China and the Global Diffusion of Solar Energy

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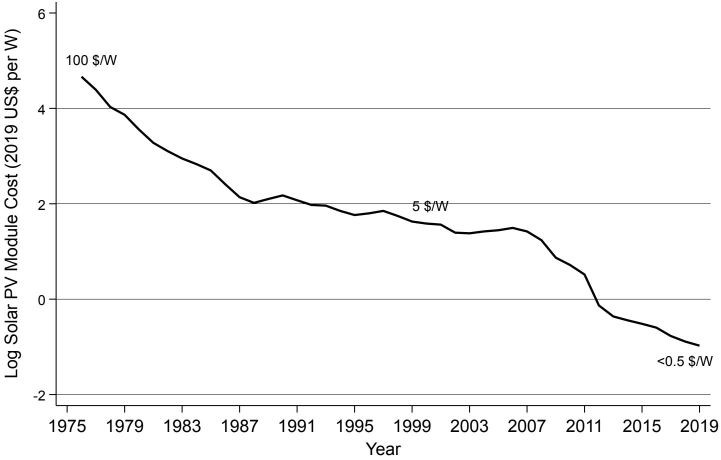
Motivation

Growing need for clean energy

- Around 73% of global greenhouse gas emissions are attributed to the energy sector
- Many emissions cuts rely on further electrification
- Many people around the world do not yet have access to electricity. Emissions will grow if this energy is produced in a carbon-intensive way
- **Clean energy is the critical factor in determining emission reductions**
- **But where does all this clean energy come from?**

Cost of solar has fallen dramatically

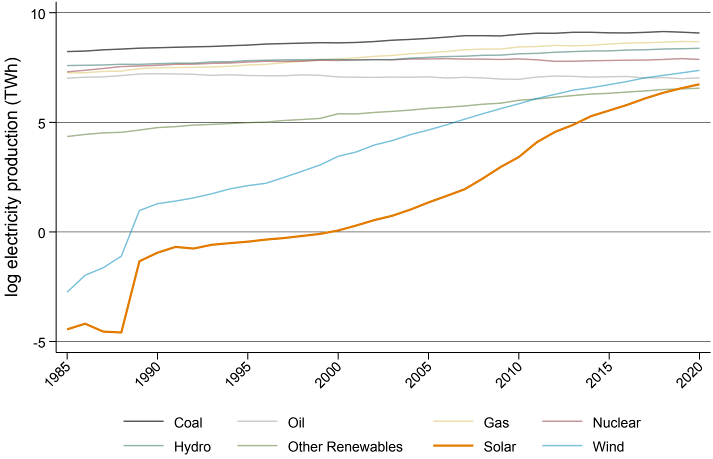
Figure: Global average price of solar PV modules (in 2019 US$ per Watt)



Source: LaFond et al. (2017) & IRENA Database

Renewable electricity capacity, especially solar, has grown rapidly

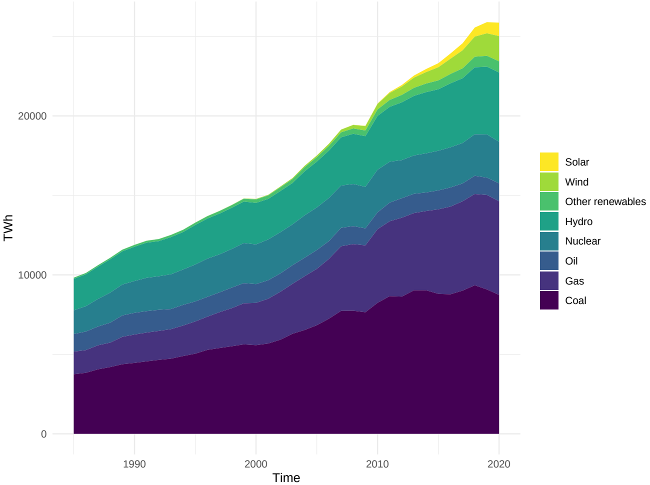
Figure: World electricity production by source



Source: International Energy Agency (IEA)

But solar is still a small share of global electricity generation

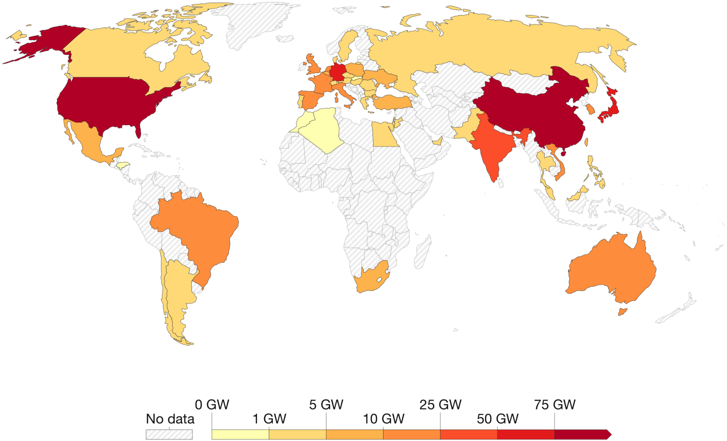
Figure: World Electricity Generation by Source



Source: Our World in Data based on BP Statistical Review of World Energy & Ember (2022)

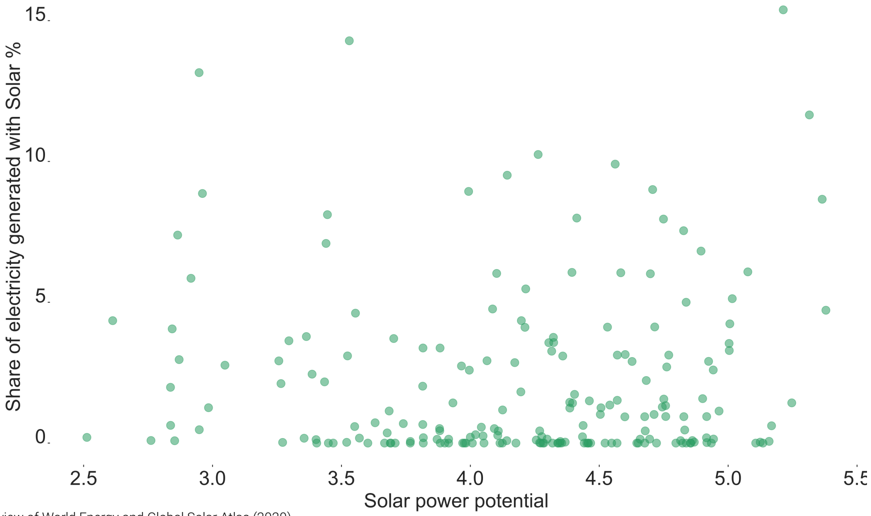
Adoption of solar is heterogeneous across countries

