Green Development

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2nd European Workshop on the Macroeconomic Implications of Migration

Introduction

- Energy is a nontrivial factor in production and consumption
  - Energy share as an input in production is around 5%
  - Energy share in final consumption around 3.5%
- Fossil and renewable (green energy) yield different emissions, but also have distinct
  - **Geography of comparative advantage**
  - **Transport costs**: Grid versus pipelines and tankers
- Hence, the relative evolution of the technology to produce each type of energy can affect
  - The cost of energy
  - The locations where energy is produced and the resulting emissions
  - The geography of economic activity in the world
- **Can green energy lead to faster growth in parts of the developing world?**

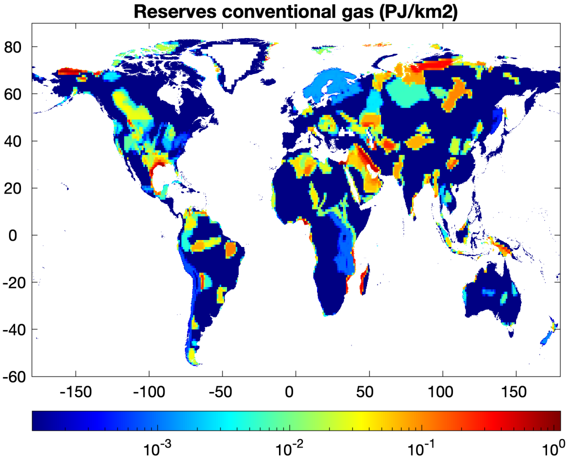
What We Do

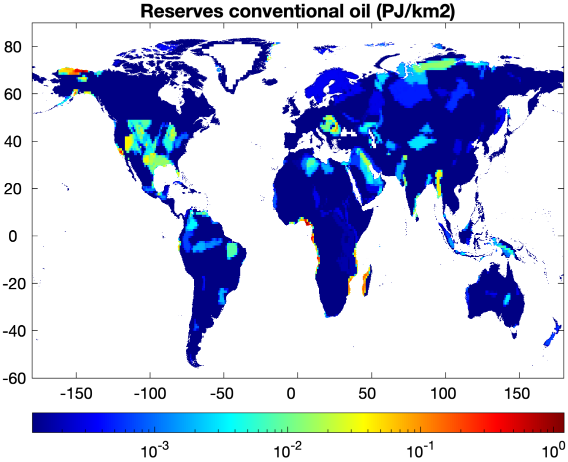
- Develop a quantitative spatial model of the world economy with an explicit energy sector:
  - **Local investments in green and fossil technology**
  - **Costly energy trade**
  - **Capability of renewables and the evolution of local fossil fuel stocks**
- Quantify using data on
  - The geography of fossil fuel reserves
  - The geography of renewable capabilities (“amount of sun”, “wind”)
  - Realistic energy and good transportation network (“Grid”, “Pipelines”)
- Improvement in renewable technology, together with their geography, can be a local development opportunity
  - Depends on the grid, transport network, and energy policy
  - Isolated locations can generate their own energy without relying on trade or the grid
- Resulting quantitative model useful to study local energy markets and climate policy

Literature Review

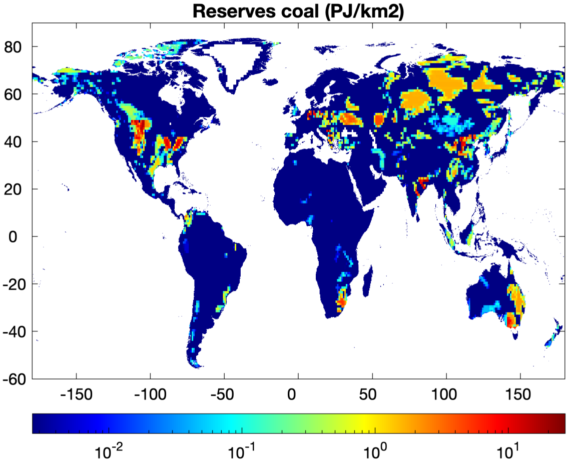
- Environmental Directed Technical Change
  - Acemoglu et al. (2012, 2014, 2016, 2023), Aghion et al. (2016), Dechezleprêtre and Hémous (2022), Fried (2018), Hassler et al. (2021), Cicala et al. (2022)
- Spatial IAMs
  - **Arkolakis and Walsh (2023)**, Balboni (2025), Bilal and Rossi-Hansberg (2023), Conte et al. (2021, 2025), Cruz (2024), Cruz and Rossi-Hansberg (2025, 2024), Desmet and Rossi-Hansberg (2015), Desmet et al. (2021), Krusell and Smith Jr (2022), Nath (2025), Rudik et al. (2022)

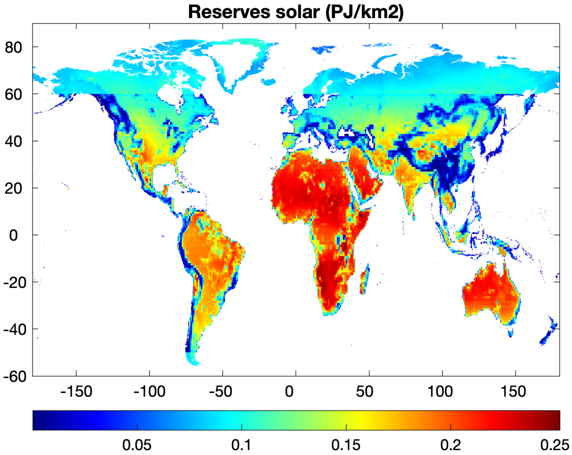
Comparative Advantage for Fossil Energy: Gas and Oil Reserves



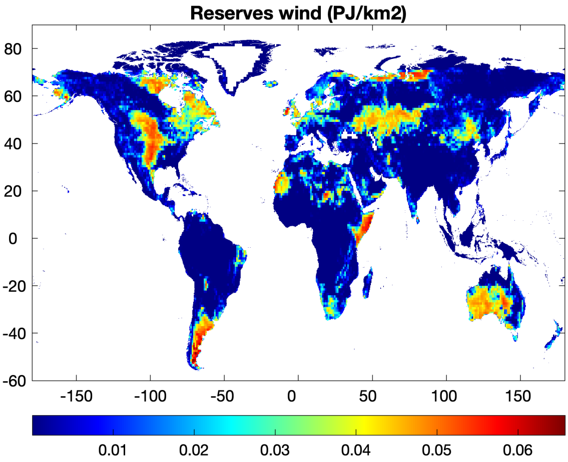


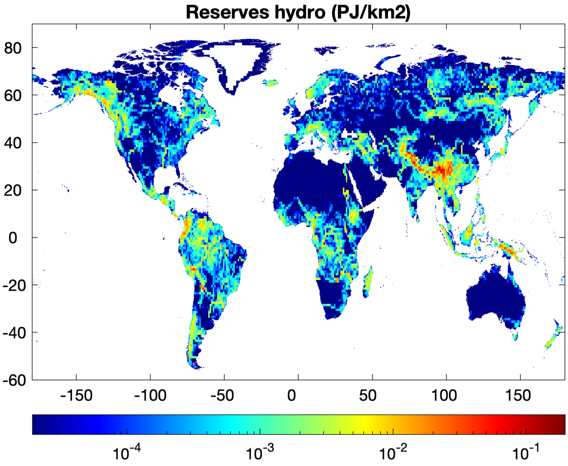
Comparative Advantage for Fossil vs Green: Coal and Solar



