Clean Growth

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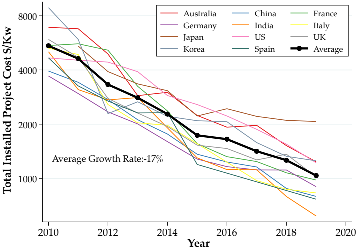
Renewable Cost Reductions in the Last Decade



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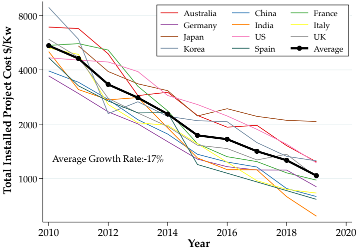

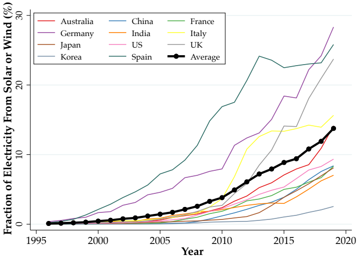

- Drastic reduction of renewables' cost and rapid adoption rate
  - Reductions expected to continue for decades to come

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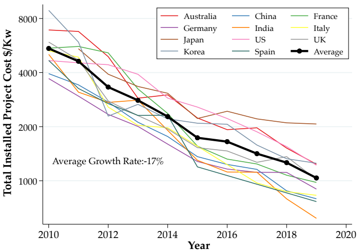

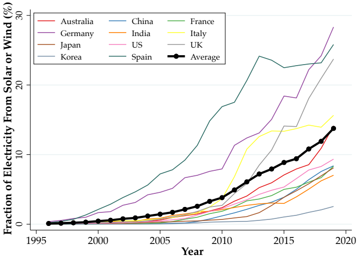

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- Analyze the global phenomenon of the rise of renewables

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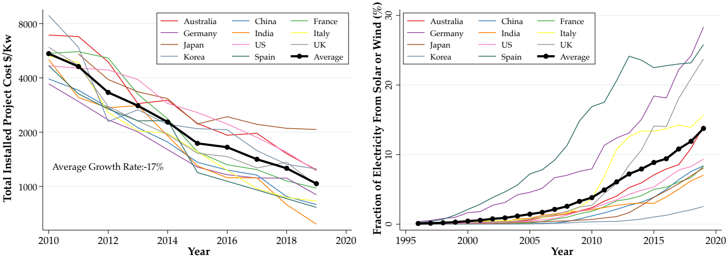


- Drastic reduction of renewables' cost and rapid adoption rate
  - Reductions expected to continue for decades to come
- Analyze the global phenomenon of the rise of renewables
  - What are its macroeconomic and regional implications?
  - What is the role for policy?

Spatial Theory of Clean Growth

- Develop a new spatial theory of clean growth. Elements
  - Supply of energy and transmission network of electricity ("the grid")
  - Electricity prices set by grid operator based on supply and demand
  - Demand of electricity determined by a multi-sectoral trade model
  - Tractable spatial theory of renewable investment with learning-by-doing in modular technologies
- Quantified with detailed regional data harmonizing new information on:
  - Entire global power and transmission network
  - Global clean and fossil energy resources/potential
  - Regional data on trade and production
- Core questions:
  - Who are the winners and loser of clean growth?
  - Impact of major interventions favoring renewables: Inflation Reduction Act

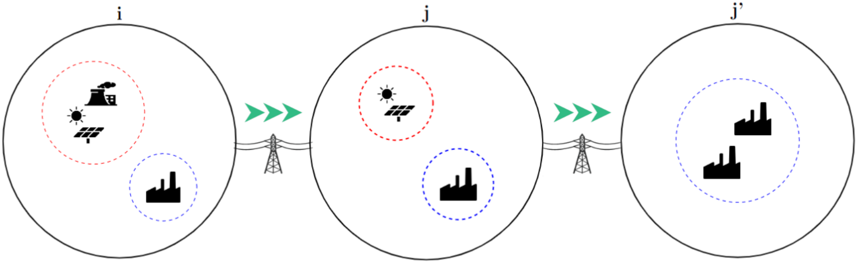
The Economy

- **Electricity Generation and Distribution**
- Demand for Electricity in the Spatial Economy
- Renewables Investment
- Equilibrium and Quantification
- Counterfactuals

