Ray of Hope? China and the Rise of Solar Energy

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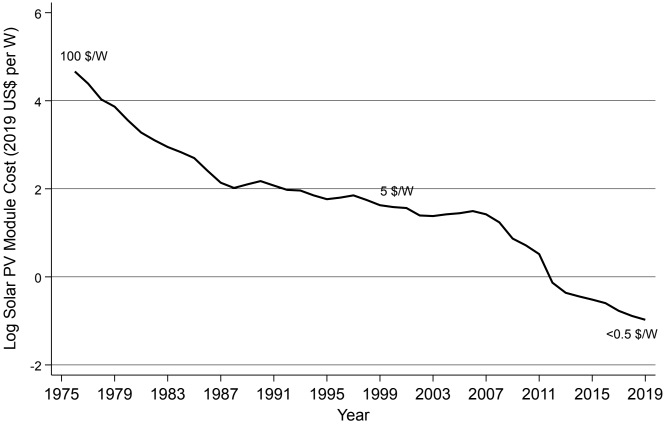
Motivation: Growing Need for Clean Energy

- 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
- **But where does all this clean energy come from?**

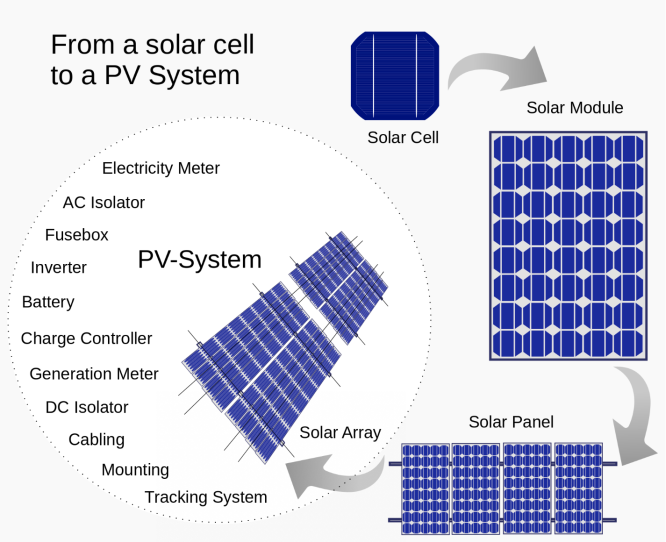
Cost of solar has fallen dramatically

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



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

Note: From cell to panels



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- Gather rich new micro-data on universe of solar panel manufacturers in China & including their production (in MWh) from ENF. Match to business register, patents (SIPO, PATSTAT, etc.), customs (exports), Orbis (revenue, labor, capital), ASIE, etc.

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- Find that production and innovation (but not so much demand) subsidy policies generated large increases in solar innovation, productivity, firm numbers, production, revenue and exports
- Data consistent with new model integrating multi-region energy demand, heterogeneous manufacturers & endogenous R&D and exporting decisions.