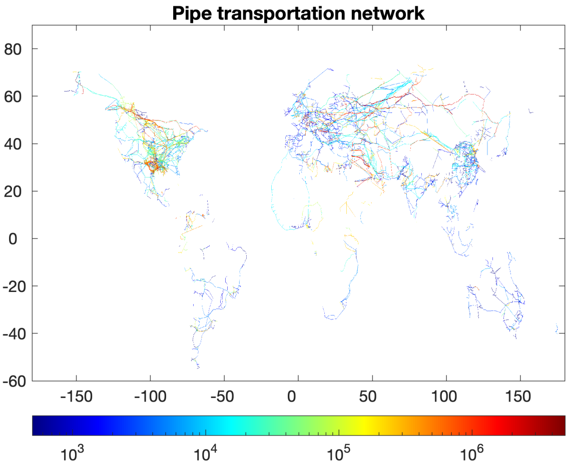


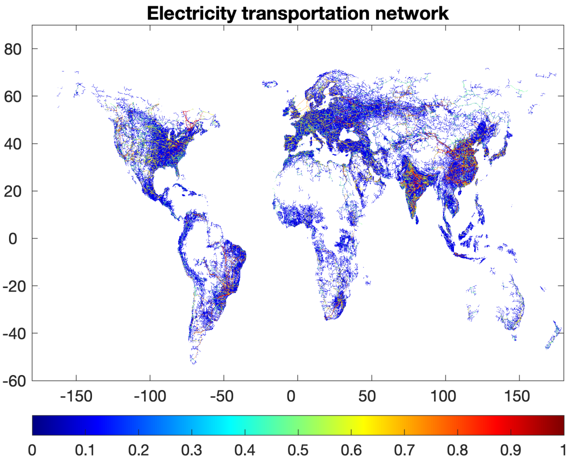
Comparative Advantage for Green Energy: Wind and Hydro





Energy transportation network





Preferences

- Household values amenities $b_t(r)$, consumption good $c_t(r)$, and **residential energy** $e_t^h(r)$ as

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

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

$$b_t(r) = \bar{b}_t(r)L_t(r)^{-\lambda}, \quad \bar{b}_t(r) = \left(1+\Lambda^b(\Delta T_t(r), T_{t-1}(r))\right)\bar{b}_{t-1}(r),$$

  - where $\bar{u} = (\iota+\gamma)/(\iota+\mu+\gamma)$ and $\bar{\varphi} = \varphi^{-\varphi}(1-\varphi)^{-(1-\varphi)}$ are constants
  - Consumption and each type of energy are CES aggregators over a continuum of varieties (with elasticities of substitution σ^f, σ^c)
  - Consider **taxes/subsidies** specific to each location r, period t, and energy source j, $\tau_t^{j,h}(r)$

$$\frac{P_t^{e,h}(v)e_t^h(v)}{1-\varphi} = \frac{P_t^q(v)c_t(v)}{\varphi}, \quad \frac{e_t^{f,h}(r)}{e_t^{c,h}(r)} = \frac{\varpi^{f,h}(r)}{\varpi^{c,h}(r)}\left(\frac{(1+\tau_t^{f,h}(r))P_t^f(r)}{(1+\tau_t^{c,h}(r))P_t^c(r)}\right)^{-\epsilon^h}$$

Mobility

- Households maximize intertemporal utility given by

$$V^w(r_0) = \sum_t \beta^t u_t(r_t) m(r_t)^{-1} \psi^{\omega}_{r_t}$$

  - where $m(r)$ denote migration costs of entering location r and ψ^{ω}_{it} is an idiosyncratic iid Fréchet shock with shape governed by Ω
  - The indirect utility in a period is then given by

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

    where $w_t(r)$ denotes the wage, $R_t(r)$ land rents, $\Psi_t(r)$ tax rebate, $D_t(r)$ trade deficit (or surplus) and $P^{e,h}_t(r)$ residential energy price index

- Fraction of households residing in each location

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

Consumption Good Technology

- Production function (of a variety) of consumption goods per unit of land

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

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

  - $h_t^q(r) = H_t^q(r)/H(r)$ is the share of land devoted to the production of goods
  - Innovation costs given by $\nu^q w_t(r)$, expressed in terms of labor
  - Each type of energy is a CES aggregator (with elasticities of substitution σ^f, σ^c)
  - $z_t^q(r)$ is a productivity draw from an iid Fréchet with shape θ^q
  - $a_t^q(r) = \bar{a}_t^q(r) L_t^q(r)^{\alpha^q}$ is good-specific productivity, evolving as

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

Gravity in Goods Trade and Trade Balance

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

$$\pi_t^q(s,r) = \frac{\bar{a}_t^q(r)(\ell_t^q(r)L_t(r))^{\alpha^q} mc_t^q(r)^{-\theta^q} \varsigma^q(r,s)^{-\theta^q}}{\int \bar{a}_t^q(v)(\ell_t^q(v)L_t(v))^{\alpha^q} mc_t^q(v)^{-\theta^q} \varsigma^q(v,s)^{-\theta^q}\, dv}$$

  - where $\varsigma^q(r,s)$ are goods transport costs, $\ell_t^q(r)$ denotes the share of labor in the goods sector, and

$$mc_t^q(r) = w_t(r)^{\iota+\mu+\gamma} P_t^{e,q}(r)^{1-\iota-\mu-\gamma} L_t(r)^{\mu}$$

Energy Production Technology

- Production function of energy type $j \in \{f, c\}$ is a CES composite of different sources

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

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

  - $z_t^{j,k}(r)$ is a productivity draw from an iid Fréchet with shape θ^j
  - $\kappa_t^{j,k}(r)$ **is the "cost" of the energy source**
  - $a_t^{j,k}(r) = \bar{a}_t^{j,k}(r) \left(\sum_{k \in K_j} L_t^{j,k}(r) \right)^{\alpha^j}$ is energy-specific productivity, evolving as