Figure: Cumulative installed solar capacity up to 2021(GW)



Source: Our World in Data, based on Statistical Review of World Energy - BP (2022)

Current use of solar uncorrelated with solar power potential



Source: BP Statistical Review of World Energy and Global Solar Atlas (2020)

How does industrial policy in China affect global solar adoption?

Global rise of solar has coincided with massive expansion of solar industry in China

Three steps to answering this question

1. Did Chinese industrial policy increase solar innovation, production and exports?
2. Did Chinese industrial policy increase global solar innovation and decrease global solar prices?
3. What are the barriers to global solar adoption?

How does industrial policy in China affect global solar adoption?

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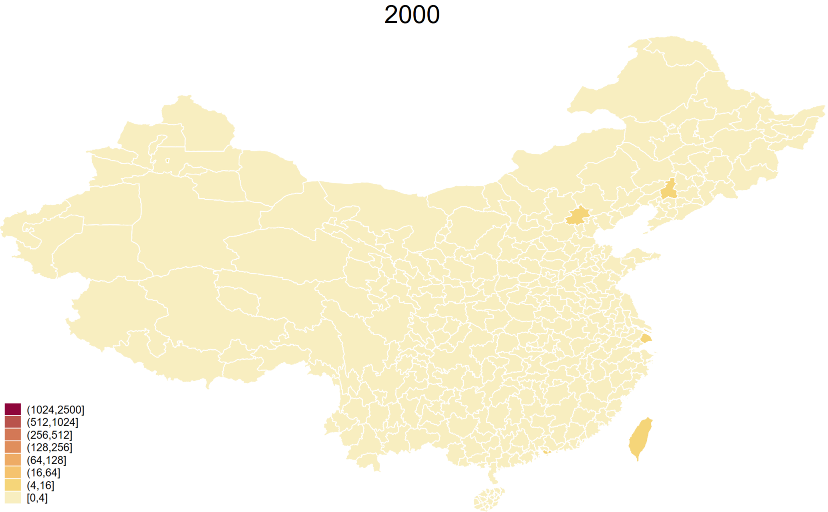
Project 1 Overview: Industrial Policy and Solar Innovation in China

- Autonomous local governments in China implemented **heterogeneous support for the solar industry**, particularly subsidies for **production and innovation** starting around 2007
- **Synthetic diff-in-diff** approach to exploit cross-sectional variation in treatment + timing
    - Control is never treated cities
    - Synthetic approach to improve plausibility of our control
- Estimate using **novel data** on solar industry in China and solar industrial policy
    - Firm level data on production, capacity, patents, exports from **ENF + SIPO + PATSTAT + Chinese customs data + Orbis + Chinese firm registration data**
    - Policy level data from **PKU Law** classified into policy type using NLP

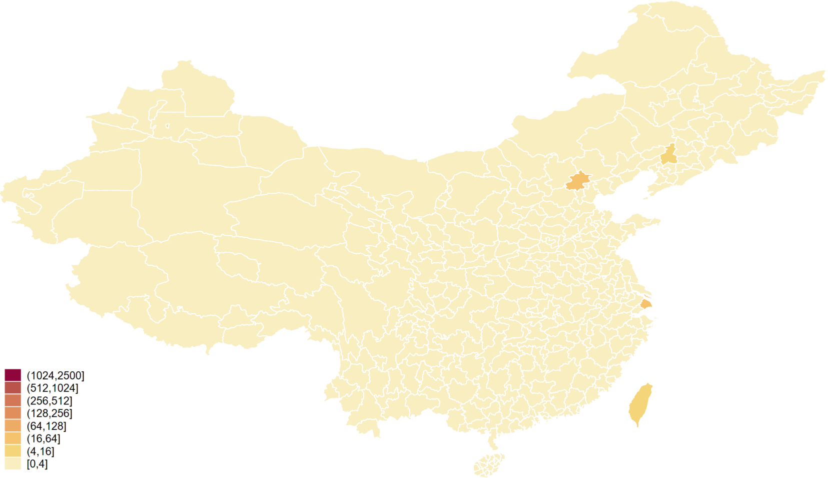
Patent distribution at city level and policy implementation



Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation

2001



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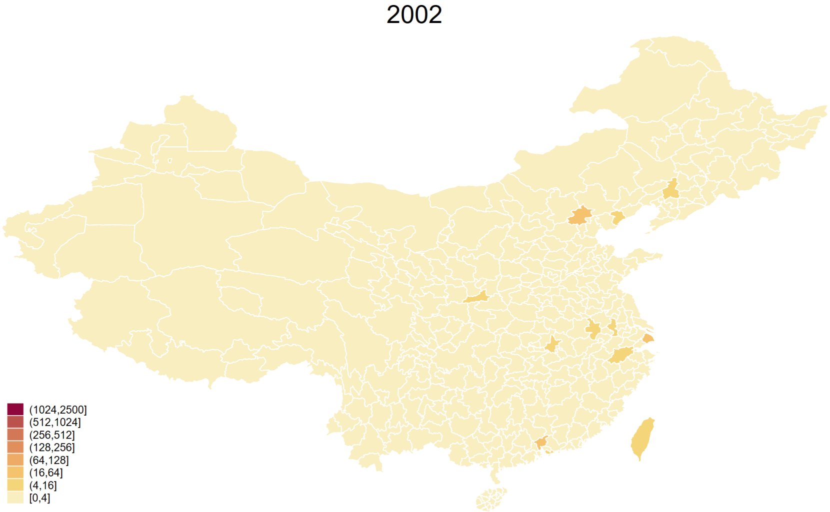

