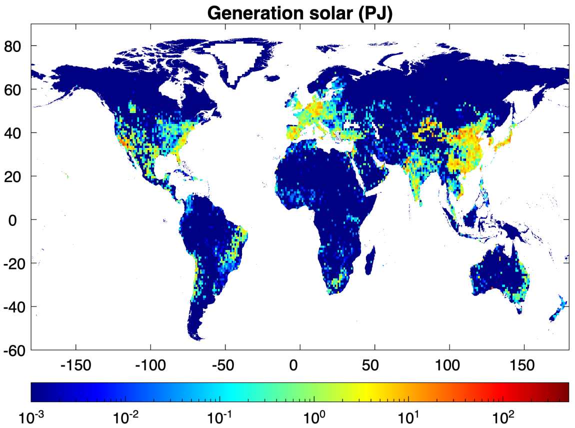




- GCP data from Rossi-Hansberg and Zhang (2025) in 2020 base year
  - Input minimum GCP per capita and population density by country in missing cells

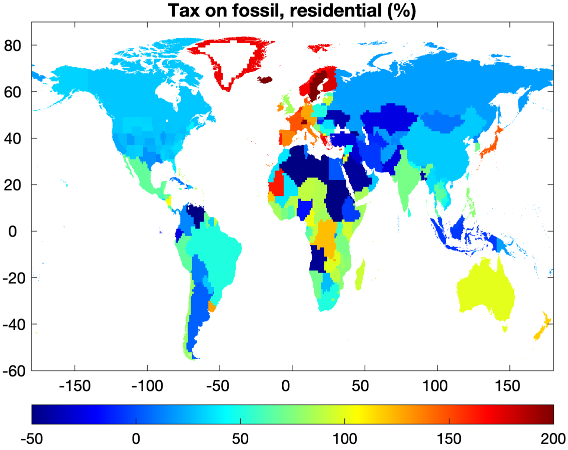
Energy Generation: Natural Gas and Solar

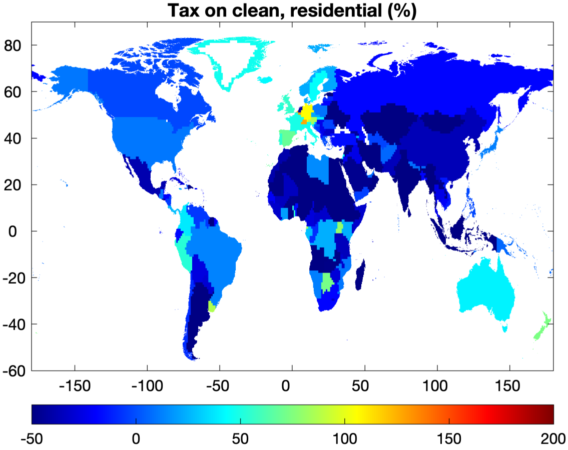




- Collect national and subnational energy data from official statistics (IEA, 2023; EIA, 2022b)
  - Disaggregate across cells based on the location of resources and capacity of power plants

Taxes and Subsidies on Residential (and Industrial) Energy





- Infer energy taxes from retail prices and supply costs (Black et al., 2023; EIA, 2022a)
- **Extraction cost estimation:** panel of stocks + extraction costs across countries

Trade Costs for Goods and Fossil Fuels

- Agents decide from which location to ship goods and the mode of transportation (Allen and Arkolakis, 2022; Fuchs and Wong, 2026)
  - Idiosyncratic iid Fréchet shocks by source and transport mode
  - Five transport modes: road, road-rail-road, road-water-road, road-air-road, road-pipe-road
  - Within each transport mode, the route is given by the least-cost path (Dijkstra, 1959)
- Parametrize cost of traversing two adjacent cells based on:
  - Quality of transport infrastructure (e.g., road density, pipeline capacity)
- Parametrize cost of switching across modes of transportation based on:
  - Quality of intermodal terminals (e.g., ports, airports)
- Estimate trade costs-related parameters to match transport trade shares

Trade Costs for Electricity

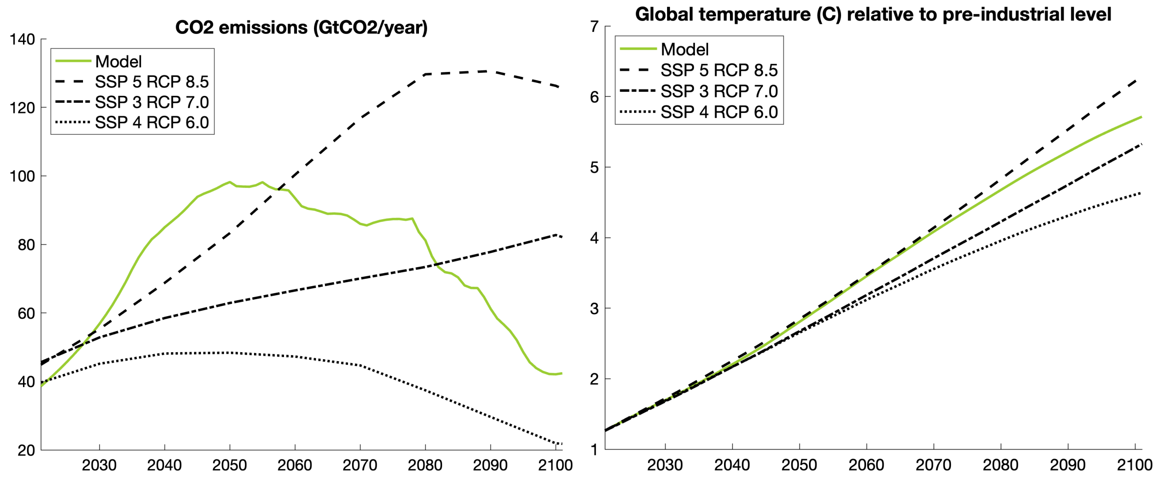
- Clean energy is transmitted exclusively by powerlines
- Parametrize cost of traversing two adjacent cells based on:
  - Voltage of distribution and transmission lines (exogenous network properties)
  - Amount of electricity transmitted (endogenous network properties)
  - Electricity flows within interconnected systems, not across them
- Electricity flows and transport costs are jointly determined
  - Iterative procedure to find fixed point
- Estimate trade costs-related parameters to match system-level energy losses

Parameters for Endogenous Growth: Estimation

- Law of motion for productivities $\bar{a}_t^{jk}(r)$ for $j \in \{q, f, c\}$ depend on $\Theta^j \equiv (\aleph^j, \nu^j, \xi^j, \varrho^j, \gamma^j)$
- Set $\{\Theta^j\}_j$ for $j \in \{q, f, c\}$ to target:
  - Country growth rates for real GDP, fossil fuels and clean energy for the first two periods of the simulation relative to the data for 2012-2021
  - Use Levenberg-Marquardt algorithm to iterate over parameters
  - Main challenge: high-dimensional problem (15 dimensions!)
  - Fairly good fit; new iteration soon available
- Final step: model inversion for fundamentals (productivities, migration costs, amenities)

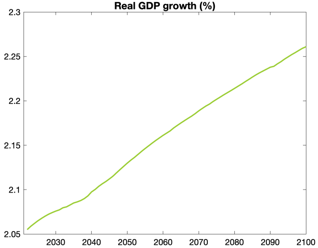
Simulations: Can Clean Energy lead to Green Development?