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

Energy Production Technology

- $\eta_t^{j,k}(r)$ is the *flow* of resource j, k used in production
  - $\eta_t^{j,k}(r)$ cannot exceed the *stock* of resource, $\Upsilon_t^{j,k}(r)$, which evolves as

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

  - Extraction of fossil fuels exhausts resources, but use of clean energy does not
- One unit of resource j, k costs

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

Gravity in Energy Trade and Trade Balance

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

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

  - where $\varsigma^j(r,s)$ are energy transport costs, and

$$mc_t^j(r) := w_t(r) L_t(r)^{\frac{\mu}{\iota+\mu+\gamma}}$$

- We impose trade balance by location across sectors so

$$p_t^q(r,r) q_t(r) \; + \; \sum_j p_t^j(r,r) \eta_t^j(r) \quad = \quad P_t^q(r) c_t(r) L_t(r) \; + \; \sum_j P_t^j(r) \left(e_t^{j,h}(r) L_t(r) + e_t^{j,q}(r) \right)$$

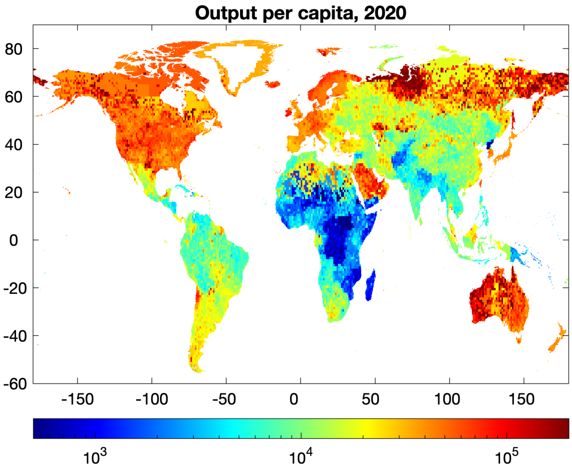
Government and Climate Evolution

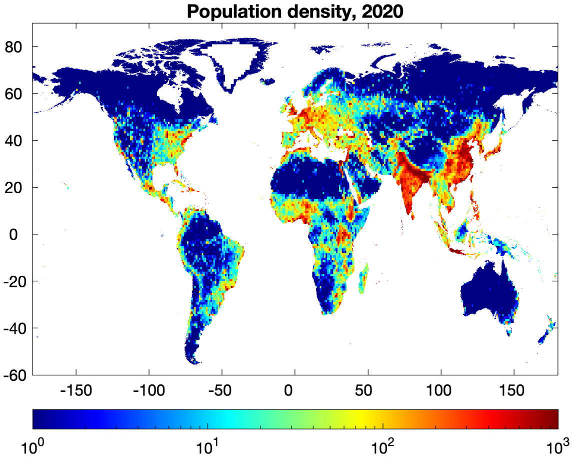
- Tax collection is rebated at the cell level to households

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

- Climate module as in Estrada et al. (2022) and Meinshausen et al. (2020) model

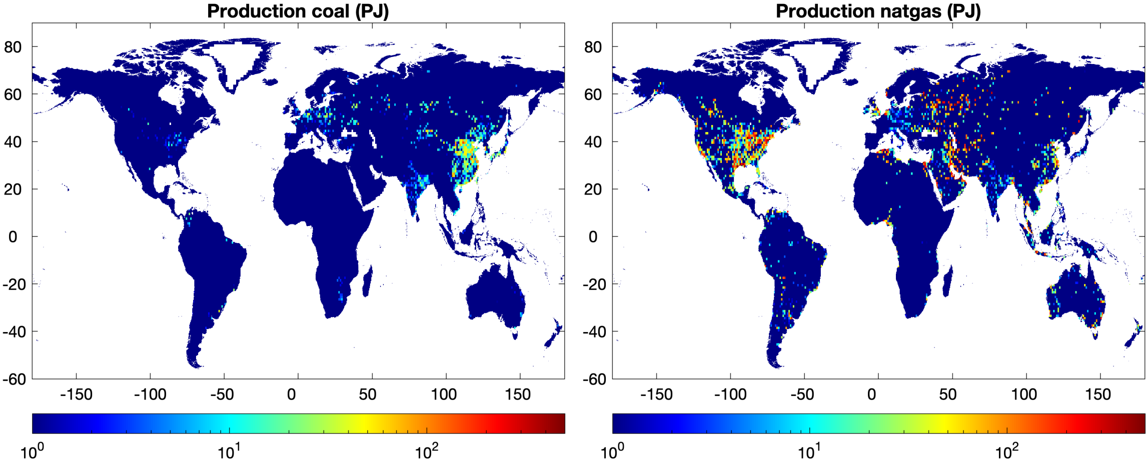
GCP and population



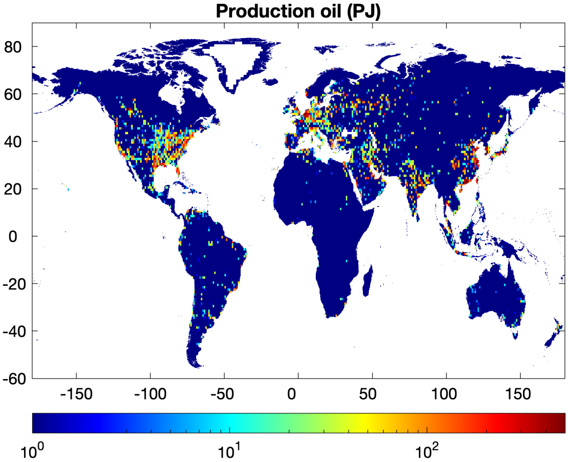


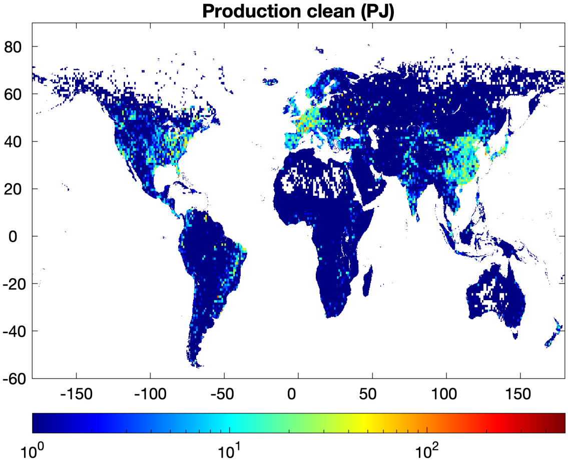
- GCP data from Rossi-Hansberg and Zhang (2025) in 2020 base year
- Input minimum GCP per capita and population by country in missing cells (20% of cells)