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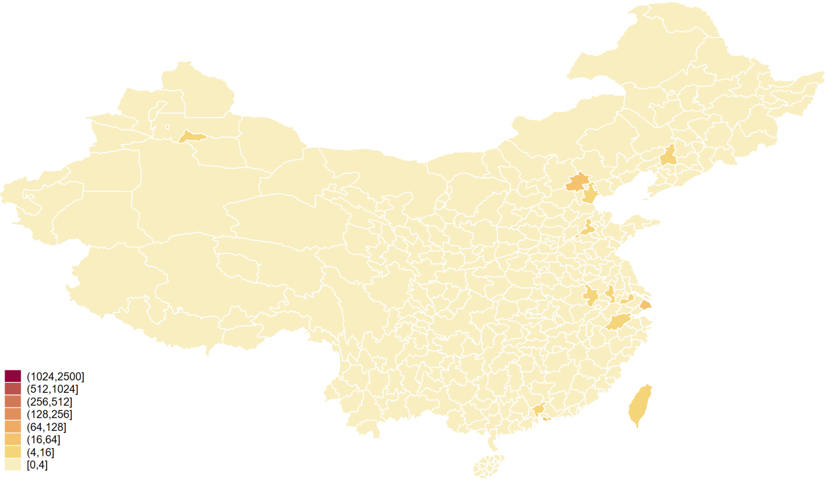

2003

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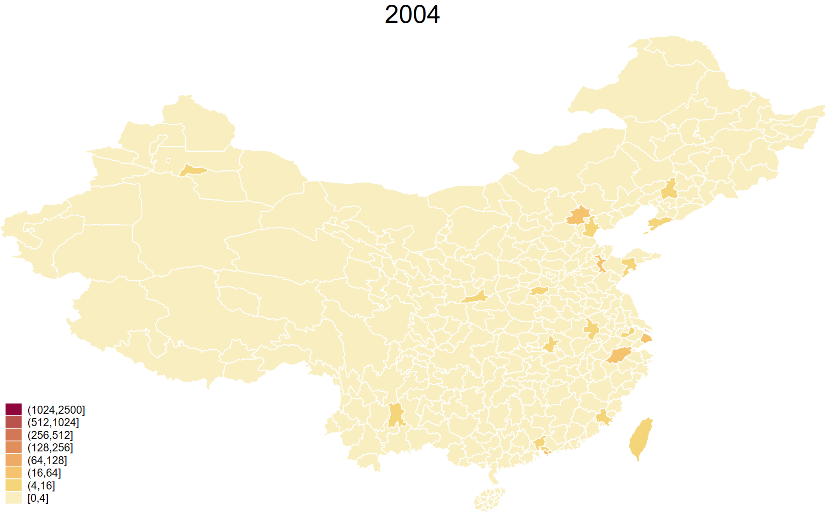

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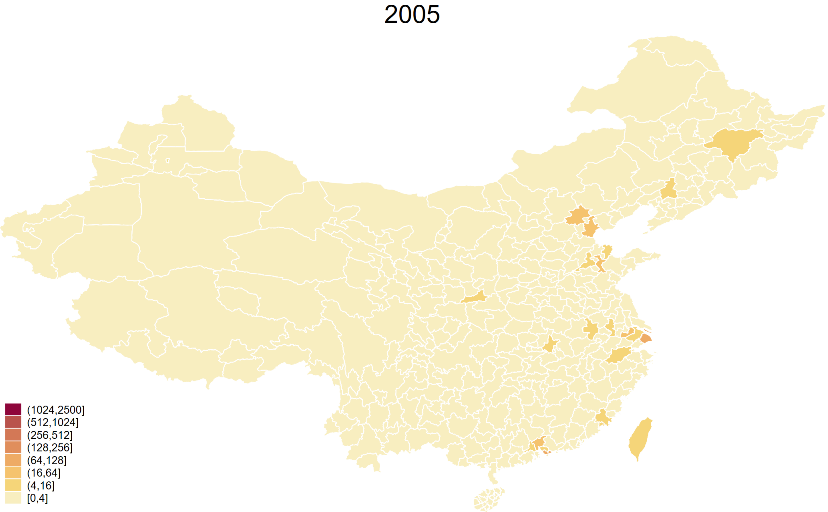

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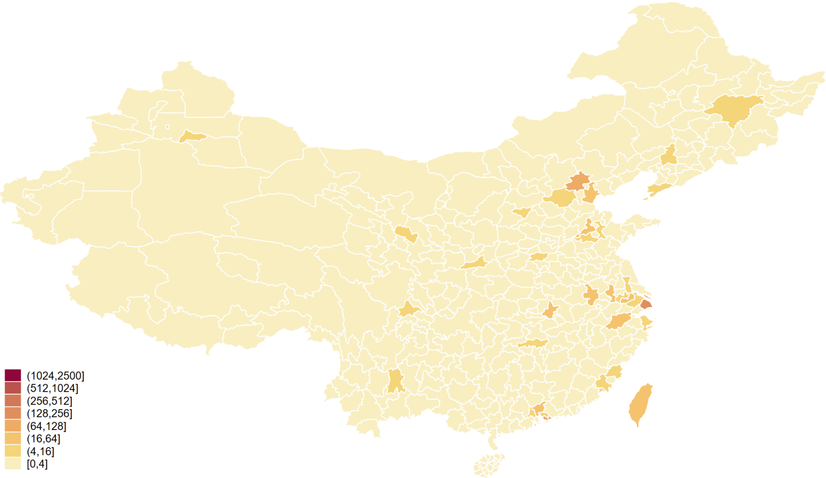