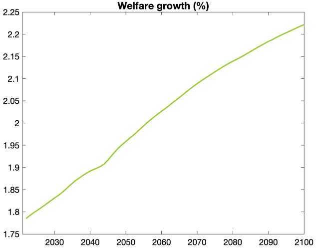
CO_2 Emissions and Temperature

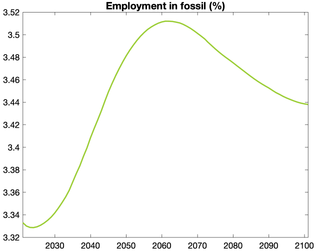


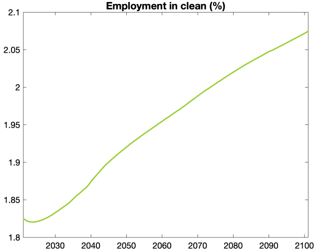
- CO_2 emissions decline because the depletion of fuel reserves increases extraction costs

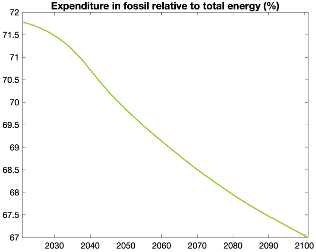
The Evolution of GDP, Welfare, Energy



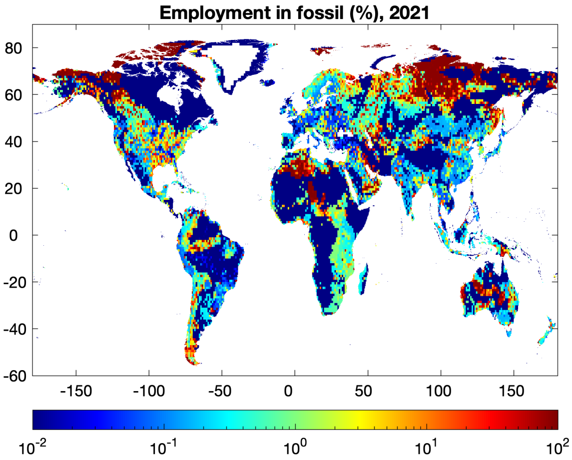


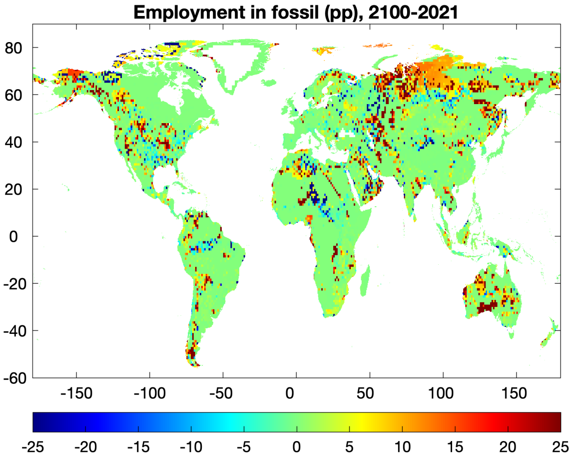






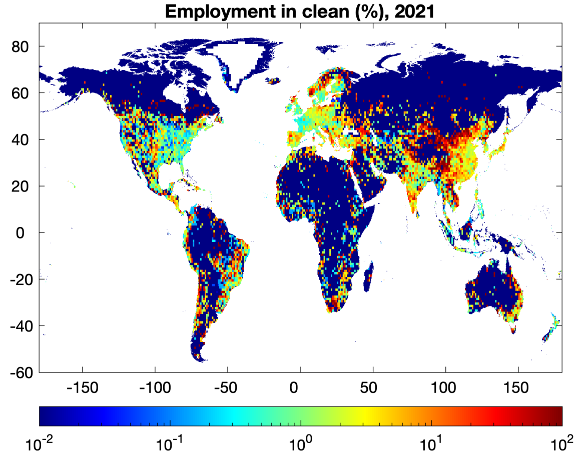
Employment in Fossil Fuel

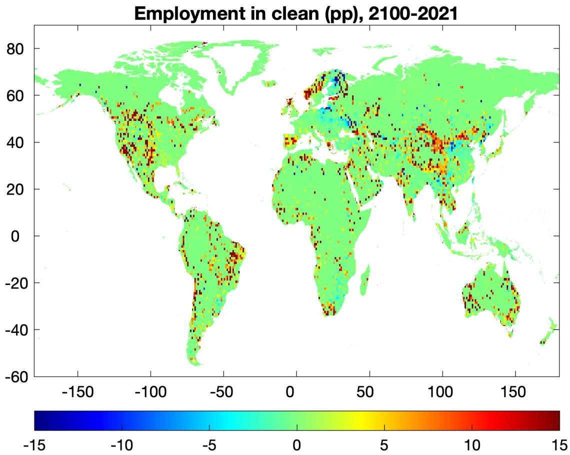




- Specialization patterns strengthen over time

Employment in Clean Energy

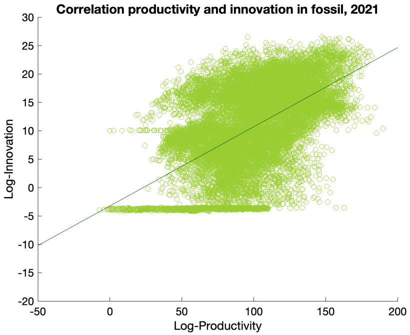


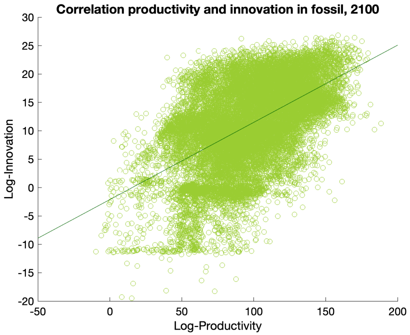


- Specialization patterns strengthen over time

Productivity and Innovation in Fossil Fuels

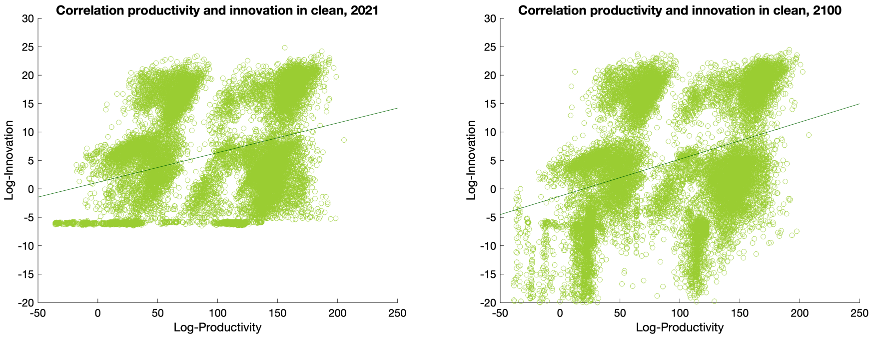
- Innovation in fossil fuels larger in productive locations with little change over time





Productivity and Innovation in Clean Energy

- Low and high productivity regions have a similar relationship with innovation
  - **Low productivity regions due to comparative advantage**
  - **High productivity regions due to initial productivity advantage and dynamic scale effects**
- Can explain the lack of **"Green Development"**



Final Remarks & Next Steps

- Implement stringent environmental policies in the developed world
  - Shift in demand from fossil fuels to clean energy
- Evaluate extensions or interconnections in the electric grid
  - High-voltage lines connecting Africa and Europe
- Promote policies that incentivize technology diffusion
  - Adopters can learn from technological leaders

Thank you!