Energy Production



Energy Production





Extraction Cost Function for Fossil Fuels

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

$$\kappa_t^{f,k}(r) = \exp\left(F_0^{f,k} + F_0^{f,k,r}\mathbb{1}\{\text{region}(r)\} + F_0^{f,k,s}\mathbb{1}\{\text{source}(r)\}\right)\left(\Upsilon_t^{f,k}(r)H(r)\right)^{F_1^{f,k}}$$

  - Welsby et al. (2021) provides cumulative resource use and their associated extraction cost for coal, gas, and oil, categorized into 16 regions and source of fossil fuels

- Gas and oil highly sensitive to reserve scarcity, but not coal

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

Standard errors in parentheses

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

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 US 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

Clean Energy Cost Function: Solar, Wind, and Hydro

	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

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

Trade Costs

- We calculate transport costs using the shortest path, and considering multimode options (Fuchs and Wong, 2022)
  - Important to consider multi-mode options for fossil
  - We use MatLab function `distances` to compute shortest path
- Parametrize transport adjacency, $\mathcal{T}_m^j(\cdot)$, and switching, $\mathcal{S}_{m,n}^j(\cdot)$, costs

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

$$\log \mathcal{S}_{m,n}^j(r,s) = \begin{cases} s_{0,m,n}^j + s_{1,m,n}^j \cdot \left(\log \mathtt{S}_m(r) + \log \mathtt{S}_n(r)\right) > 0 & \text{if } r = s \\ \infty & \text{otherwise} \end{cases}$$

- Consider six transport modes: road, road-rail-road, road-air-road, road-water-road, road-pipe-road, electricity lines
- Estimate to match predicted and observed transport shares using gravity equation in each sector

Trade Mode for Goods and Fossil Energy

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

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

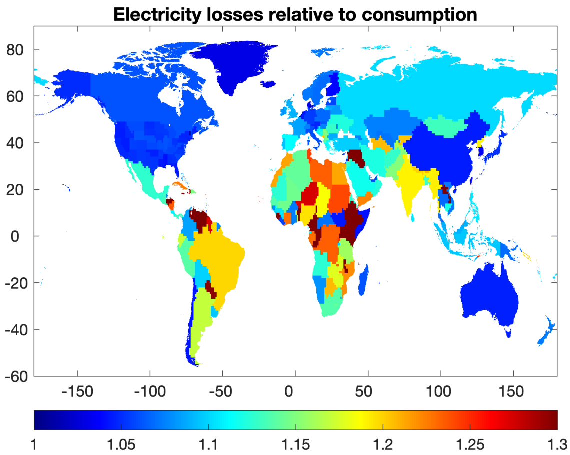
Electricity Trade Costs

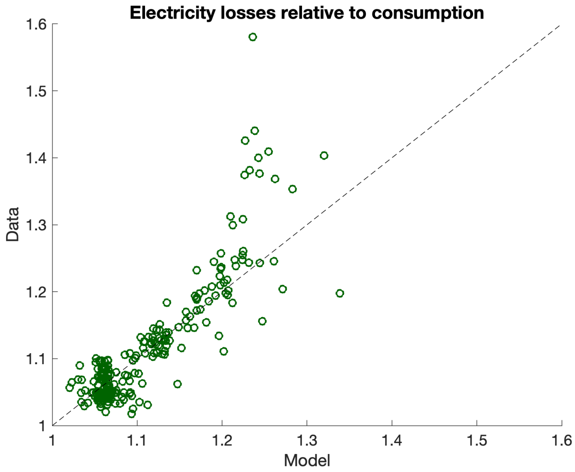
- Bohn et al. (1984) and Arkolakis and Walsh (2023) establish that electricity losses in line ℓ are

$$\text{losses}_\ell \approx \left(\frac{\text{line length}_\ell}{\text{voltage}_\ell}\right)(\text{power flow}_\ell)^2$$

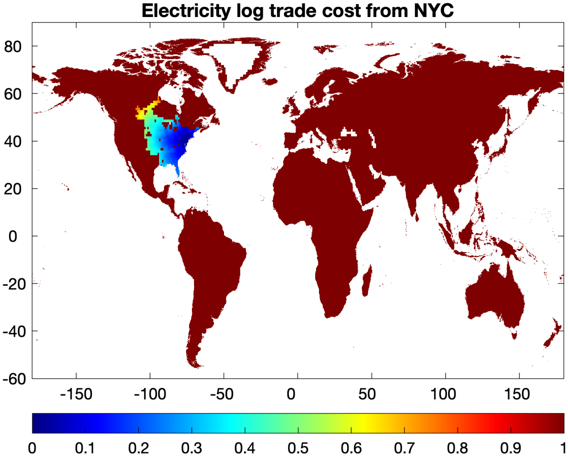
- US EIA provides yearly electricity generation, consumption, exports, imports, and distribution losses at the country- and US state-level (238 regions)
  - Allocate electricity consumption at the cell-level using the distribution of GDP, so that country-, USA state- and CHN province-level totals match EIA and NBSC data
- Flows depend on transport costs (losses) and transport costs depend in turn on power flows
  - Need an iterative procedure to find fixed point

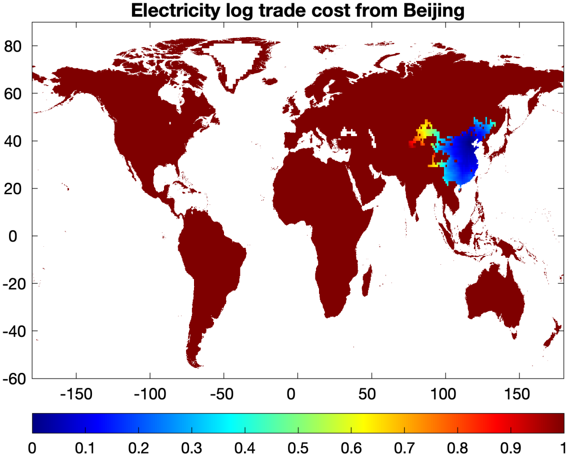
Electricity Trade Costs





Electricity Trade Costs





Growth Parameters

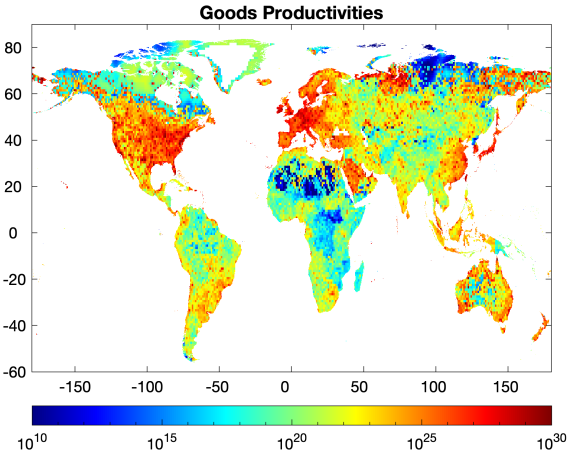
- Evolution of productivity in sectors $x \in \{q, f, c\}$