Main Elements

- Spatial nodes denoted by $j \in J$ (in data commuting nodes, NUTS-3 etc)
- Production of electricity, $\mathcal{E}$, using fossil assets, $\mathcal{F}$, or renewables, $\mathcal{R}$
  - Electricity used in region or injected elsewhere through the transmission network
    - Transmission lines $k \in K$
  - Sending electricity to other nodes incurs losses, λ
- Multi-sector trade-spatial model with iceberg shipping costs
- Discuss these elements and then turn to study investment in renewables

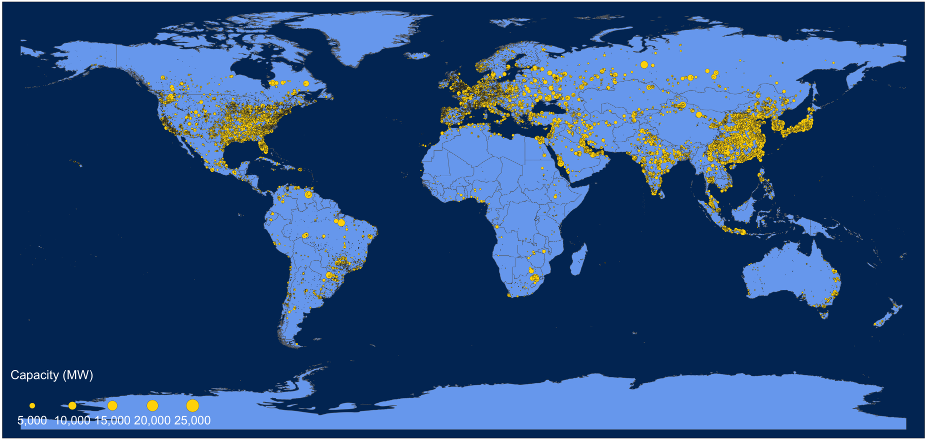
A Graphical Representation



Electricity Generation

- Cost of of generation $M_j(Y_j^{\mathcal{E}})$, where $Y_j^{\mathcal{E}}$ is power produced in j
  - Electricity generated by fossil assets, $Y_j^{\mathcal{F}} = f(K_j^{\mathcal{F}}, F_j)$,
  - $K_j^{\mathcal{F}}$ is the capacity of the asset, F_j fossil fuels used
  - Max fossil fuel output governed by F_j^{max}

Location and Capacity of Fossil Assets

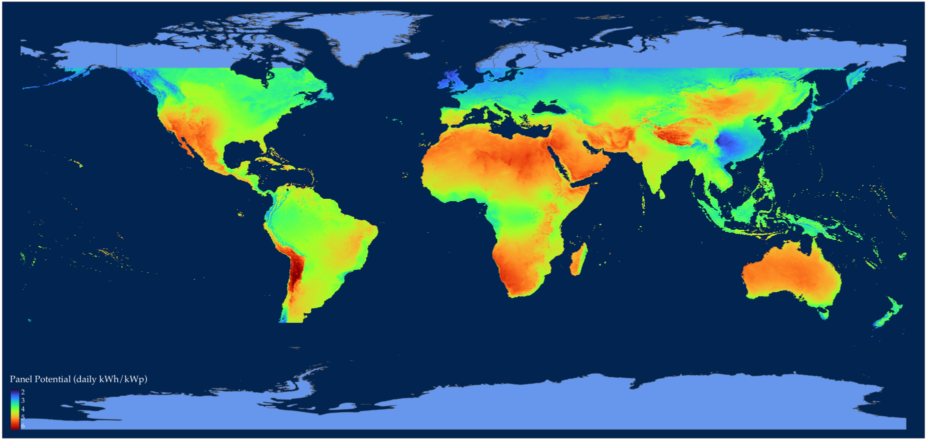


Electricity Generation

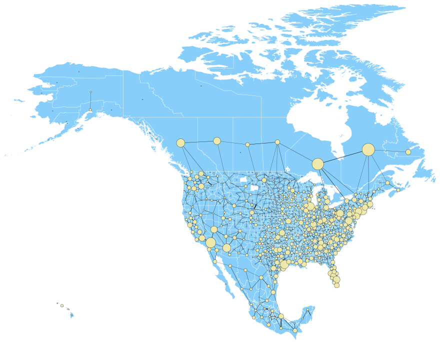
- Develop a new spatial theory of clean growth
  - Spatial nodes denoted by $j \in J$ (in data commuting nodes, NUTS-3 etc)
  - Nodes where economic activity, electricity production, or both, take place