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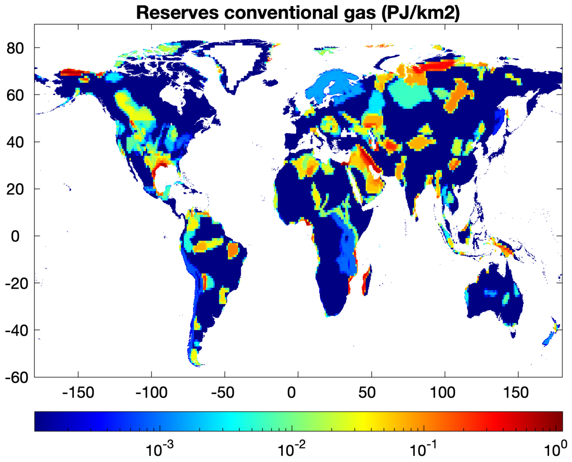
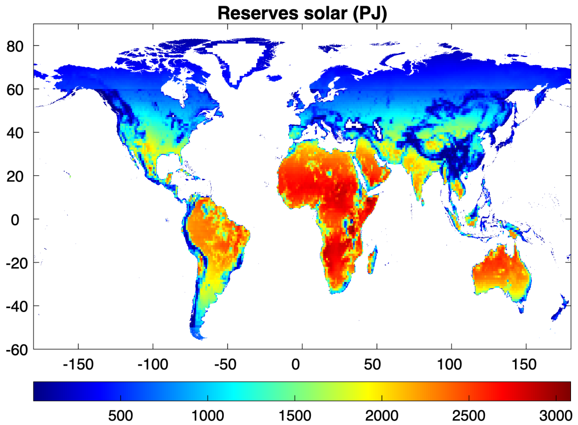
Endowments for Energy: Natural Gas and Solar





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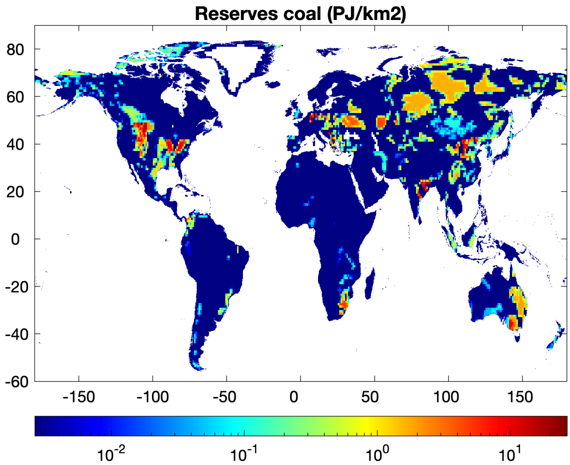
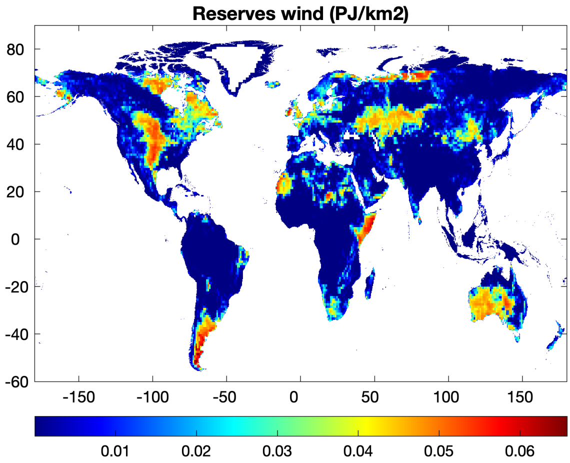
Endowments for Energy: Coal and Wind





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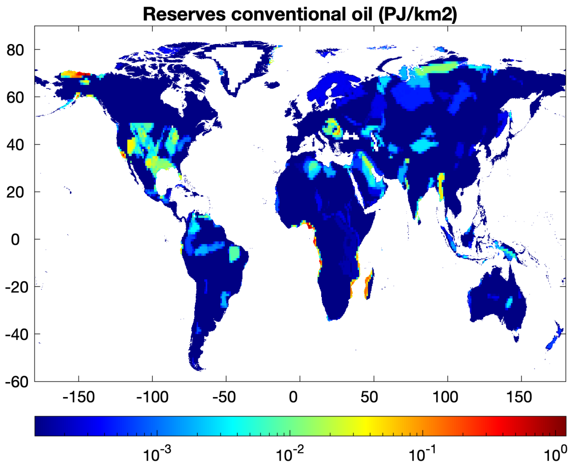
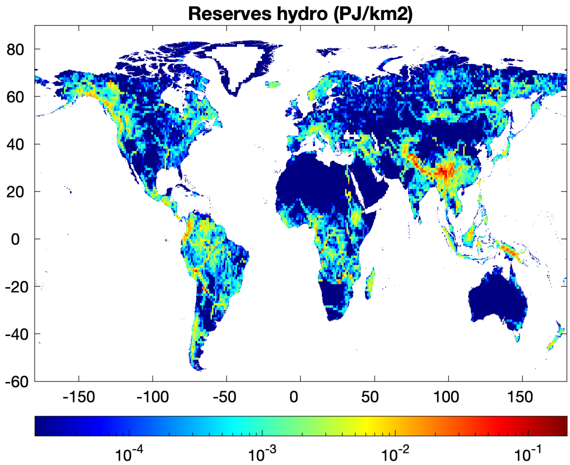
Endowments for Energy: Oil and Hydro





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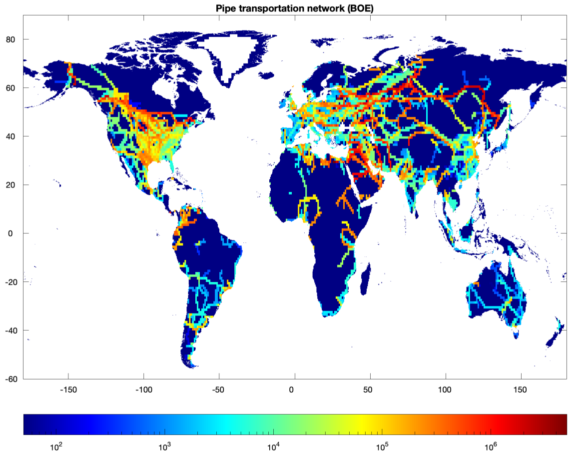
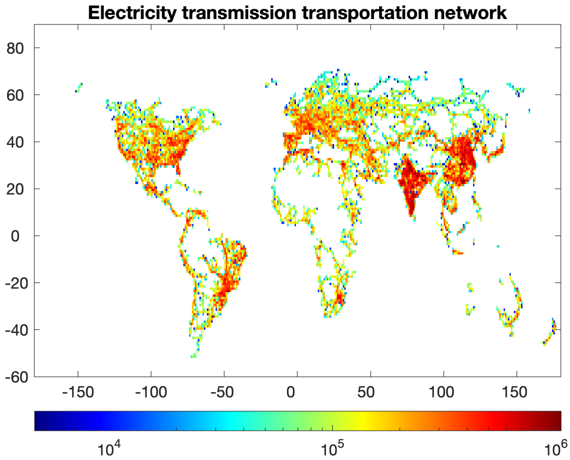
Energy Transportation Network





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Literature Review and Outline

- Environmental Directed Technical Change
  - Acemoglu et al. (2012, 2016, 2023), Aghion et al. (2016), Dechezleprêtre and Hémous (2022), Fried (2018), Hassler et al. (2021), Cicala et al. (2022)
- Spatial Integrated Assessment Models
  - **Arkolakis and Walsh (2023)**, Balboni (2025), Bilal and Rossi-Hansberg (2023), Conte et al. (2021, 2025), Cruz (2024), Cruz and Rossi-Hansberg (2024, 2025), Desmet and Rossi-Hansberg (2015), Desmet et al. (2021), Krusell and Smith Jr (2022), Nath (2025), Rudik et al. (2022)

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Mobility

- Households decide where to live in each period in order to maximize

$$V^i(r_0) = \sum_{t=0}^{\infty} \beta^t u_t(r_t) m(r_t)^{-1} \varepsilon_t^i(r_t)$$

$$u_t(r) = \bar{u} b_t(r) \left(\frac{w_t(r) + R_t(r)/L_t(r) + \Psi_t(r)}{P_t^q(r)^{\varphi} P_t^{e,h}(r)^{1-\varphi}} \right)$$

  - $w_t(r)$ is wage, $R_t(r)$ land rents, $\Psi_t(r)$ tax rebate
  - $P_t^q(r)$ represents goods price and $P_t^{e,h}(r)$ residential energy price
  - $m(r)$ denotes the migration cost of residing in r and ε_t^i is an iid Fréchet shock with shape $1/\Omega$