$$\bar{a}_t^x(r) = \left(1 + \Lambda_t^a(r)\right)\Big(\underbrace{\frac{\gamma/\nu^x}{\iota + \gamma} L_{t-1}^x(r)}_{L_{t-1}^{\text{innov},x}(r)}\Big)^{\gamma}\left(\int_{v \in S} D^x(v, r)\bar{a}_{t-1}^x(v)\,\mathrm{d}v\right)^{1-\xi^x} \bar{a}_{t-1}^x(r)^{\xi^x}$$

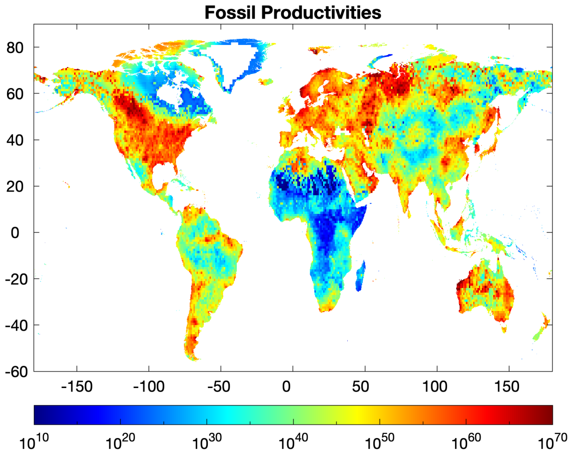
$$D^x(v, r) = \exp\left(-\aleph^x \operatorname{dist}(v, r)\right) \Big/ \int_{s \in S} \exp\left(-\aleph^x \operatorname{dist}(s, r)\right)\,\mathrm{d}s$$

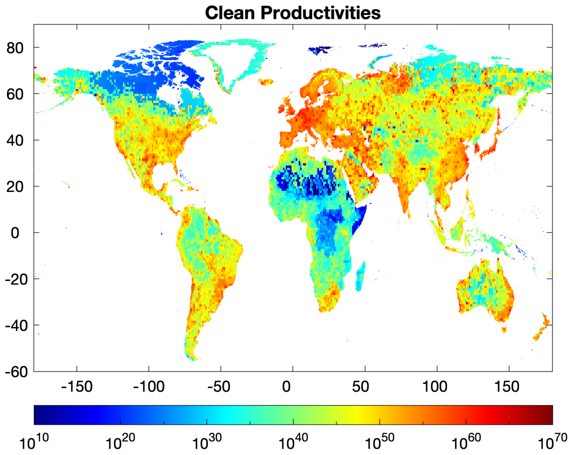
- Set the parameters $\aleph^q, \aleph^f, \aleph^c, \nu^q, \nu^f, \nu^c$ to target:
  - Standard deviation of productivities in 2021 equal to that in 2020
  - Real GDP growth of 2% (Desmet et al., 2018)
  - CO_2 emissions growth of 3.7% (Arias et al., 2021) (2020-2030 in scenario SSP 5 RCP 8.5)
  - Clean energy growth of 6.0% (IEA, 2024) (2020-2050 in scenario Stated Policies, similar to growth rate during 2010-2022 of 6.9%)
  - Fix $\gamma = 0.0024$ and $\xi^q = \xi^f = \xi^c = 0.993$ as in Desmet et al. (2018)