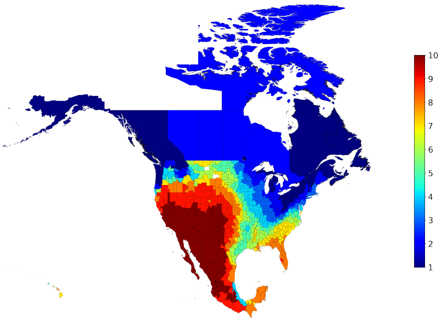
- Cost of of generation $M_j(Y_j^{\mathcal{E}})$, where $Y_j^{\mathcal{E}}$ is electricity produced in j
  - Electricity generated by fossil assets, $Y_j^{\mathcal{F}} = f(K_j^{\mathcal{F}}, F_j)$,
    - $K_j^{\mathcal{F}}$ is the install capacity of the asset, F_j fossil fuels used
    - Max output determined by F_j^{max}
  - Electricity generated also by renewables $Y_j^{\mathcal{R}} = \theta_j K_j^{\mathcal{R}}$
    - $K_j^{\mathcal{R}}$ is the installed renewable capacity, θ_j the renewable potential

Solar Potential



Spatial Mismatch of Renewable Potential/Installed Fossil





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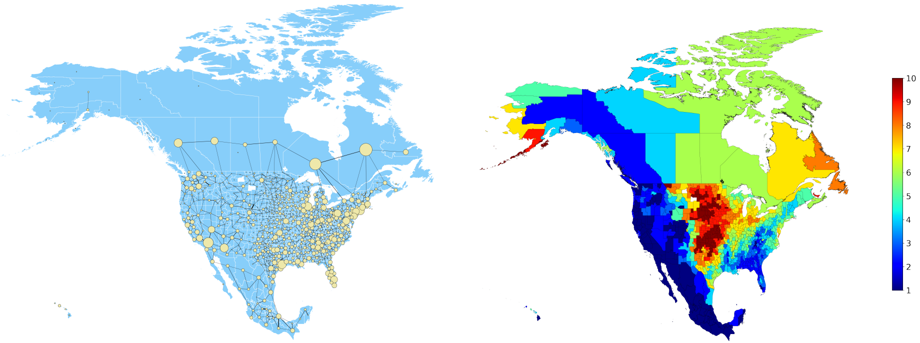


Demand for Electricity

- Demand for electricity, $D_j(p_j^{\mathcal{E}})$, is dictated by trade, aggregate demand and supply of labor
  - Will be determined in our spatial equilibrium setup

- **P** vector of dimension $(J-1)$ and its element P_j to be the net power output of node j, such that

$$P_j = Y_j^{\mathcal{E}} - D_j. \tag{1}$$

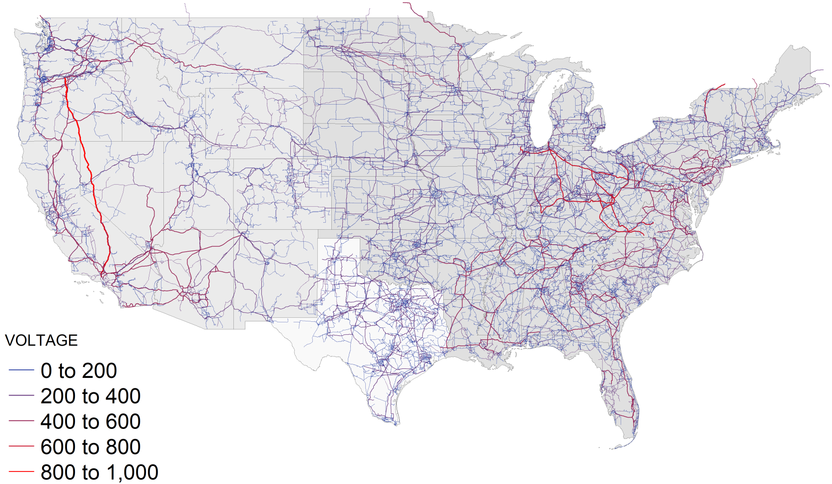
  where $Y_j^{\mathcal{E}} = Y_j^{\mathcal{F}} + Y_j^{\mathcal{R}}$