- Fraction of households residing in each location

$$\frac{L_t(r)H(r)}{L_t} = \frac{\left[u_t(r)m(r)^{-1}\right]^{1/\Omega}}{\int \left[u_t(v)m(v)^{-1}\right]^{1/\Omega} dv}$$

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Gravity in Goods

- Iceberg trade costs lead to gravity equation for bilateral trade flows in goods

$$\pi_t^q(s,r) = \frac{a_t^q(r) mc_t^q(r)^{-\theta^q} \varsigma^q(r,s)^{-\theta^q}}{\int a_t^q(v) mc_t^q(v)^{-\theta^q} \varsigma^q(v,s)^{-\theta^q} \, dv}$$

  - where $mc_t^q(r)$ is marginal cost and $\varsigma^q(r,s)$ are goods transport costs

back

Energy Production Technology

- $\kappa_t^{j,k}(r)$ is an **extraction friction**

$$\kappa_t^{j,k}(r) = f^{j,k}\left(\Upsilon_t^{j,k}(r)H(r)\right)$$

  - which increases as the local stock of resources $\Upsilon_t^{j,k}(r)H(r)$ is depleted

$$\Upsilon_t^{j,k}(r) = \Upsilon_{t-1}^{j,k}(r) - \mathbb{1}\{j = f\} \cdot \eta_t^{j,k}(r)$$

  - where $\eta_t^{j,k}(r)$ is the *flow* of resource j, k extracted for production
  - The generation of clean energy does not exhaust the available resources

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Government, Market Clearing and Climate

- Tax collection is rebated lump sum at the cell level to households

$$\Psi_t(r) = \frac{\sum_{j\in\{f,c\}} \left(\tau_t^{j,h}(r)P_t^j(r)e_t^{j,h}(r)L_t(r)H(r) + \tau_t^{j,q}(r)P_t^j(r)e_t^{j,q}(r)H(r)\right)}{L_t(r)H(r)}$$

- Markets for labor, land, goods, fossil fuels and clean energy clear
- Climate module follows Estrada et al. (2022) and Meinshausen et al. (2020)
  - Damage functions follow Cruz and Rossi-Hansberg (2024)

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Extraction Cost Function for Fossil Fuels

- Parametrize the extraction cost, $\kappa_t^{f,k}(\cdot)$, as a function of reserves, $\Upsilon_t^{f,k}(\cdot)H(\cdot)$

$$\log(\kappa_t^{f,k}(r)) = F_0^{f,k,r} + F_0^{f,k,s} + F_1^{f,k} \log\left(\Upsilon_t^{f,k}(r)H(r)\right) + \epsilon_t^{f,k}(r)$$

  - Welsby et al. (2021) provides cumulative resources and their associated extraction cost for coal, gas, and oil; categorized into 16 regions and by subvariety
  - Allocate fuel reserves over space with data from Oakleaf et al. (2015, 2019)
- Gas and oil highly sensitive to reserve scarcity, but not coal
  - Similar estimation for clean sources: solar is the most sensitive to suitability, and hydro the least

back

Extraction Cost Function: Coal, Natural Gas, and Oil

	Coal	Natural Gas	Oil
log(resource)	0.0786*	-0.1421***	-0.0496***
	(0.0463)	(0.0181)	(0.0103)
FE region	X	X	X
FE source		X	X
N	102	300	304
R^2	0.1489	0.5031	0.6483

Robust standard errors in parentheses

$^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

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Clean Energy Cost Function

- Parametrize the clean energy costs, $\kappa_t^{c,k}(\cdot)$, as a function of suitability, $\Upsilon_t^{c,k}(\cdot)H(\cdot)$
  - NREL (State and Local Planning for Energy) provides the Levelized Cost of Energy (usd/MWh) at the U.S. county-level for 2020

$$\log\left(\kappa_t^{c,k}(r)\right) = F_0^{c,k} + F_1^{c,k}\log\left(\Upsilon_t^{c,k}(r)H(r)\right) + \epsilon_t^{c,k}(r)$$

- Solar is the most sensitive to suitability, and hydro the least
  - Global data on natural suitability from Oakleaf et al. (2015, 2019)

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	Commercial Solar	Residential Solar	Commercial Wind	Residential Wind	All Hydro
log(suitability)	-0.6628***	-0.6795***	-0.2672***	-0.2181***	-0.0090***
	(0.0069)	(0.0074)	(0.0181)	(0.0113)	(0.0018)
weight pop	X	X	X	X	X
N	3,048	3,048	1,955	1,985	1,562
R^2	0.7522	0.734	0.1006	0.1579	0.0155

Standard errors in parentheses

$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

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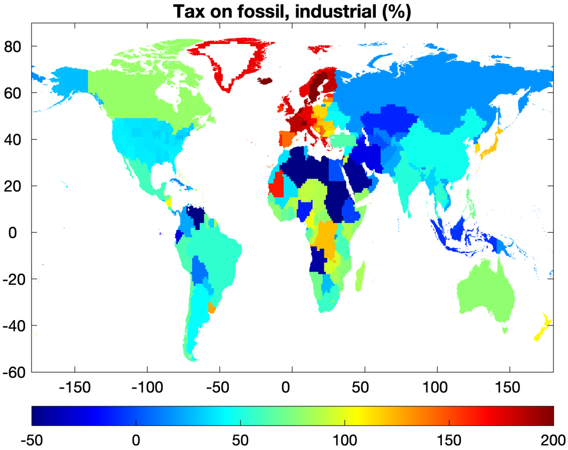
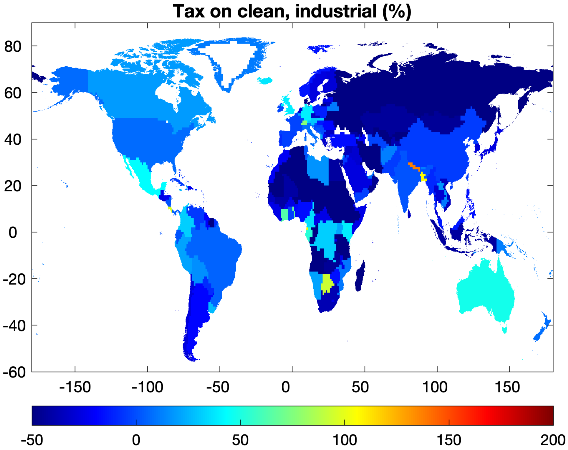
Taxes and Subsidies on Energy





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Trade Costs: Fréchet structure

1. Define the model-derived share of good j shipped through mode m
   1. Agents in destination s first choose from which location r to source the good
   2. Then select the mode of transportation $m \in M$ (single- or multi-modal) to ship the good
   3. Finally choose on which route $x \in X_m(r, s)$ to ship the good

$$p_t^{j,\omega}(r,s,m,x) = \frac{a_t^j(r)^{-1/\theta^j} mc_t^j(r)}{z_t^{j,\omega}(r)} \frac{\varsigma_{m,x}^j(r,s)}{\nu_t^{j,\omega}(r,s,m) \cdot \varepsilon_t^{j,\omega}(r,s,m,x)}$$

- $\varsigma_{m,x}^j(r,s)$ is the trade cost from r to s along route x of transport mode m
- $z_t^{j,\omega}(r)$ is iid Fréchet with shape θ^j and scale 1
- $\nu_t^{j,\omega}(r,s,m)$ is iid Fréchet with shape ρ^j and scale $\Gamma(1-1/\rho^j)^{-1}$ and is observed after $z_t^{j,\omega}(r)$
- $\varepsilon_t^{j,\omega}(r,s,m,x)$ is iid Fréchet with shape f_m^j and scale $\Gamma(1-1/f_m^j)^{-1}$ and is observed after $z_t^{j,\omega}(r)$ and $\nu_t^{j,\omega}(r,s,m)$

back

Trade Costs: Solution by Backward Induction

iii. Conditional on sourcing from r by transport mode m, agent in s chooses route x to minimize shipping costs