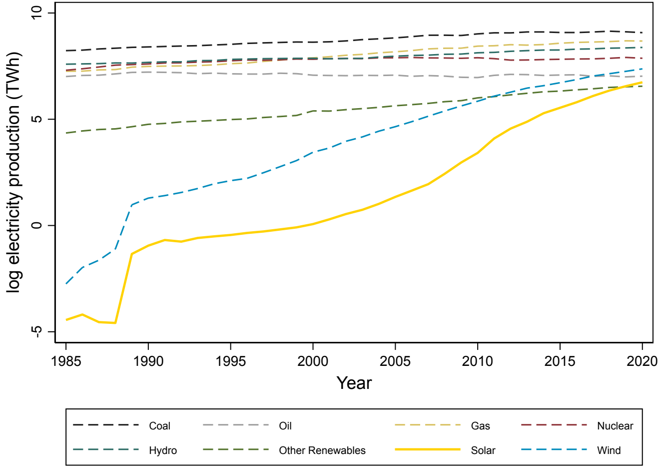
Some Existing Literature

- **Industrial Policy: Empirics**: Lane (2020) survey; Criscuolo et al (2019); Juhasz et al. (2022); Choi and Levchenko (2021); Choi and Shim (2022); Liu and Song (2022)
- **Industrial Policy: Theory**: Rodrik (2004); Harrison and Rodriguez-Clare (2010) survey; Liu (2019); Bartelme et al, (2021), Buera, Moll and Shin (2013); Itskhoki and Moll (2019); Murphy, Shleifer and Vishny (1989)
- **(Green) Directed Technical Change**: Aghion et al. (2016); Acemoglu et al. (2012, 2016, 2019); Arkolakis and Walsh (2023); Popp (2022, 2019); Nemet (2019)
- **Chinese Growth and policy**: Kalouptsidi (2018); Aghion et al (2015); Bai et al. (2019); Ball et al. (2017); Chen and Xie (2019), Wang and Yang (2021), Song, Storesletten and Zilibotti (2011); Konig, Lorenz and Zilibotti (2021)
- **Technology and Trade**: Melitz and Redding (2023) survey; Bustos (2011); Coelli, Ulltveit-Moe and Moxnes (2020); Aghion et al (2017)
- **Place-Based Policies**: Moretti (2011, 2012); Kline (2010); Ku, Schonberg and Schreiner (2019); Gruber and Johnson (2019); Greenstone, Hornbeck and Moretti (2010)

Background

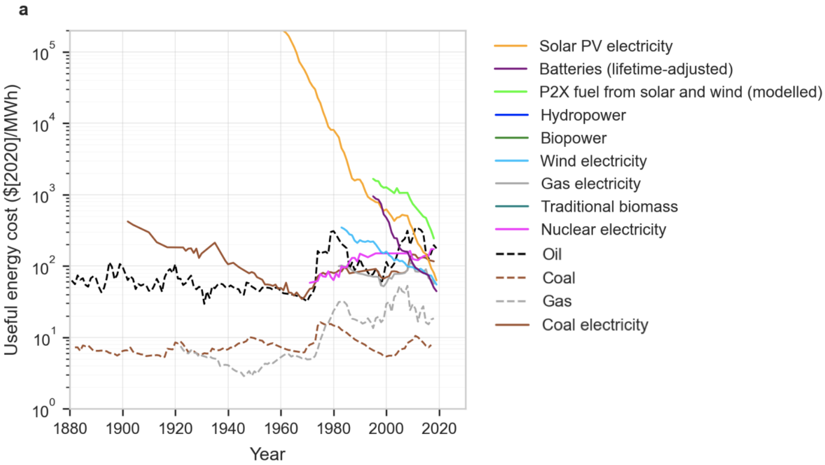
Renewable electricity capacity, especially solar, has grown rapidly

Figure: World electricity production by source



Source: International Energy Agency (IEA) Example of China and Chile

Huge fall in cost of solar relative to other energy sources (1880-2020)

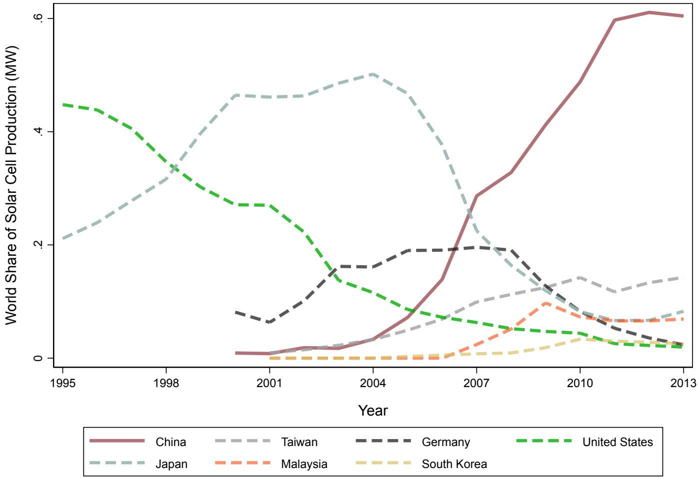


Forecasts

Source: Way, Ives, Mealy and Farmer (2021) “Empirically grounded technology forecasts and the energy transition”

China's global share of solar production rose from near zero to 60% in the decade to 2013