The Grid

- We now discuss the electricity network
  - $\bar{\mathbf{A}}$ is a matrix of dimension $K \times (J-1)$, with an entry of 1 in the (k, j) cell if node j is connected to line k where K is the number of lines
  - $\bar{\mathbf{R}}$ is a $K \times K$ diagonal matrices of line resistances

- Assume grid run by a public utility over a connected set of regions

The Grid



The Grid

Lemma

Power losses in the system obtain a quadratic form

$$\lambda = \mathbf{P}'(\bar{\mathbf{A}}'\bar{\mathbf{R}}^{-1}\bar{\mathbf{A}})^{-1}\mathbf{P} \tag{2}$$

and the flows on each line $\mathbf{Z} = \bar{\boldsymbol{\Omega}}\bar{\mathbf{A}}(\bar{\mathbf{A}}'\bar{\boldsymbol{\Omega}}\bar{\mathbf{A}})^{-1}\mathbf{P}$ *where* $\bar{\Omega}$ *is a* $K \times K$ *diagonal matrix with* $\Omega_k = (2R_k^2)^{-\frac{1}{2}}$ *on the diagonal and* 0 *on the off-diagonal elements.*

Electricity Market and Power Planner

- Define the output function of the electricity planner $Q_j(D_j)$
  - Dictating prices over a connected set $j \in J^P$

- The electricity planner maximizes

$$\max_{\{p_j^{\mathcal{E}}\}} \sum_{j \in J^P} p_j Q_j(D_j(p_j^{\mathcal{E}})) - \sum_{j \in J^P} M_j(Y_j(p_j^{\mathcal{E}}))$$

subject to

$\sum_{j \in J^P} D_j + \lambda = \sum_{j \in J^P} Y_j^{\mathcal{E}}$	Energy Balance
$\lambda = \mathbf{P}'(\bar{\mathbf{A}}'\bar{\mathbf{R}}^{-1}\bar{\mathbf{A}})^{-1}\mathbf{P}$	Losses
$P_j = Y_j^{\mathcal{E}} - D_j$	Net Power
$Y_j^{\mathcal{E}} \leq Y_j^{max}$	Max Output
$\mathbf{Z} \leq Z^{\max}$	Max line output

- Planner takes p_j (good prices) as given

Planner Problem Characterization

Proposition

If Q_j is strictly concave, the planner problem has unique solution, and

$$p_j^{\mathcal{E}} = \sum_{k \in J^P} \eta_k \frac{\partial Z_k}{\partial D_j} + \mu \left(1 + \frac{\partial \lambda}{\partial D_j} \right)$$

where η_k is the shadow value of extra capacity on a constrained line k, and μ is the shadow value of total generation capacity

Roadmap

- Electricity Generation and Distribution
- **Demand for Electricity in the Spatial Economy**
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Spatial Economy with Power

- Cobb-Douglas preferences over goods from different sectors s,

$$C_{j,t} = \prod_s C_{js,t}^{\beta_{js}}$$

where β_{js} is the consumption share of region j in sector s

- For each sector s, each j produces differentiated good (Armington '69)
  - CES aggregator with an elasticity across varieties σ_s

- Output of region j in sector s is

$$q_{js,t} = z_{js,t} \underbrace{\left(e_{js,t}^{1}\right)^{v_{js}^{\mathcal{E}}}}_{\text{direct electricity use}} \underbrace{\left(\kappa_{js,t}\left(e_{js,t}^{2}\right)^{\frac{\psi-1}{\psi}} + f_{js,t}^{\frac{\psi-1}{\psi}}\right)^{\frac{\psi}{\psi-1}v_{js}^{\mathcal{F}}}}_{\text{indirect use substitutable with fuel}} k_{js,t}^{v_{js}^{K}} L_{js,t}^{v_{js}^{L}}$$