- Probability of choosing route x is $\pi^j_{m,x}(s,r)$ and expected shipping cost is $\varsigma^j_m(r,s)$

$$\pi^j_{m,x}(s,r) = \frac{\varsigma^j_{m,x}(r,s)^{-\mathit{f}^j_m}}{\int_{x'\in X_m(r,s)} \varsigma^j_{m,x'}(r,s)^{-\mathit{f}^j_m}\,\mathrm{d}x'}$$

$$\varsigma^j_m(r,s)^{-\mathit{f}^j_m} = \int_{x'\in X_m(r,s)} \varsigma^j_{m,x'}(r,s)^{-\mathit{f}^j_m}\,\mathrm{d}x'$$

- $X_m(r,s)$ is the set of all paths connecting r and s by transport mode m

back

Trade Costs: Solution by Backward Induction

- Conditional on sourcing from r, agent in s picks transport mode m to min shipping costs
  - Probability of choosing transport mode m is $\pi^j_m(s,r)$ and expected shipping cost is $\varsigma^j(r,s)$

$$\pi^j_m(s,r) = \frac{\varsigma^j_m(r,s)^{-\rho^j}}{\sum_{n\in M}\varsigma^j_n(r,s)^{-\rho^j}}$$

$$\varsigma^j(r,s)^{-\rho^j} = \sum_{n\in M}\varsigma^j_n(r,s)^{-\rho^j}$$

- Knowing the expected shipping cost $\varsigma^j(r,s)$, agent in s chooses origin r to minimize shipping costs, so that the probability of choosing origin r is

$$\pi^j_t(s,r) = \frac{a^j_t(r)mc^j_t(r)^{-\theta^j}\varsigma^j(r,s)^{-\varsigma^j_0\theta^j}}{\int a^j_t(v)mc^j_t(v)^{-\theta^j}\varsigma^j(v,s)^{-\varsigma^j_0\theta^j}\,dv}$$

back

Trade Costs: Single Transport Mode (e.g., road)

- A route x is a sequence of locations starting in r and ending in s, $x := \{r = x_0, x_1, \cdots, x_L = s\}$
  - And L is the number of links crossed on the route

$$\underbrace{\varsigma^j_{m,x}(r,s)}_{\substack{\text{transport cost}\\ \text{between } r \text{ and } s\\ \text{by mode } m\\ \textbf{and route x}}} = \prod_{\ell=1}^{L} \underbrace{\mathcal{T}^j_m(x_{\ell-1}, x_\ell)}_{\substack{\text{cost of crossing}\\ \text{two adjacent cells}\\ \text{by mode } m}},$$

$$\underbrace{\varsigma^j_m(r,s)}_{\substack{\text{transport cost}\\ \text{between } r \text{ and } s\\ \text{by mode } m}}{}^{-f^j_m} = \left[\sum_{L=0}^{\infty} \mathcal{T}^L_m\right]_{(r,s)},$$

  - where $\mathcal{T}_m := [\mathcal{T}^j_m(r,s)^{-f^j_m}]$ is the adjacency cost matrix of mode m
  - When $f^j_m \to \infty$, transport costs converge to those of the least-cost route
  - Compute the shortest path distance with the MatLab function `distances`

back

Trade Costs: Multiple Transport Modes (e.g., road-rail-road)

- Consider paths that start and end in sub-mode n_1 but move through n_2
  - For instance, mode m = road-rail-road, starts and ends in sub-mode n_1 = road but might use sub-mode n_2 = rail
  - Transition back and forth between n_1 and n_2 several times subject to costly mode switching
  - A route x is a sequence of locations and sub-modes starting in cell r and sub-mode n_1 and ending in cell s and sub-mode n_1

$$\underbrace{\varsigma_m^j(r,s)}_{\substack{\text{transport cost} \\ \text{between } r \text{ and } s \\ \text{by mode } m}}^{-f_m^j} = \left[\sum_{L=0}^{\infty} \begin{bmatrix} \mathcal{T}_{n_1} & \mathcal{S}_{n_1,n_2} \\ \mathcal{S}_{n_2,n_1} & \mathcal{T}_{n_2} \end{bmatrix}^L\right]$$

  - Consider $f_m^j \to \infty$ and compute the shortest path distance

back

Trade Costs: Parametrization

2. Parametrize transport adjacency, $\mathcal{T}^j_m(\cdot)$, and switching, $\mathcal{S}^j_{m,n}(\cdot)$, costs

$$\log \mathcal{T}^j_m(r,s) = \begin{cases} t^j_{0,m} + t^j_{1,m} \cdot \log \text{dist}(r,s) + t^j_{2,m} \cdot \left(\log \mathtt{T}_m(r) + \log \mathtt{T}_m(s)\right) > 0 & \text{if } r \text{ and } s \text{ are adjacent cells} \\ \infty & \text{otherwise} \end{cases}$$

$$\log \mathcal{S}^j_{m_1,m_2}(r,s) = \begin{cases} s^j_{0,m_1,m_2} + s^j_{1,m_1,m_2} \cdot \left(\log \mathtt{S}_{m_1}(r) + \log \mathtt{S}_{m_2}(r)\right) > 0 & \text{if } r = s \\ \infty & \text{otherwise} \end{cases}$$

- Cells r and s are adjacent if $|\text{lat}(r) - \text{lat}(s)| \leq 1^\circ$, $|\text{lon}(r) - \text{lon}(s)| \leq 1^\circ$ and $r \neq s$
- Where dist(r,s) is the average of the great-circle distance between a uniform distribution of 100 points in cell r and cell s

back

Trade Costs: Parametrization

- $\mathtt{T}_m(\cdot)$ measures the transport infrastructure quality of mode m
  - CO_2 emissions for road, rail, water and air; capacity for pipes; and voltage for electricity lines
  - with $\mathtt{T}_{\text{road}}(r) > 0$ if r is in land, $\mathtt{T}_{\text{water}}(r) > 0$ if r is over water, and $\mathtt{T}_{\text{air}}(r) > 0$ for every r
- $\mathtt{S}_m(\cdot)$ measures the switching infrastructure quality between modes m_1 and m_2
  - CO_2 emissions for road stations, rail stations, maritime ports and airports; and capacity for pipe stations
  - with $\mathtt{S}_{\text{road}}(r) > 0$ and $\mathtt{S}_{\text{air}}(r) > 0$ if r is in land, and $\mathtt{S}_{\text{water}}(r) > 0$ if r is in the coast

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Trade Costs: Transport network

- Transport modes: road, road-rail-road, road-air-road, road-water-road, road-pipe-road
  - Roads: Global Roads Inventory Project `https://www.globio.info/download-grip-dataset`, EDGAR Road CO_2 Emissions –set inter-modal linkages at all cells with roads
  - Railroads: Natural Earth (Global and North America Supplement) `https://www.naturalearthdata.com/downloads/10m-cultural-vectors/railroads/`, EDGAR Rail CO_2 Emissions –set inter-modal linkages at the start and end of each rail line
  - Water: EDGAR Maritime CO_2 Emissions `https://edgar.jrc.ec.europa.eu/dataset_ghg70` Ports location `https://msi.nga.mil/Publications/WPI`
  - Air: EDGAR Aviation CO_2 Emissions `https://edgar.jrc.ec.europa.eu/dataset_ghg70`, Airports location and routes `http://arm.64hosts.com`
  - Pipelines: Global Energy Monitor `https://globalenergymonitor.org/projects/global-oil-infrastructure-tracker/` and `https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/` –set inter-modal linkages at the start and end of each pipeline

back

Trade Costs: Parameter estimation

3. Estimate $(t^j_{\ell,m}, s^j_{\ell,m}, \rho^j)$ to match predicted and observed transport shares

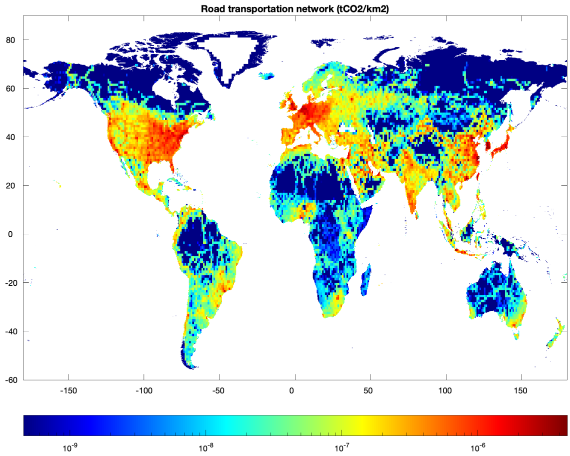
$$\min \quad \sum_{\mathcal{R}} \sum_{\mathcal{S}} \sum_{m} Z^j_m(\mathcal{S},\mathcal{R}) \left(\frac{Z^j_m(\mathcal{S},\mathcal{R})}{\sum_n Z^j_n(\mathcal{S},\mathcal{R})} - \pi^j_m(\mathcal{S},\mathcal{R}) \right)^2$$