Good Sector Productivities

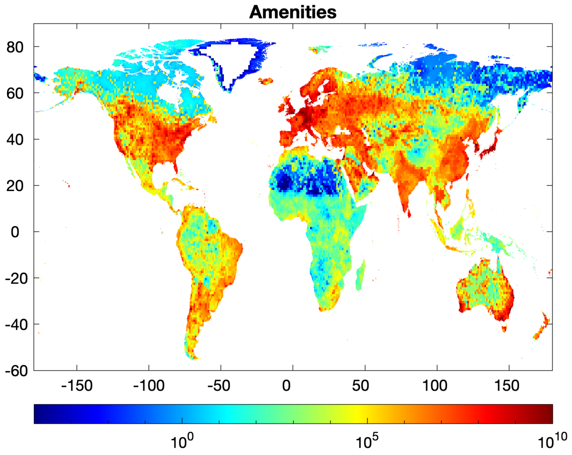


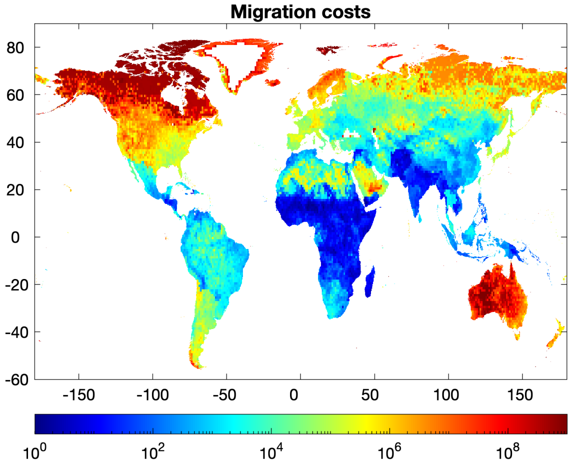
Fossil and Clean Energy Productivities



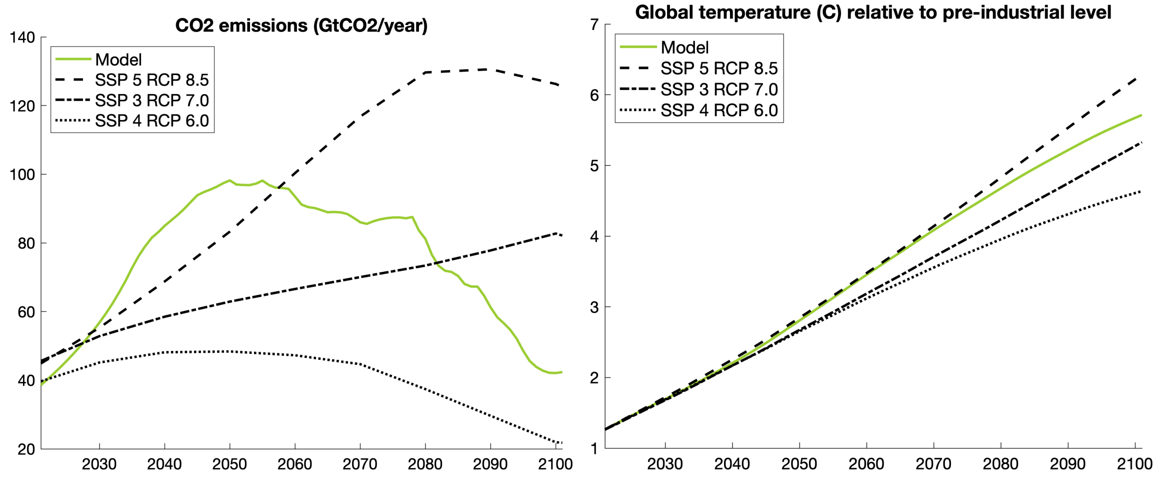


Amenities and Migration Costs

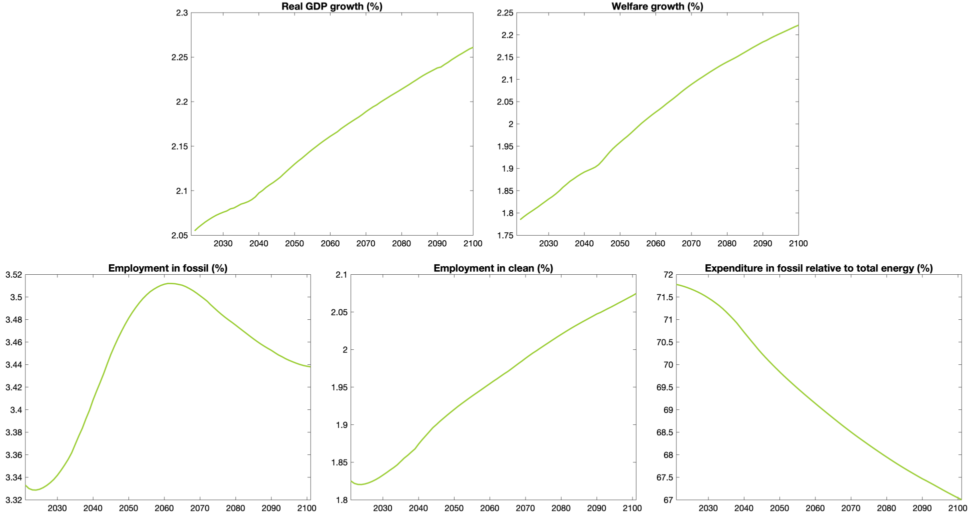




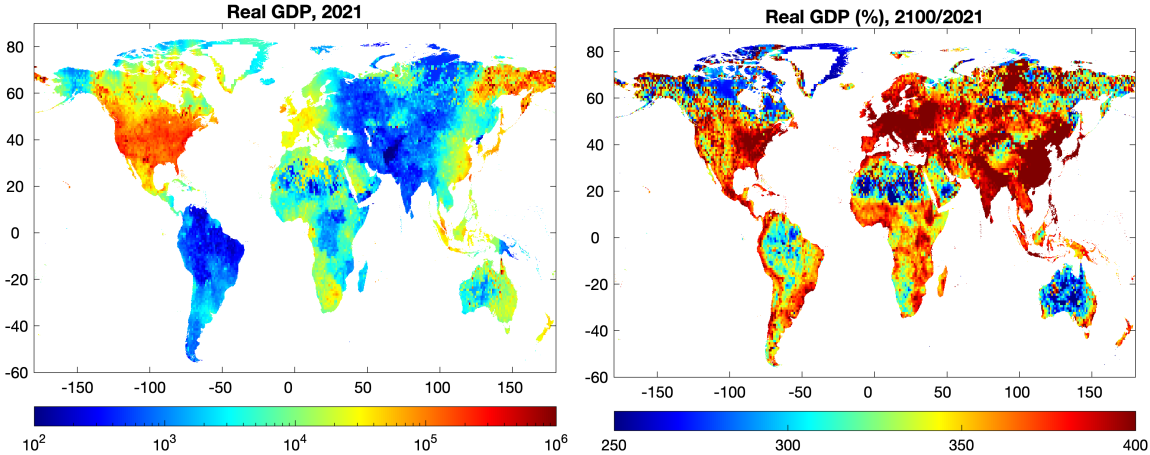
Results: CO^2 Emissions and Temperature



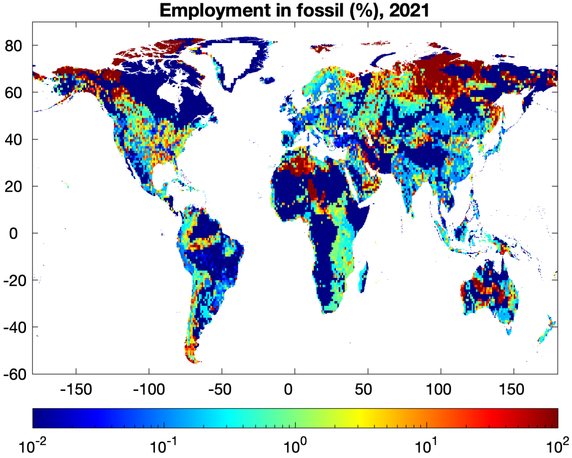
Results: The Evolution of GDP, Welfare, Energy