Closing the Model

- Sectoral demand is

$$X_{is,t} = \sum_j \frac{p_{ijs,t}^{1-\sigma}}{\left(\sum_i p_{ijs,t}^{1-\sigma_s}\right)^{1/(1-\sigma_s)}} \beta_{js} E_j$$

  where β_{js} is sectoral spending shares, E_j total spending and

$$p_{ijs,t} = \frac{\tau_{ijs,t}}{z_{is,t}} w_{i,t}^{v_{is}^L} (p_{i,t}^{\mathcal{E}})^{v_{is}^{\mathcal{E}}+v_{is}^{\mathcal{F}}} \left(r_{i,t}^K\right)^{v_{is}^K} \left(\kappa_{is,t} + \left(\frac{\kappa_{is,t} p_{i,t}^{\mathcal{F}}}{p_{i,t}^{\mathcal{E}}}\right)^{1-\psi}\right)^{-\frac{\psi}{\psi-1} v_{is}^{\mathcal{F}}}$$

- Assume we know $p_i^{\mathcal{F}}$, $K_i^{\mathcal{F}}$ (to be calibrated) and $K_i^{\mathcal{R}}$ (TBD up next)
- To close the model we assume that markets clear

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Renewable Investment

- Law of motion of Renewable capital

$$K^{\mathcal{R}}_{j,t+1} = (1-\delta)K^{\mathcal{R}}_{j,t} + Q^{\mathcal{R}}_{j,t+1}. \quad (3)$$

Renewable Investment

- Law of motion of Renewable capital

$$K^{\mathcal{R}}_{j,t+1} = (1-\delta)K^{\mathcal{R}}_{j,t} + Q^{\mathcal{R}}_{j,t+1}. \tag{3}$$

- Renewable capital produced by transforming $I^{\mathcal{R}}_{j,t}$ units of final good

$$Q^{\mathcal{R}}_{j,t} = \underbrace{\left(\sum_{j'}\sum_{i=1}^{\infty}(\mu)^i Q^{\mathcal{R}}_{j',t-i}\right)^{\gamma}}_{\text{learning by doing}} I^{\mathcal{R}}_{j,t}.$$

γ is the *learning rate and* $I^{\mathcal{R}}_{j,t}$ *is in units of the final good in* j

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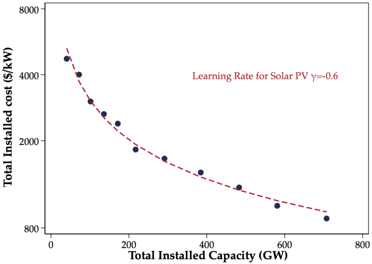

Renewable Investment

- Renewable technology
  - Is modular
  - Has zero marginal cost

- Private investors install renewable capital receive

$$V_{j,t} = p^E_{j,t} \times \theta_j + \frac{1-\delta}{1+R_t} V_{j,t+1}$$

- Free entry across space (Walsh '21). Electricity price satisfies

$$p^{\mathcal{R}}_{j,t} \geq p^{\mathcal{E}}_{j,t}\theta_j + \frac{1-\delta}{1+r_{j,t}} p^{\mathcal{R}}_{j,t+1} \quad \text{with “=” if investment is positive}$$

  - More likely to bind in regions with high renewable potential

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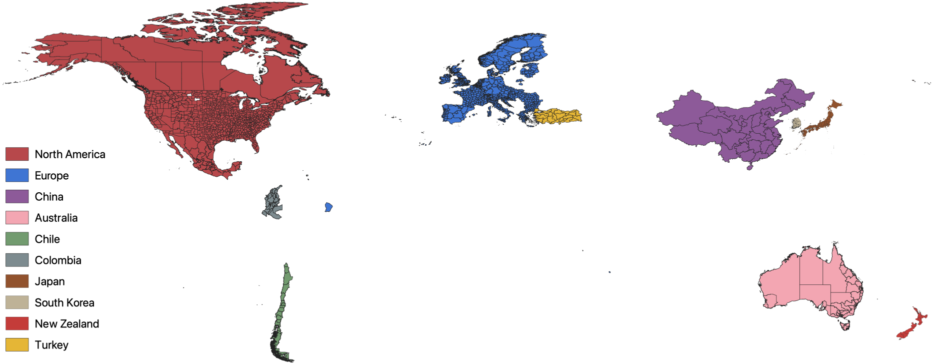
Taking Stock