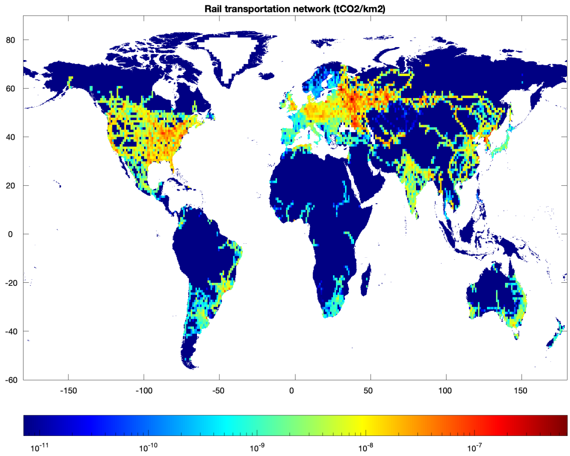
$$\text{s. t.} \quad \pi^j_m(s,r) = \frac{\varsigma^j_m(r,s)^{-\rho^j}}{\sum_{n \in M} \varsigma^j_n(r,s)^{-\rho^j}}$$

- $\varsigma^j_m(r,s)$ is the least-cost route from r to s by mode m
- Use gravity equation to aggregate transport shares from $1^\circ \times 1^\circ$ cells, indexed by r, s, to FAF regions, indexed by $\mathcal{R}, \mathcal{S}$
- Use Levenberg-Marquardt algorithm to solve non-linear least squares

back

Transportation Network





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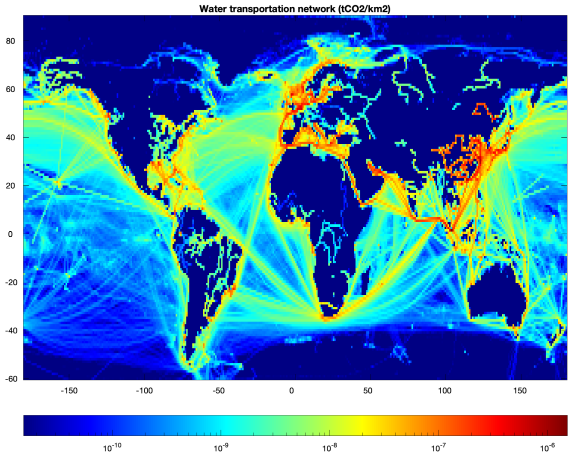
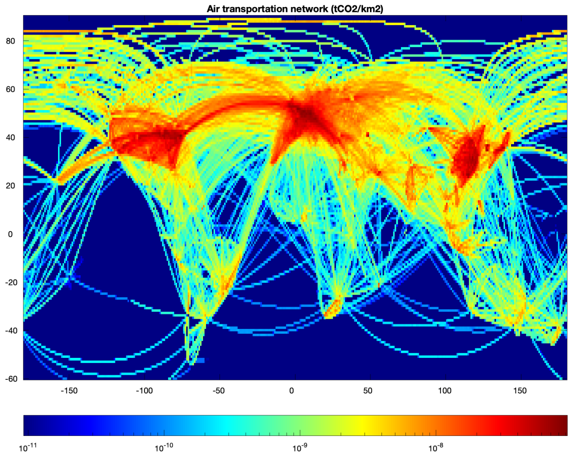
Transportation Network





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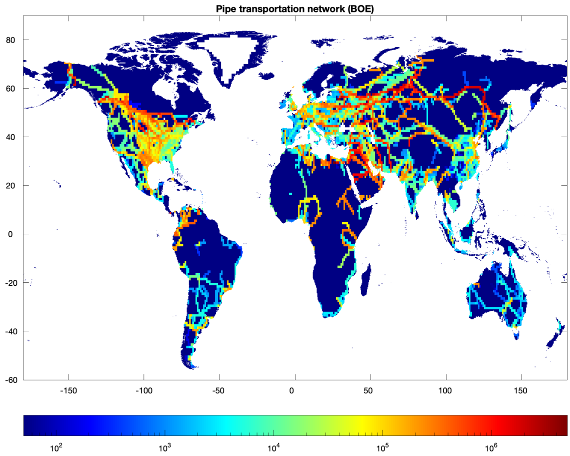
Transportation Network



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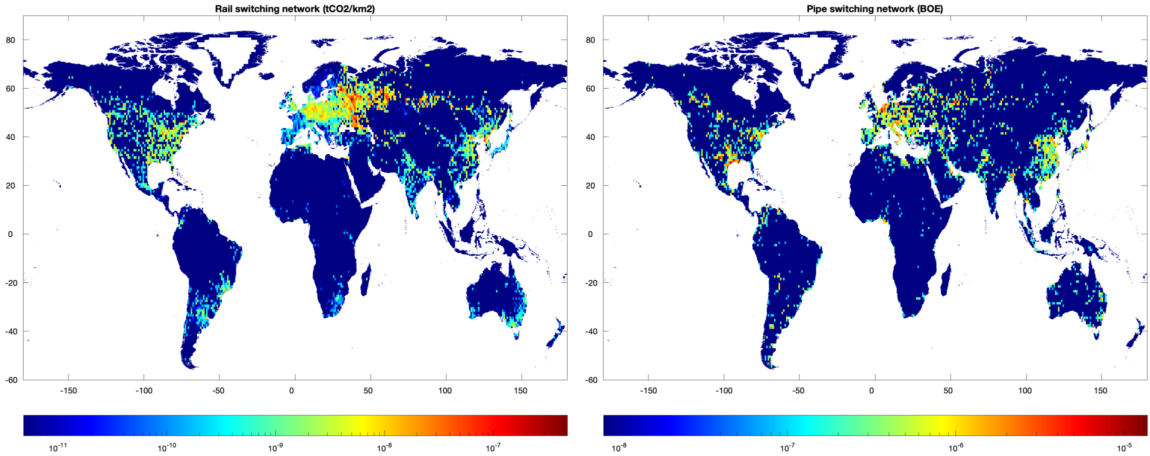
Switching Network