2006

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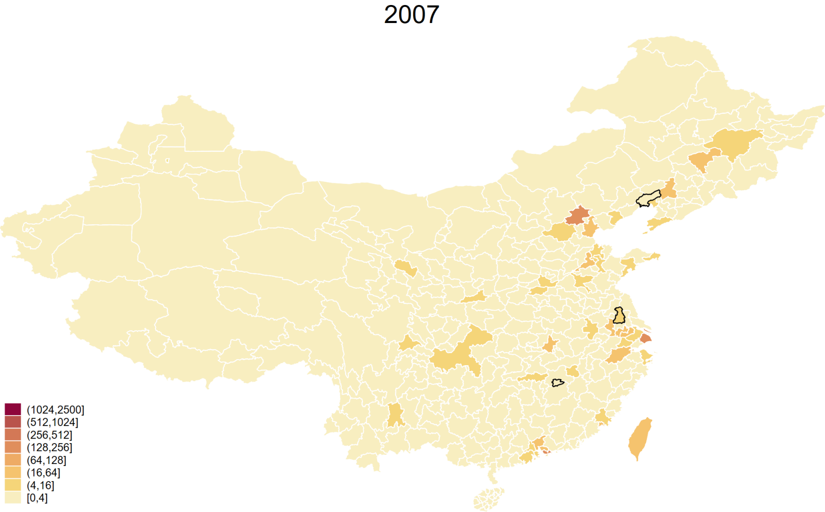

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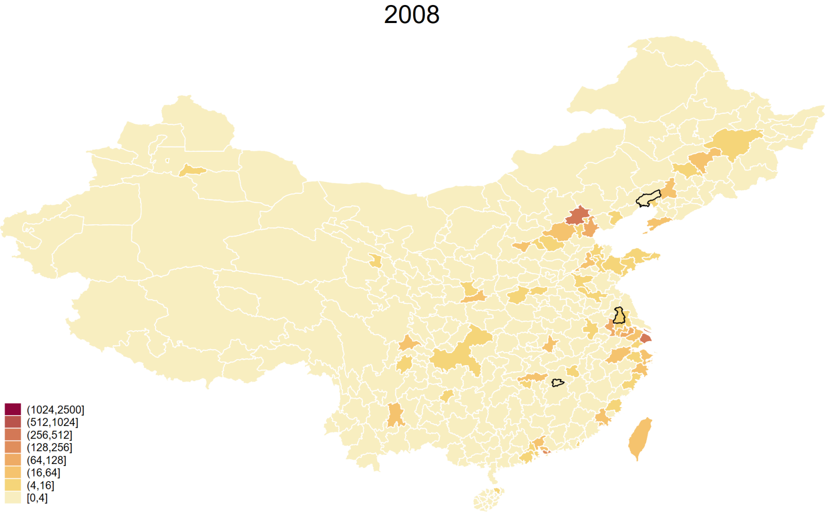

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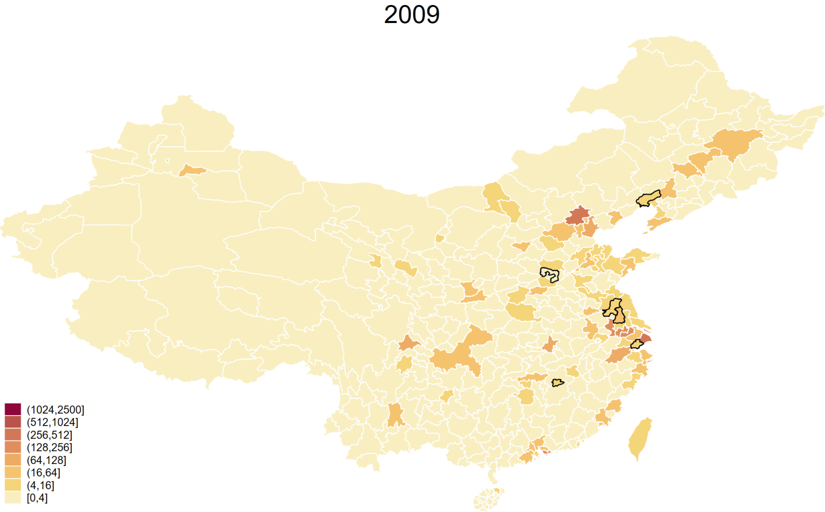
2009

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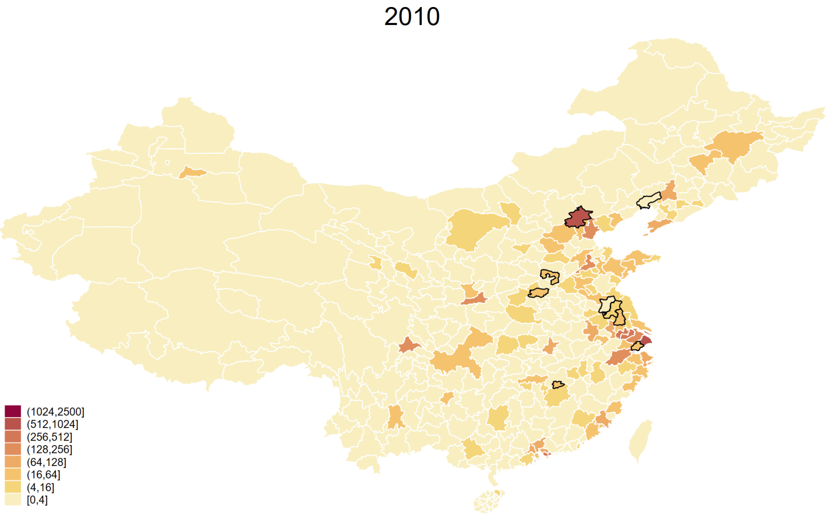

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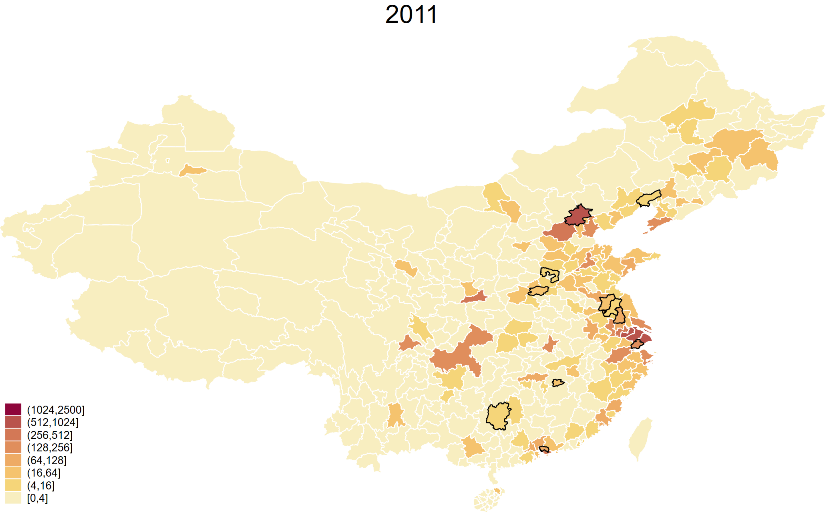