- We have developed a model of:
  - Supply/losses of electricity
  - Demand of electricity based on a spatial multi-sector model with trade
  - Renewable investment at the regional level

- To quantify the model we need data on
  - Supply: i) renewable potential/ existing fossil assets ii) electricity grid
  - Demand: i) Regional output/ employment ii) regional trade for trade costs
  - Returns to Energy Investment: i) shares of electricity and fossil fuels in production ii) fossil assets in the future

Quantitative Analysis

- Compile, combine, harmonize regional datasets (e.g. commuting zone)
  - 40 countries, 1916 regions (more to come)



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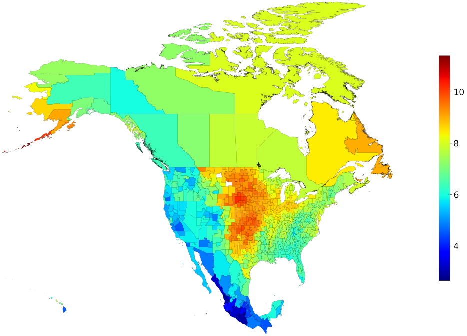
θ_j: **Renewable potential**

Source: Global Solar Atlas,

Global Wind Atlas



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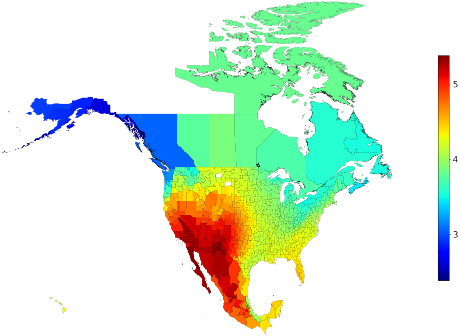

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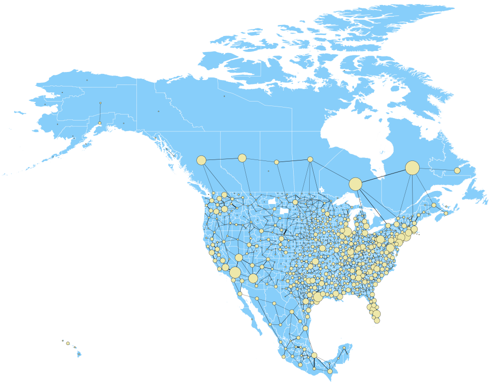
$K_j^{\mathcal{F}} \& \bar{A}$:**Current power capital & electrical grid**

Source: World Resources Institute, OpenStreetMap



Quantitative Analysis

- Compile, combine, harmonize regional datasets (e.g. commuting zone)

$\tau_{ij,s}$: **Regional-sectoral trade data**

Source: Regional IO tables

$\nu_{is}^{\mathcal{E}}, \nu_{is}^{\mathcal{F}}$: **Country-Sectoral energy share**

Source: GTAP IO tables

$p_i^{\mathcal{F}}$: **Fossil asset price projection**

Source: Asker et al '19 and trend extrapolations

Table 1: Gravity regression estimates: 8 SNA/ISIC sectors

$\ln(Distance_{ij})$	
Agriculture	-0.890^{***} (0.013)
Mining and Industrial	-0.865^{***} (0.011)
Construction	-2.090^{***} (0.019)
Wholesale, Transportation, Accomodation	-1.284^{***} (0.014)
Information and communication	-0.573^{***} (0.011)
Financial and insurance activities	-0.767^{***} (0.016)
Real estate/Professional	-0.733^{***} (0.014)
Public administration, defence/other	-0.837^{***} (0.014)
Intra-Country Border	-4.193^{***} (0.062)
Inter-Country Border	-7.435^{***} (0.064)
Industry FE	✓
Region of origin FE	✓
Destination region FE	✓
Observations	542,771
R^2	0.57