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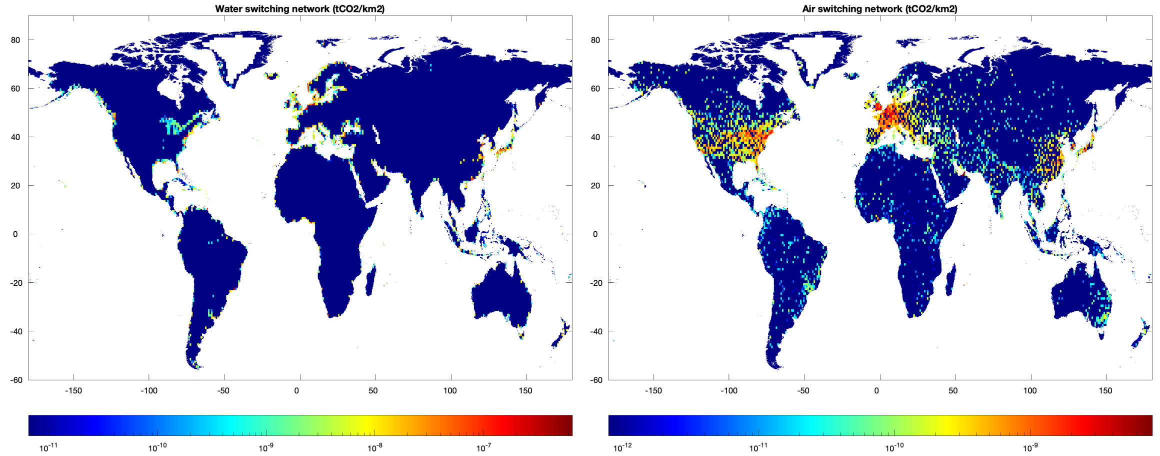
Switching Network



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Trade Costs for Goods and Fossil Fuels

- Estimate parameters to match predicted and observed transport shares using gravity equation in each sector

Trade value by good and transportation mode
(billion usd 2017)

	Road	Rail	Water	Air	Pipes
Goods	12,584.61	2,782.41	397.21	645.31	0
Fossil	1,030.03	625.47	294.20	0.03	388.05

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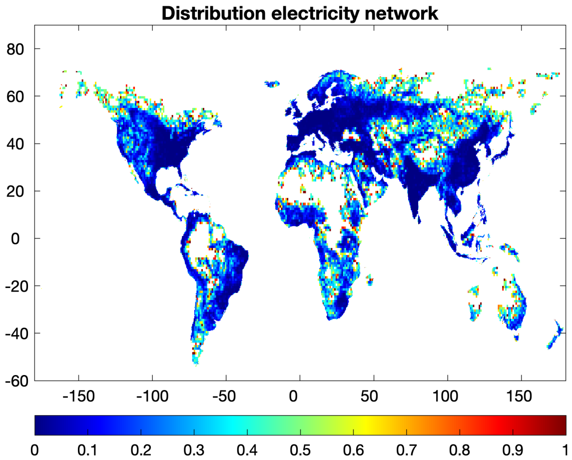
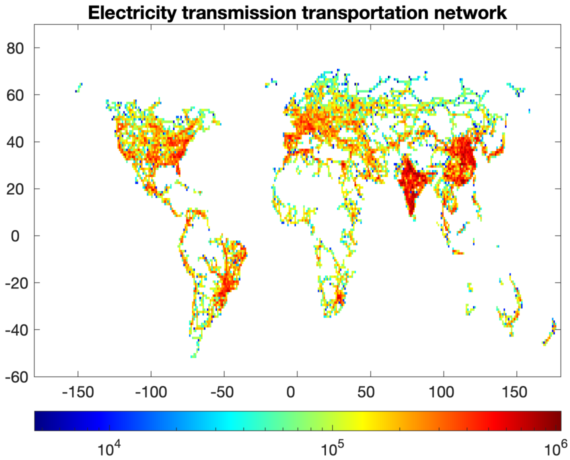
Electricity Network





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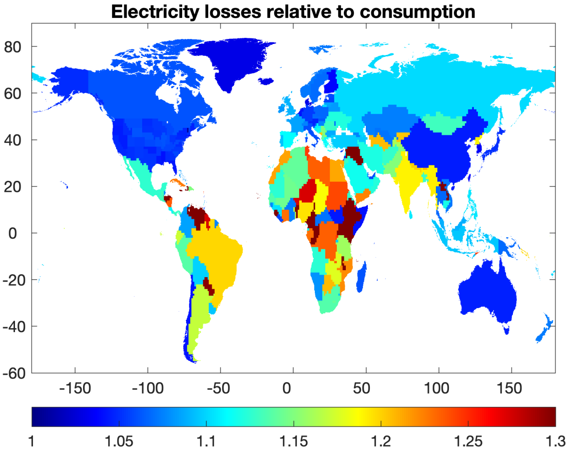
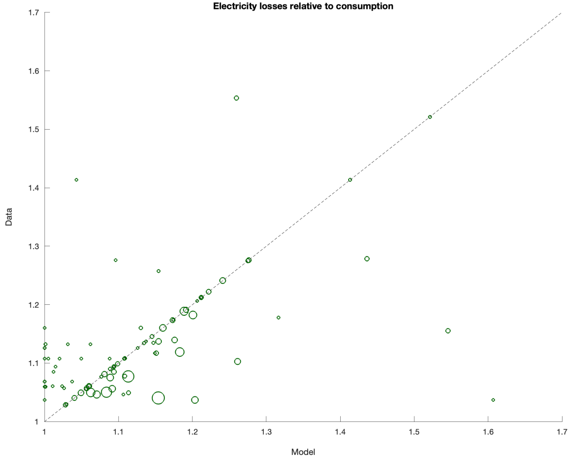
Trade Costs for Electricity





- Estimate transport cost parameters to match predicted and observed electricity losses
  - National and U.S. subnational data from the Energy Information Administration

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Parameters for Endogenous Growth: Estimation

- Law of motion for productivities $\bar{a}_t^{jk}(r)$ for $j \in \{q, f, c\}$:

$$\bar{a}_t^{jk}(r) = \left(1 + \Lambda_t^a(r)\right) \left(L_{t-1}^{\text{innov},jk}(r)\right)^{\gamma^j} \left(d_{t-1}^{jk}(r)\right)^{1-\xi^j} \left(\bar{a}_{t-1}^{jk}(r)\right)^{\xi^j},$$

$$L_{t-1}^{\text{innov},jk}(r) = \left(\frac{\gamma^j/\nu^j}{\iota^j + \gamma^j}\right) L_{t-1}(r) \ell_{t-1}^{jk}(r),$$

$$d_{t-1}^{jk}(r) = \left(\int_{v \in S} \exp\left(-\aleph^j \operatorname{dist}(v, r)\right) \bar{a}_{t-1}^{jk}(v)^{\varrho^j} \, dv\right)^{\frac{1}{\varrho^j}}, \text{ and}$$

$$\bar{a}_t^j(r) = \left(\sum_k \left(\bar{a}_t^{jk}(r) \kappa_t^{jk}(r)^{-1}\right)^{\frac{\vartheta^j - 1}{\theta^e}}\right)^{\frac{\theta^e}{\vartheta^j - 1}} \text{ if } \quad j \in \{f, c\}$$

- To keep the structure of the solution, impose $\iota^q + \gamma^q = \iota^f + \gamma^f = \iota^c + \gamma^c$

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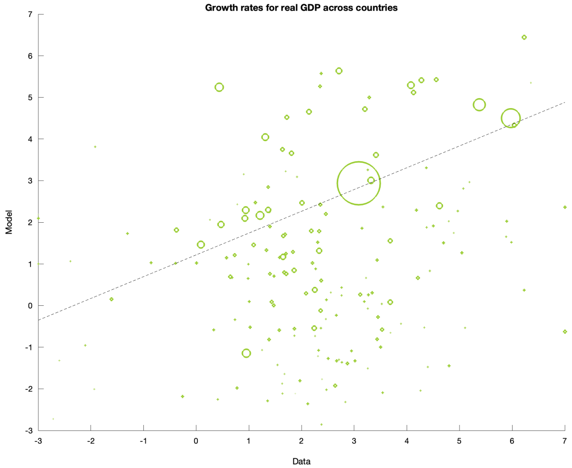
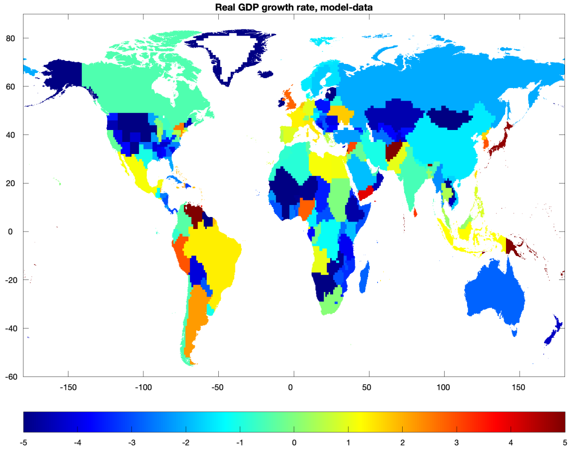
Growth: Real GDP