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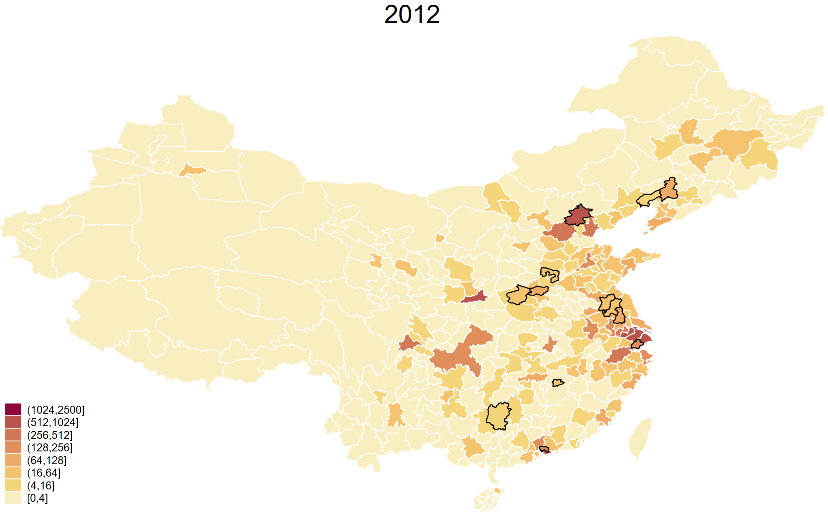

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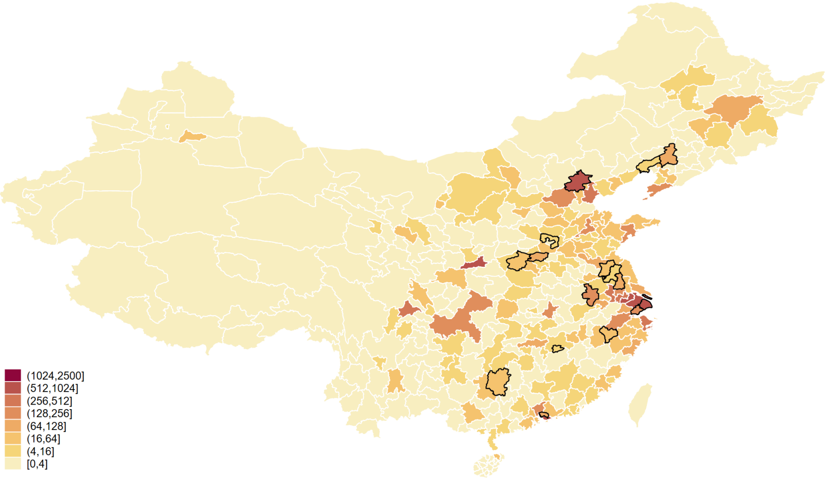
2013

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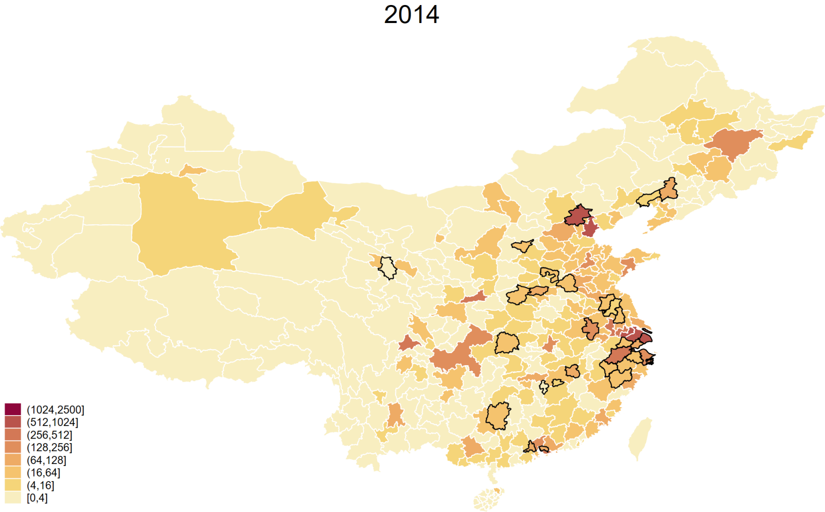

2014

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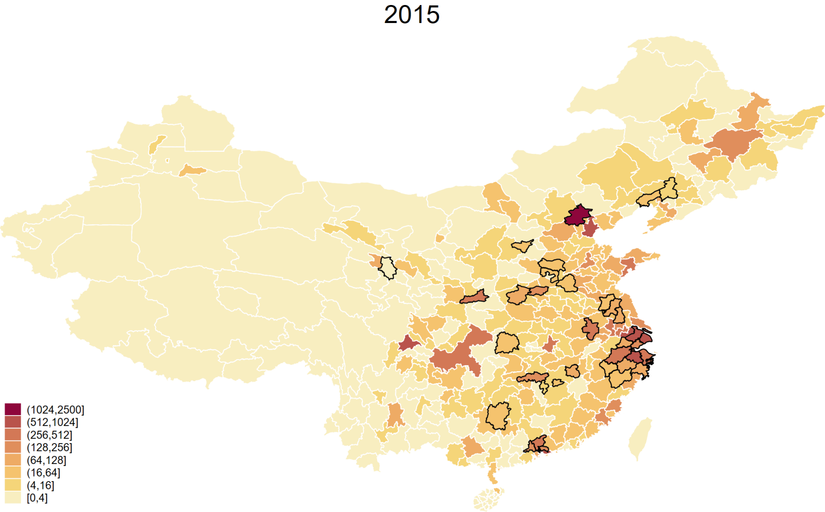