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Calibration Details

- (Summary) Calibrate model to
  - 1. θ_j: to renewable potential
  - 2. $K_j^{\mathcal{F}} \& \bar{\mathbf{A}}, \bar{\mathbf{R}}$: fossil power capacity, and grid length and voltage
  - 3. z_{js} : to match initial employment of region/sectors
  - 4. τ_{ijs} : based on gravity regression
  - 5. $\nu_i^{\mathcal{E}}$,$\nu_i^{\mathcal{F}}$: sectoral energy and fossil assets share
  - 6. $p_i^{\mathcal{F}}$: fossil asset prices projection
- In addition:
  - Set $\gamma_S = 0.6$ and $\gamma_W = 0.27$ (based on effects of scale)
  - Set depreciation of renewable capital to 3% (Jordan Kurtz '13)
  - Set steady state yearly interest rate of 5%

Intermittancy

Two model additions to address renewable intermittancy:

1. Each unit of capital must be paired with a certain **battery** size (0, 2, 4 hrs storage)
   1.1 Battery production also subject to learning economies

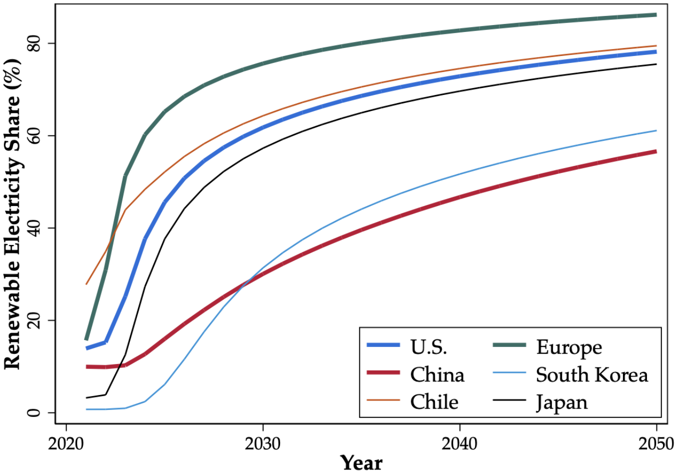
$$Q^{\mathcal{B}}_{j,t} = \underbrace{\left(\sum_{j'} \sum_{i=1}^{\infty} (\mu)^i Q^{\mathcal{B}}_{j',t-i} \right)^{\gamma_B}}_{\text{learning by doing}} I^{\mathcal{B}}_{j,t}$$

2. **Capacity payments** to fossil fuels sufficient to keep 1/3rd current stock in LR

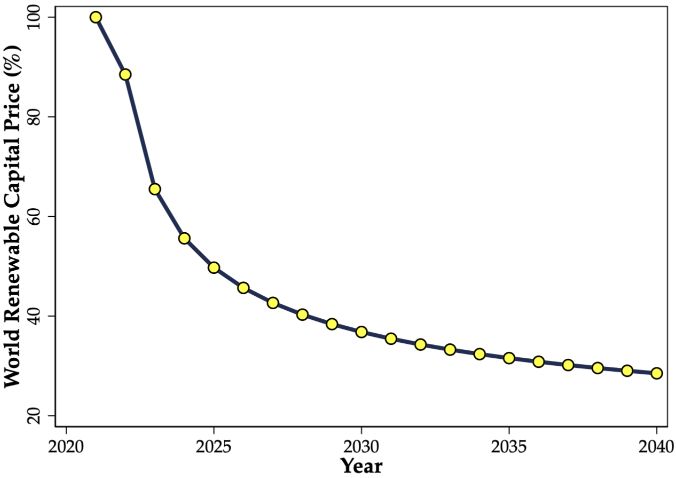
Winners and Losers from the Rise of Renewables

- We first simulate the model to find a new steady state
- Solve transitional dynamics with perfect foresight
- Dominance of renewables in the long run: who wins and who losses?