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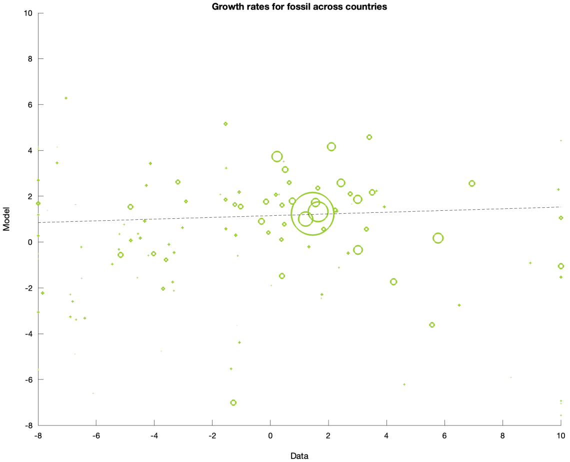
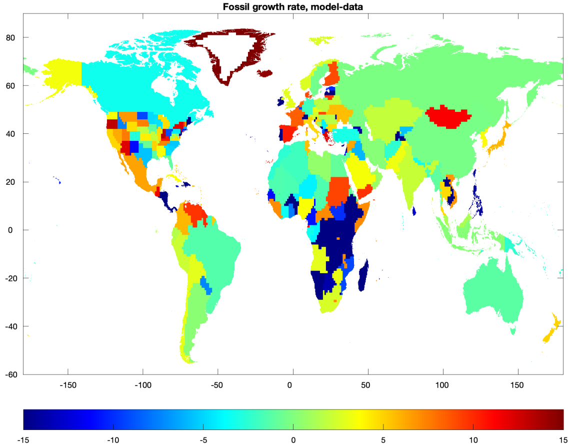
Growth: Fossil fuels





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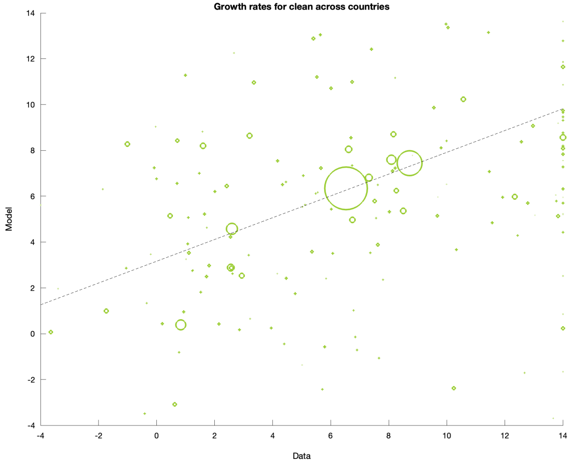
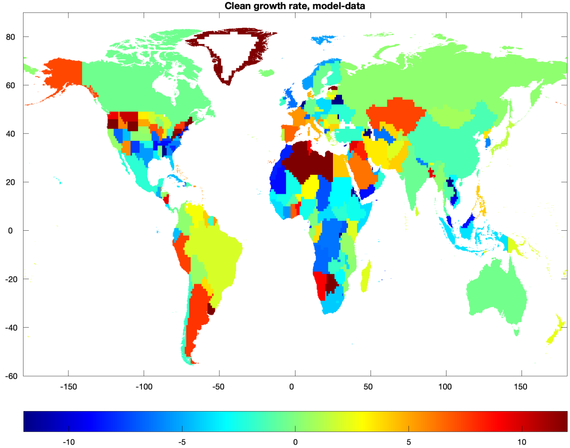
Growth: Clean energy





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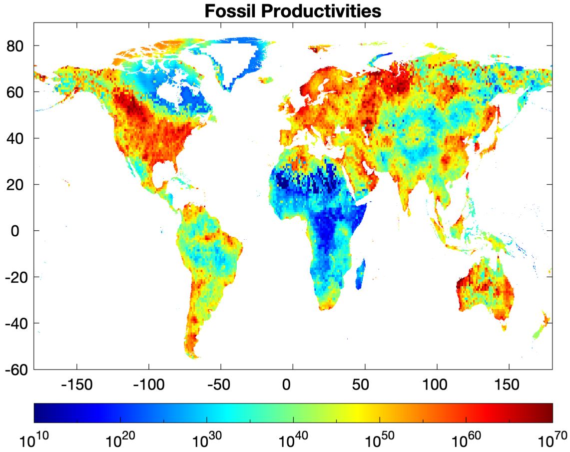
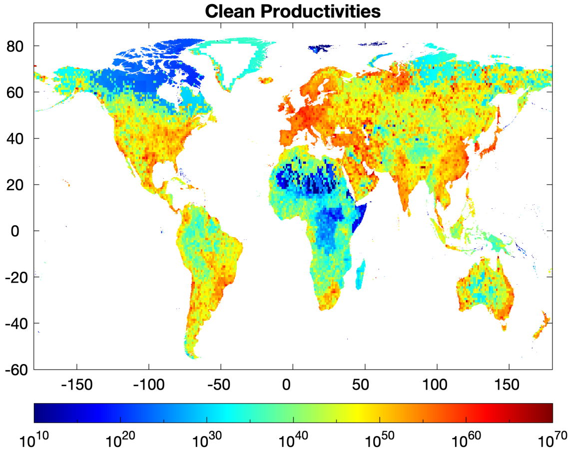
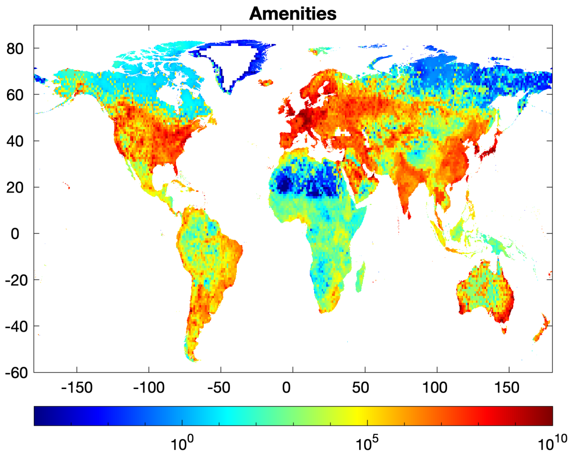
Fossil and Clean Energy Productivities

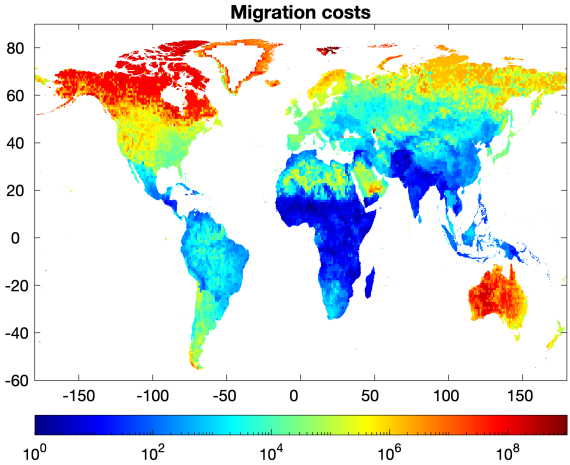




- Compute the productivities that exactly rationalize the observed data on:
  - Cell-level population, income, and energy, given environmental policy and trade costs

Amenities and Migration Costs





- With data on real income, population, and Human Development Index, retrieve amenities
  - Compute the migration costs that reproduce the population allocation in 2021

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