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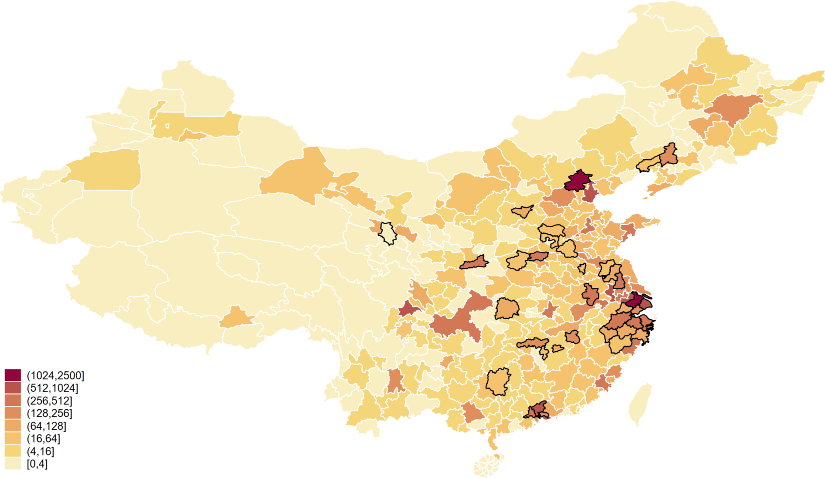
2016



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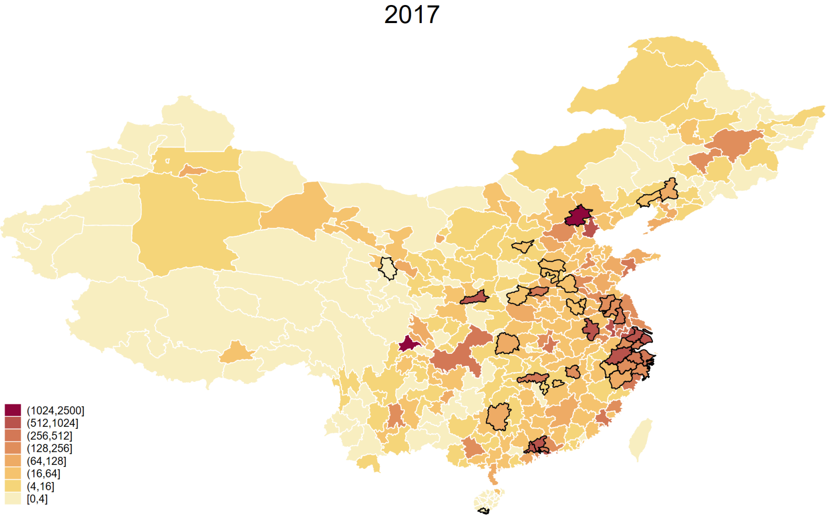

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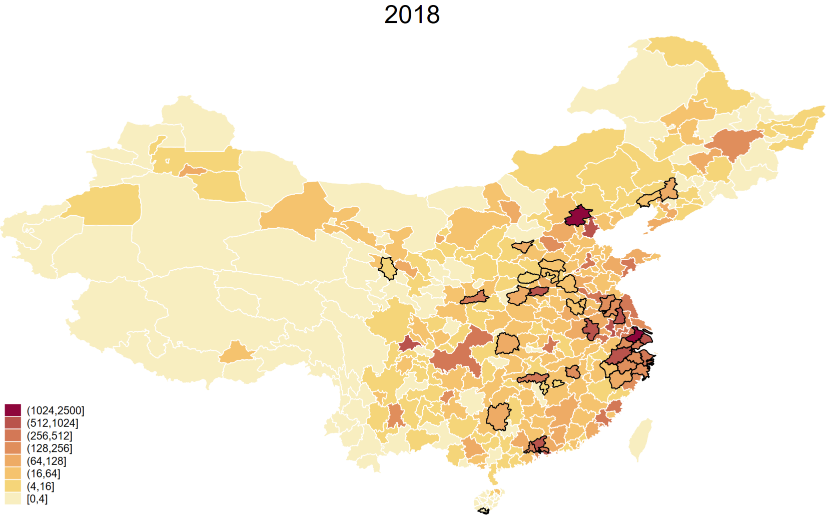

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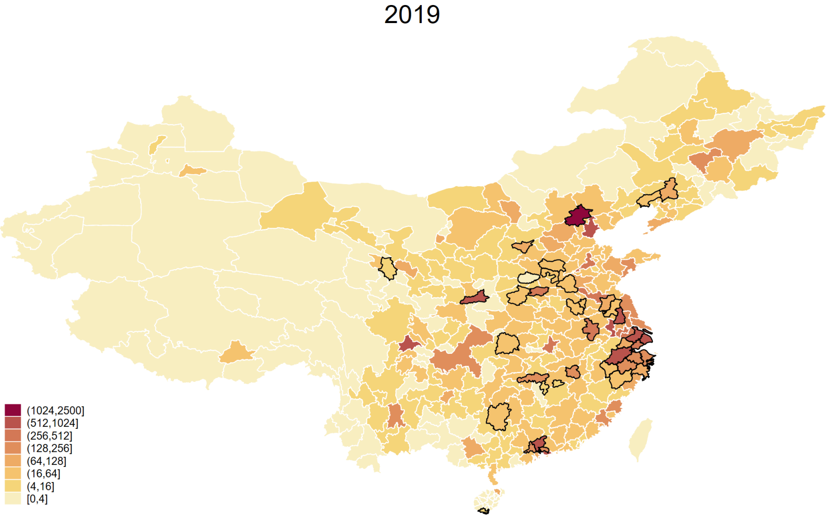

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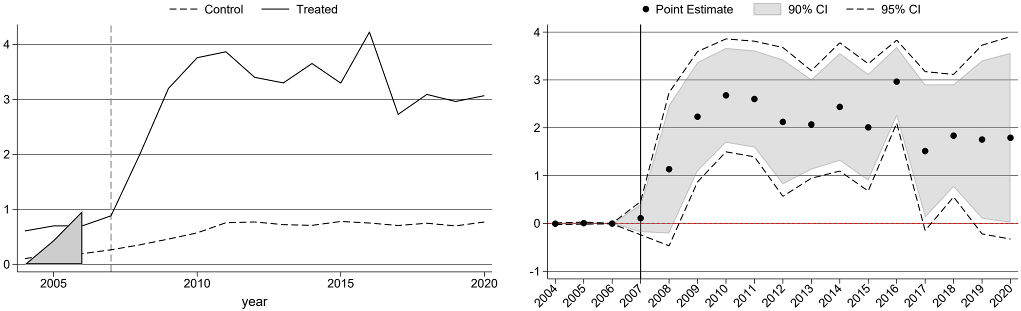
Results: Subsidies increase innovation

Figure: Patents (2007 Cohort)



Notes: SDID estimates on 358 cities, 3 that introduced policy in 2007. Outcome: IHS of patents by solar firms in a city-year. SE cluster bootstrapped by city.