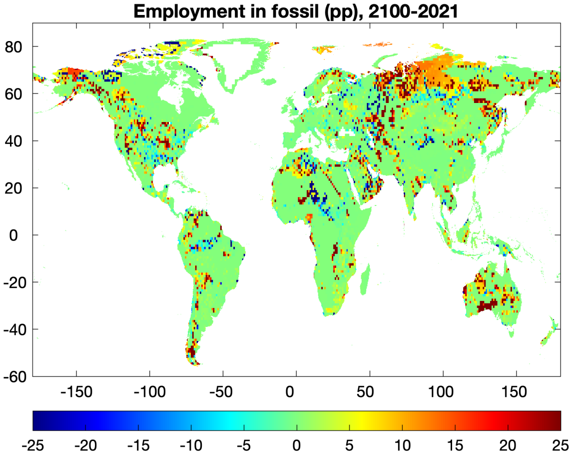


Results: Real GDP per Capita

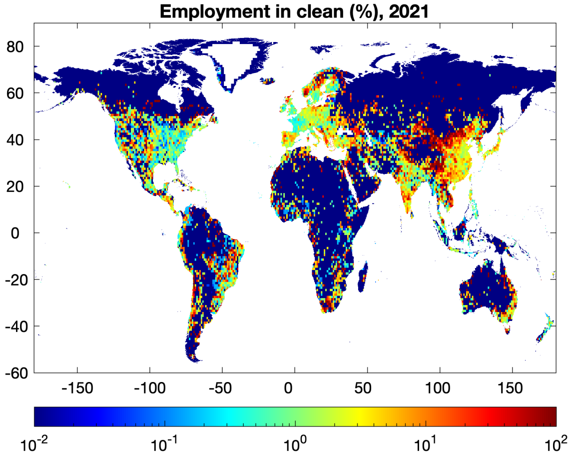


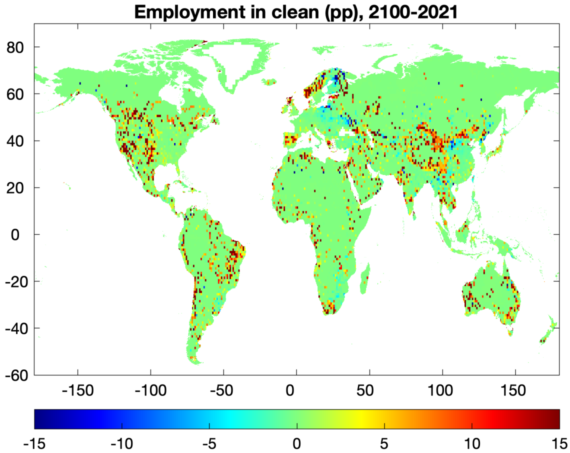
Results: Employment in Fossil Fuel Industry



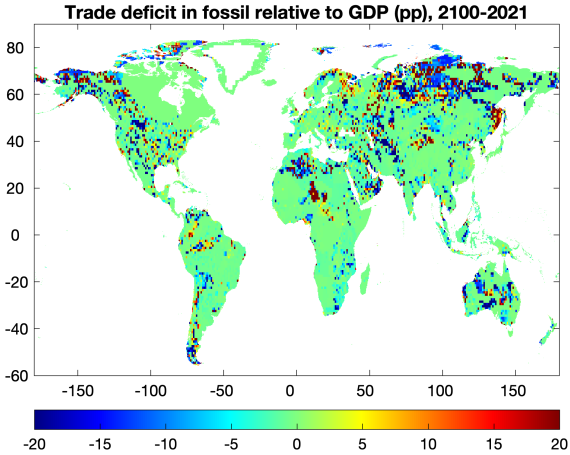


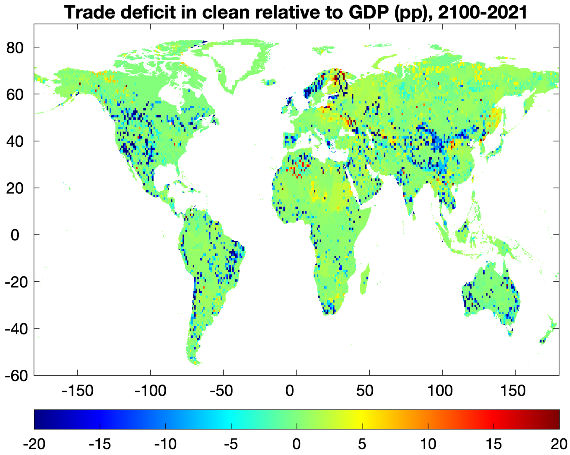
Results: Employment in Clean Energy Industry





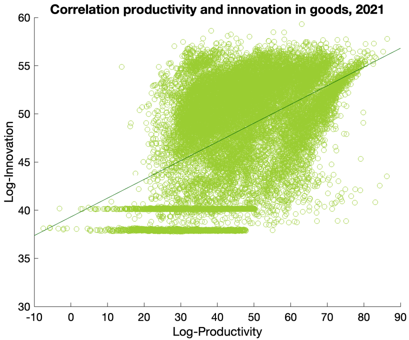
Results: Trade Deficit in Fossil Fuel and Clean Energy Industry

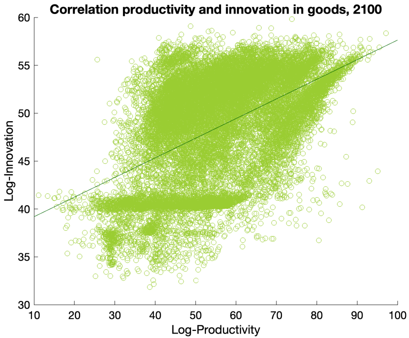




Results: Productivity and Innovation in Goods

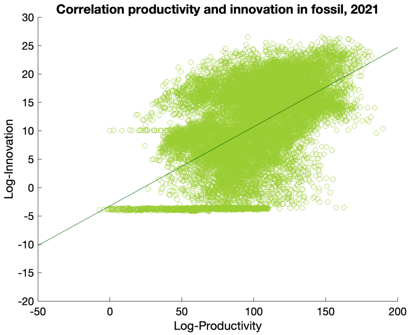
- Innovation in goods larger in productive locations with little change over time

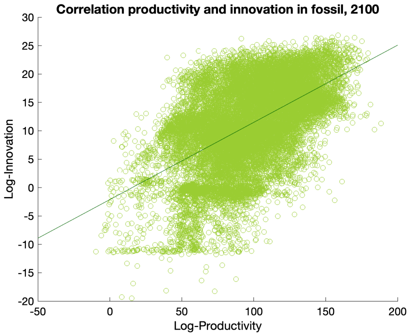




Results: Productivity and Innovation in Fossil Fuels

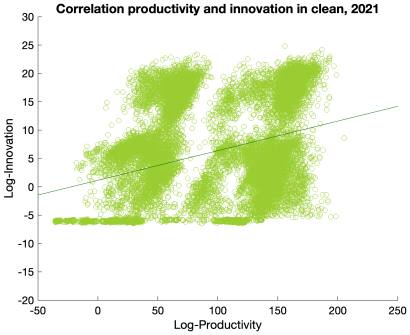
- Similar correlation between innovation and productivity. Similar over time.