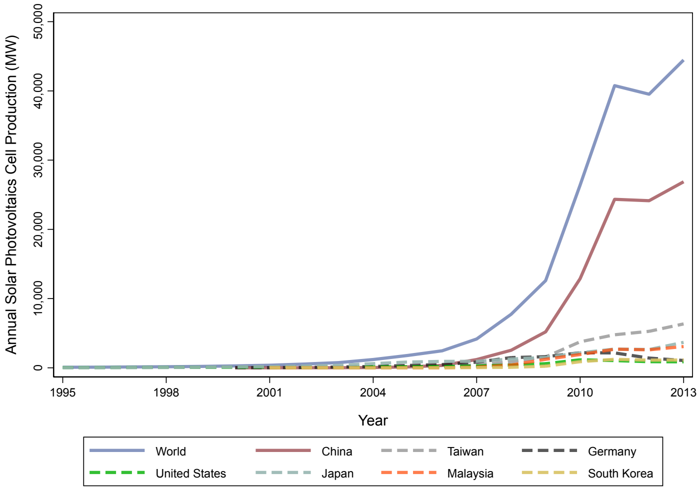
Figure: Share of Annual Solar Photovoltaics Cell Production in Leading Countries, 2000-2013



Note: The original data was compiled by the Earth Policy Institute from GTM Research, PV Cell Module Production Data, electronic database, updated June 2014.

The boom in global solar production basically due to China

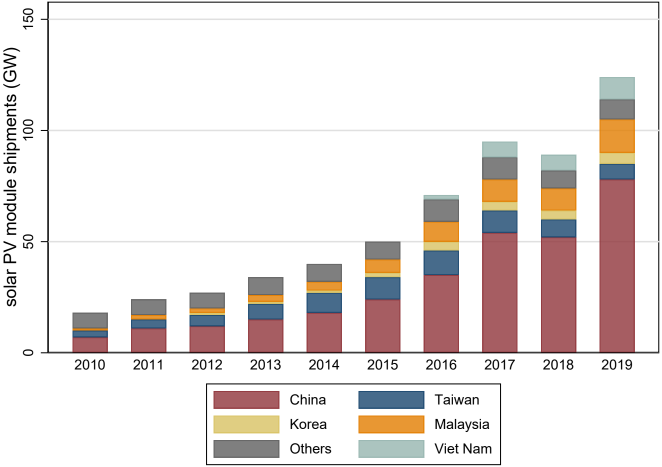
Figure: Solar PV cell production 2000-2013



Note: The original data was compiled by the Earth Policy Institute from GTM Research, PV Cell Module Production Data, electronic database, updated June 2014.

China's rise in solar shipments (later years)

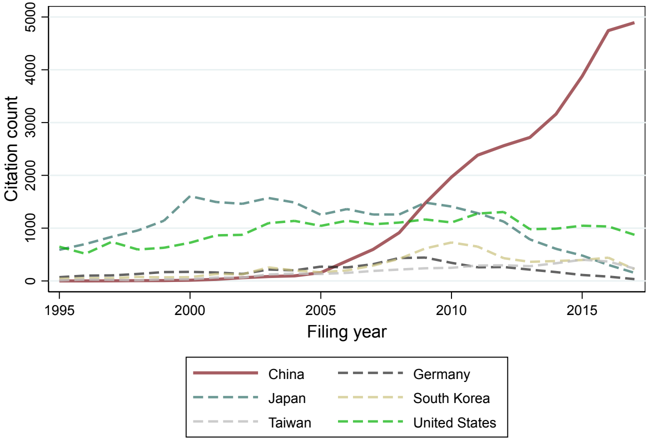
Figure: Solar PV module shipments (GW) by country of origin, 2010-2019



Source: International Energy Agency (IEA)

China is innovating not just imitating: Huge growth in Solar Patents

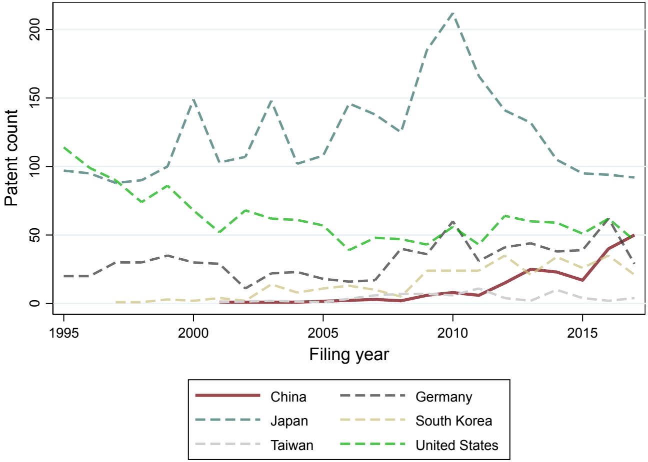
Figure: Cite-weighted Chinese solar patents



Note: Total yearly citations are divided by the number of years since the patent's filing to adjust for differences in the number of years when patents can be cited.