Results: Subsidies increase innovation

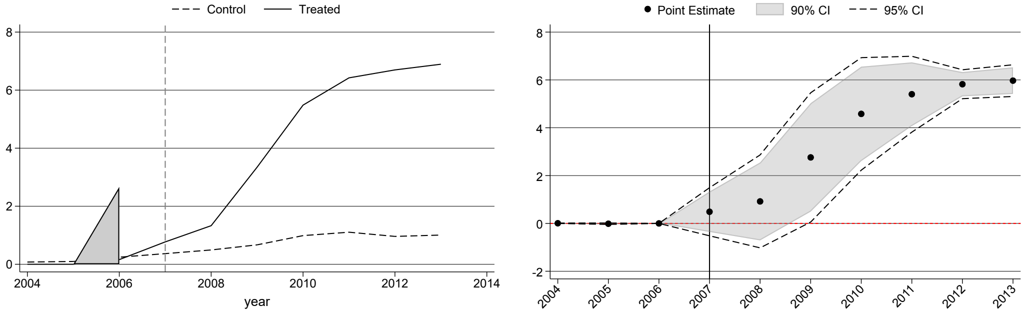
Table: Patents (Aggregate ATT)

	Any subsidy	*Demand subsidy*	*Production subsidy*	*Innovation subsidy*
All patents	0.496**	0.236	0.871***	1.060***
	(0.200)	(0.275)	(0.227)	(0.367)
Observations	6,086	6,086	6,086	6,086

Notes: * 0.1 ** 0.05 *** 0.01. SDID on 358 cities 2004-2020. Outcome is IHS of patents by solar firms in a city-year pair (av. = 13.1). SE cluster bootstrapped by city.

Results: Subsidies increase production

Figure: Panel Production Capacity (2007 Cohort)



Notes: SDID estimates on 358 cities, focusing on the 3 that introduced a policy in 2007. Outcome is IHS of Solar Panel production capacity in a city-year pair.

Results: Subsidies increase production

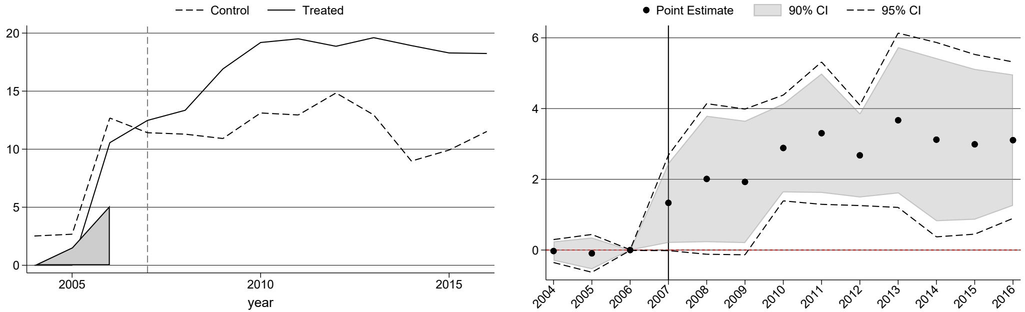
Table: Solar Panel Production Capacity (Aggregate ATT)

	Any subsidy	*Demand subsidy*	*Production subsidy*	*Innovation subsidy*
Panel production	2.098***	0.587	2.496***	2.930***
	(0.532)	(0.467)	(0.575)	(0.773)
Observations	3,580	3,580	3,580	3,580

Notes: * 0.1 ** 0.05 *** 0.01. SDID estimates on 358 cities 2004-2019. Outcome is IHS of production capacity of solar firms in a city-year pair.

Results: Subsidies increase exports

Figure: Export Value (2007 Cohort)



Notes: SDID estimates on 358 cities, focusing on the 3 that introduced a policy in 2007. Outcome is IHS of export value of Solar firms in a city-year pair.

Results: Subsidies increase exports

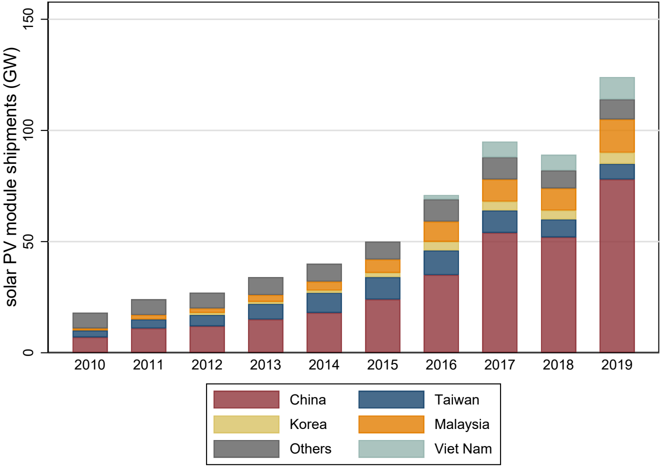
Table: Exports (Aggregate ATT)

	Any subsidy	*Demand subsidy*	*Production subsidy*	*Innovation subsidy*
Export value	0.658**	0.095	0.941***	1.404**
	(0.263)	(0.182)	(0.363)	(0.570)
Export volume	2.111**	0.090	2.875**	3.826*
	(0.999)	(0.774)	(1.287)	(1.984)
Solar export value	0.964***	0.311	1.311***	1.917***
	(0.359)	(0.273)	(0.477)	(0.607)
Solar export volume	3.984***	0.980	5.289***	7.501***
	(1.133)	(0.688)	(1.502)	(1.953)

Notes: * 0.1 ** 0.05 *** 0.01. Solar exports classified via HS8. SDID on 358 cities 2004-2016. Outcome is IHS.