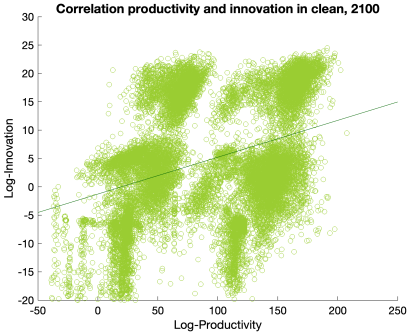




Results: Productivity and Innovation in Clean Energy

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





Next Steps

- Resulting model can be useful to do many **potentially interesting counterfactuals**
  - Changes in clean energy policy in the developed world
    - Could help developing countries gain comparative advantage in clean energy given their endowments
  - Technology diffusion incentives and policies
    - Green energy technology in the developing world is not sufficient to generate green clusters
  - Changes in the grid and changes in energy trading costs
    - Can high voltage grid connections between Africa and Europe help?
  - Implications of large energy innovations (fusion)

Thank you!

Appendix

Resources and Energy Suitability

- James Oakleaf provided access to reserve data in yields/km^2 (Oakleaf et al., 2019, 2015)
  maps
  - Coal (tons/km^2), conventional gas and oil (boe/km^2), unconventional gas and oil (boe/km^2), concentrated and photovoltaic solar power (MW/km^2), wind (MW/km^2), hydropower (MW/km^2)
  - Transform projection from Mollweide (5km) to latitude-longitude (1°) coordinates (Snyder, 1987)
  - Express all sources in TJ/km^2
  - Complete missing data for solar: interpolate solar potential by regressing it on elevation, latitude and longitude ($R^2 = 0.61, 0.88$)
- Adjust from fossil fuels reserves to resources with the region-level estimates of Welsby et al. (2021)
  - Differentiate between conventional and unconventional fuels
  - At the country- or US state-level, proportionally adjust reserves so that extraction/reserves lies between (global extraction/global reserves)/5 and (global extraction/global reserves)*5

Energy Extraction, Production and Consumption

- Energy balances at the country-level are taken from IEA (2023) and at the US-state level from the State Profiles and Energy Estimates of the U.S. Energy Information Administration energy
- Energy consumption
    - Industrial energy consumption in the IEA dataset is represented by the sum of the following flows: Agriculture, Fishing, Total Industry, Commercial and Public Services, Energy industry own use,
    - Residential energy consumption in the IEA dataset is represented by the flow of Residential
    - The flows of International marine bunkers, International aviation bunkers, Transport, Non-energy use and Final consumption not specified elsewhere are proportionally allocated between Industrial and Residential energy consumption

Energy Extraction, Production and Consumption

- Accounting identity for energy balances (IEA, 2023)

$$\begin{aligned} &\text{Production} + \text{Imports} - \text{Exports} - \text{International Transport} \pm \text{Stock changes} \\ &= \mp \text{Transformation} + \text{Energy own use} + \text{Final uses} \mp \text{Stat diff} \end{aligned}$$

  - Production is that of primary energy, does not include secondary energy
  - Transformation processes comprise the conversion of primary energy (e.g., crude oil) into secondary (e.g., gasoline) –inputs have negative values and outputs positive
  - Energy industry own use covers the amount of fuels used by the energy producing industries (e.g., heating, lighting, operation of equipment)
  - Final uses = Residential + Commercial + Domestic Transport + Non-energy
  - Data at the country- or region-, product-, and year-level

Energy Production and Consumption

- Disaggregate energy across states within the US with data from EIA
  - Differentiate between residential and commercial consumption
  - Allocate production of fossil fuels with production of raw sources
  - Allocate production of electricity with consumption

products extraction trade raw production and consumption production adjusted

Disaggregate energy across cells

- Construct the capacity and location of energy plants, $K_t^j(\cdot)$ maps
  - Collect plant-level data from Global Energy Monitor (coal, oil and gas, solar, wind, hydro, geothermal, bioenergy and nuclear plants) (Global Energy Monitor, 2025a,b,c,d, 2024)
  - Consider all plants (including those canceled) and harmonize capacity units across energy sources
  - Supplement with World Resource Institute data (World Resource Institute, 2021) (remove duplicate observations: same energy source and same plant name, or same energy source and distance between plant locations is less than 1 km)
  - Eliminate fossil plants located in cells with no fuel yields
  - In cells with fuel yields but no plants, assume there is a plant with the lowest worldwide capacity
  - Normalize $K_t^j(r) = \left(\frac{\int_{r \in \mathcal{R}} Y_t^j(r)\, \mathrm{d}r}{\int_{r \in \mathcal{R}} K_t^j(r)\, \mathrm{d}r} \right) K_t^j(r)$

Energy Prices

- Supply costs and retail prices of coal, oil, natural gas and electricity at country-level from IMF Fossil Fuel Subsidies Data (Black et al., 2023) maps
- Prices of coal, oil, natural gas and electricity at US state-level from US Energy Information Agency
  - Aggregate across end-users (i.e., residential, industry) and fuel types (e.g., gasoline, kerosene)
  - Transform energy prices from MER to PPP with data from Rossi-Hansberg and Zhang (2025)
  - Carbon pricing is defined as Retail prices net of Value Added Taxes minus Supply costs –applicable VAT rate is the actual VAT times the share of final consumption

Employment in Fossil Fuels and Clean Energy

- From the energy firm's optimality conditions

$$\ell_t^j(r) = \left(\frac{\iota+\gamma}{\iota+\gamma+\mu}\right)\left(\frac{p_t^j(r,r)\eta_t^j(r)H(r)}{w_t(r)L_t(r)H(r)}\right)$$

  - Global average of fossil and clean employment: 2.75% and 3.85%
  - IEA (2023) estimates global energy employment of 2%, equally distributed into fossil and clean

$$\min \quad \int_{r\in\mathcal{R}} \sum_{j\in\mathcal{J}} W^j(r)\left(\hat{\ell}_t^j(r) - \ell_t^j(r)\right)^2 \mathrm{d}r$$

$$\text{s. t.} \quad \int_{r\in\mathcal{R}} w_t(r)L_t(r)H(r)\hat{\ell}_t^j(r)\,\mathrm{d}r = \left(\frac{\iota+\gamma}{\iota+\gamma+\mu}\right)\int_{r\in\mathcal{R}} p_t^j(r,r)\eta_t^j(r)H(r)\,\mathrm{d}r \quad \forall j\in\mathcal{J},$$

$$\hat{\ell}_t^f(r) + \hat{\ell}_t^c(r) \le 0.9 \quad \forall r\in\mathcal{R}, \quad \hat{\ell}_t^j(r) \ge 10^{-6} \quad \forall j\in\mathcal{J} \quad \forall r\in\mathcal{R},$$

$$W^j(r) > 0 \quad \text{are weights}$$

  - Weights are such that in cells with no fossil yields, $\hat{\ell}_t^f(\cdot)$ takes its minimum value

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