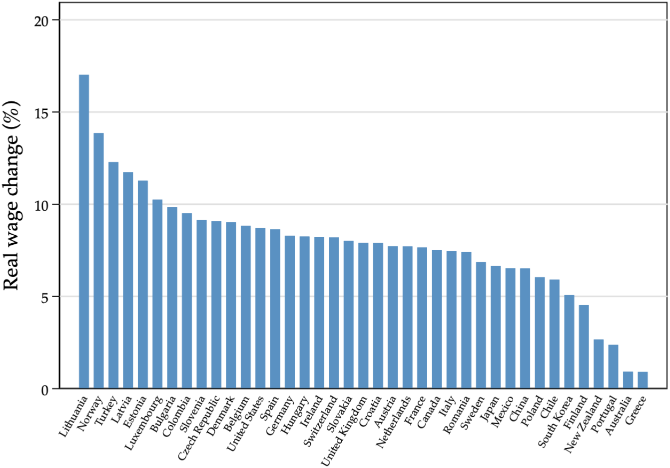
The Transition



Costs continue to fall



Large Welfare Gains



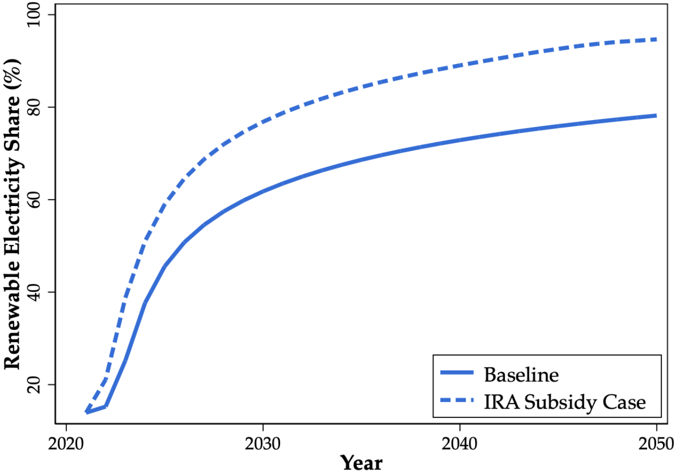
Implications of the Inflation Reduction Act

- Inflation Reduction Act signed into law by President Biden August 2022
- Provides a production tax credit to renewable energy of $26 mWh
- Assume that the renewable power generation receives a subsidy in price.
- Then free entry:

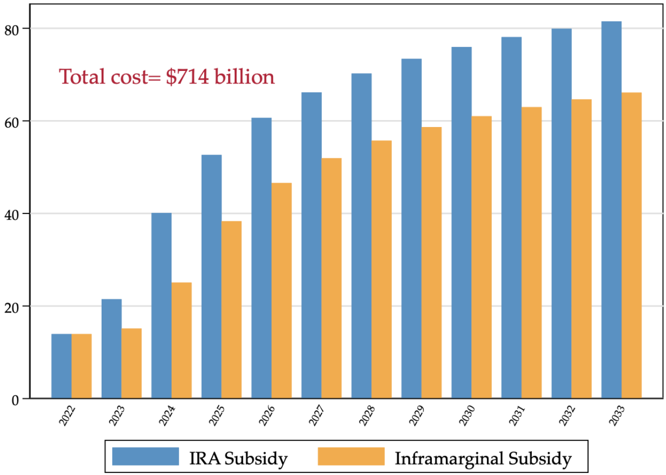
$$p^{\mathcal{R}}_{j,t} = (p^{\mathcal{E}}_{j,t} + s_t)\theta_j + \frac{1-\delta}{1+r_{j,t}} p^{\mathcal{R}}_{j,t+1}$$

  Subsidiy lump-sum taxed from consumers
- Phases out in 2034: no impact on long-run allocations! Only timing of transition.

Implications of the Inflation Reduction Act



Cost of the Inflation Reduction Act



Global Spillovers

- US is quite large on the world stage
- Purchases of this scale move the global capital price
- Modest speedups in other country transitions:
  - Europe 2% share increase by 2030
  - China 5% share increase by 2030

Conclusion

- Clean growth is likely to reshape the global energy system, even absent policy
- But policies will accelerate the changes...cheap power is coming!
- Next steps: Grid investment (Infrastructure Act)