China’s rise in solar shipments

Figure: Solar PV module shipments (GW) by country of origin, 2010-2019



Source: International Energy Agency (IEA)

How does industrial policy in China affect global solar adoption?

Global rise of solar has coincided with massive expansion of solar industry in China

Three steps to answering this question

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2. **Did Chinese industrial policy increase global solar innovation and decrease global solar prices?**
3. What are the barriers to global solar adoption?

Chinese industrial policy and global innovation

There are a few steps between Chinese industrial policy and a global price decline...

- **Policy spillovers:**
  - What are the geopolitics of solar industrial policy?
  - Did Chinese industrial policy crowd out policy efforts elsewhere? or the opposite?
  - How does it depend on the distance to the technological frontier?
  - An inverted-U relationship (as for competition and innovation)?

- **Innovation spillovers:**
  - Holding policy constant, how does Chinese innovation diffuse across the globe?
  - Does it stimulate innovation elsewhere?
  - An inverted-U relationship?

- Global net innovation $\rightarrow$ global price decline?

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Three steps to answering this question

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Cost declines may not translate into immediate uptake

- **Long-run adoption** driven by:
  - relative costs, solar potential, timing/intermittency, contracting frictions, discount rate
  - See Arkolakis and Walsh (2023) for global model ft. some of these factors

- **Pathway to long-run equilibrium** depends on
  - Political economy: fossil fuel resources, energy independence, lobbying, state ownership of
  - Policy: ‘pro-environment’ attitudes and subsidy policies
  - Lock-in: sunk costs (power plants, transmission lines) and depreciation rate
  - Strategic delay: anticipation of future price declines
  - Market structure and incentives: long-term contracts, public vs. private
  - Growth rate of energy demand

- **Transition path matters** for meeting climate goals
  - 10 years of ’status quo’ emissions left before we severely limit chances of sticking to 1.5
  - **This paper** → what are the biggest barriers to renewables adoption and how do these vary across countries?

Simple model: many countries, representative consumer

- Many countries, no trade (for now) in goods, services, electricity
- Representative consumer in country j obtains utility from electricity services
- Electricity services in country j are a CES of output of two energy sectors - solar and non-solar

$$e_j = \left(\kappa_{j,s'} e_{j,s'}^{\rho} + \kappa_{j,s} e_{j,s}^{\rho}\right)^{1/\rho} \tag{1}$$

- Where:
  - e_j is total electricity services in country j
  - $e_{j,s}$ and $e_{j,s'}$ are output of the solar and non-solar sector
  - ρ governs substitutability between solar and non-solar (captures intermittency / flexibility)
  - $\kappa_{j,\text{sector}}$ reflects productivity differences in energy sources across countries

Simple model 2: power plants

- Electricity output is the combined output of many power plants.
  - Each power plant is operated by a single firm, and each firm operates at most one power plant.
  - For now, each power plant is of a fixed capacity, e.g. 1MW.
  - Continuum of potential entrant firms in each sector (solar, dirty)

- In period t, a potential entrant pays
  - fixed cost to learn productivity
  - fixed cost to build a power plant after learning productivity (innovation shifts distribution over time)
  - does not operate in first period ($\rightarrow$ lead times)

- An incumbent plant (which was built prior to period t)
  - Faces an exogenous probability of shut-down
  - Experiences idiosyncratic shock to their productivity
  - Pays variable costs of operation (varies by sector $\rightarrow$ input costs)
  - Cannot change its capacity
  - Can choose to exit and receive some portion of the initital build cost back

Simple model 3: Electricity markets and government

- Simple, decentralised electricity market
  - Need to be parsimonious and flexible if building a globally applicable model
  - Aim to capture (i) alternative market structures (ii) grid balancing considerations in a reduced form way

- Government can
  - tax/subsidise set up costs
  - tax/subsidise operational costs
  - tax/subsidise shut-down costs
  - tax/subsidise output prices

- These can be levied at the
  - sector level (e.g. policies to support renewables)
  - firm level (e.g. preferential treatment of state-owened firms, long-term contracts etc)

Using the model

- Theoretical predictions about impact of cost changes on composition of the electricity grid
- Structural estimation to rationalise cross-country differences in adoption rates
- Policy counterfactual analysis, e.g. subsidise to coal shut down (reduce form version of Germany's reverse coal auctions)

Prediction example: decline in solar costs

- A decline in the cost of solar panels will
    - increase entry of solar firms
    - push down electricity prices
    - increase exit of incumbent fossil firms only if post-tax running costs $>$ post-tax electricity price

- In long-run equilibrium quantity of solar will increase, but will not move there immediately
    - Speed of adjustment depends on (i) depreciation rate/shutdown probability (ii) energy demand growth

Data

- **Upfront and operational costs by sector**
  - IEA projected costs of generating electricity
  - IRENA renewable power generation costs
  - Potentially hard to get country-specific data
- **Consumer electricity prices**: OECD Energy Prices and Taxes quarterly (patchy availablility)
- **Power plants**: Plant level data from World Resources Institute/Global Energy Monitor
- **Renewable potential**: Global Solar/Wind Atlas
- **Global Energy Policies**
  - Multiple supposedly 'global' datasets exist → cross-reference and combine...
  - All Energy Sector Policies: (i) OECD Policy Instruments for the Environment (PINE) Database (ii) Climate Policy Database (iii) IEA policy database
  - Subsidies: IRENA, OECD/IISD Fossil Fuel Subsidy Tracker, OECD Inventory of Support Measures for Fosil Fuels, IEA Energy subsidies database, IMF Fossil Fuel Subsidies database
- **Environmental attitudes**: World Values Survey

Data: still looking for...

- Suggestions for additional sources for any of the above
- Construction times (to estimate lead times)
- Timing of electricity demand by country (to estimate intermittency index)
- Fossil fuel reserves
- Share of government revenues from fossil fuels