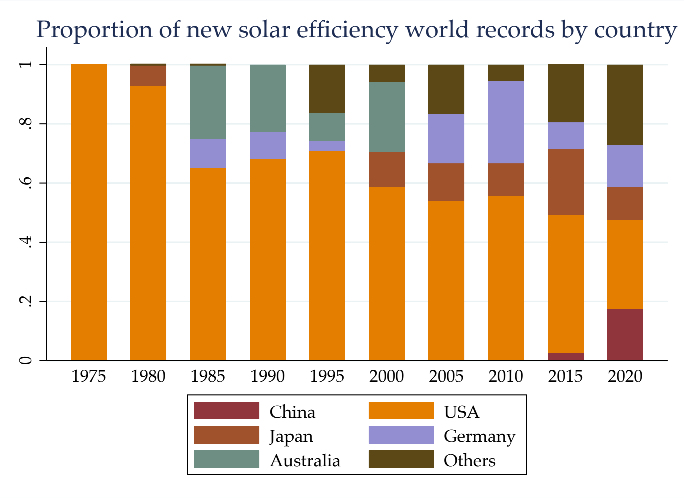
Source: PATSTAT database: Patents by priority date in all patent offices.

China is innovating not just imitating: Triadic Solar Patents



Source: PATSTAT database, Triadic patents = filed in USPTO, EPO and JPO

China is innovating not just imitating: Technological Frontier



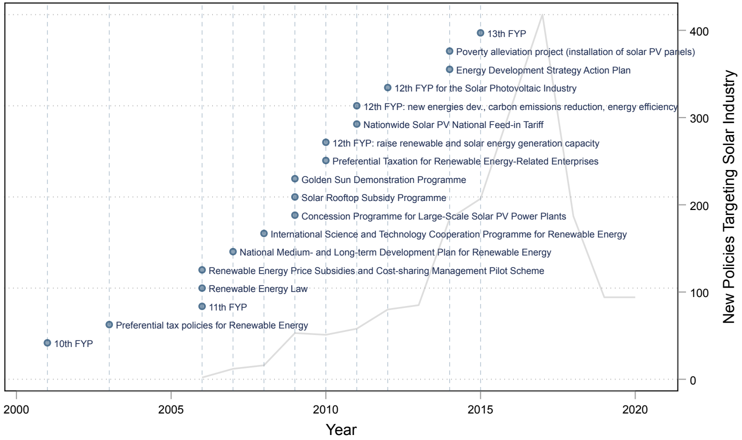
Source: Solar World Record Database

Data

Multiple sources of Data

- ENF Register (Solar Industry Directory) - universe of Solar PV and cell manufacturers: 1,718 firms in China 2004-2020
- SIPO All patent filings in China and PATSTAT (USPTO, EPO, etc.). Match to ENF Register
  Example
- ENF Production Data - production and capacity in MWh by firm, 2004-2013
- BVD Orbis Company Accounts (revenue, labor, capital) match by name, location, etc. 2004-2019. Validate with ASIE
- Customs Data - exports HS8 by country, match at firm level 2004-2016
- Policies (see below)
  Dstats

Figure: Selected main solar policies & all new solar-related policies (PKULaw data)



Note: Highlighted main policies are from Shubbak (2019). The time series of new solar policies is constructed using PKULaw data

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Local determination of solar production and R&D subsidies

- Subsidies to solar manufacturing were primarily developed, implemented and allocated by local governments
- Timing, size, and targeting of policy support varied significantly by city (358 "admin2 regions")
- Tax incentives, discounts for land acquisitions, cheap loans, financial support, esp. in solar industrial parks (consultancy)
- Spatial heterogeneity in R&D funding. Cities support local labs and research centers dedicated to solar engineering and technology

Measuring solar industrial policy

Challenges

- Intrinsically hard to measure industrial policy
- Retrieving quantitative data on solar subsidies in China is very hard (International legal disputes)

Our approach (similar to Lane, 2020 and Juhasz et al, 2022)

- Gather the universe of laws and regulations in solar industry from PKULaw dataset
- Analyze all policy documents and classify policies through text analysis
- Distinguish solar subsidies to: (i) Demand, (ii) Production and (iii) Innovation

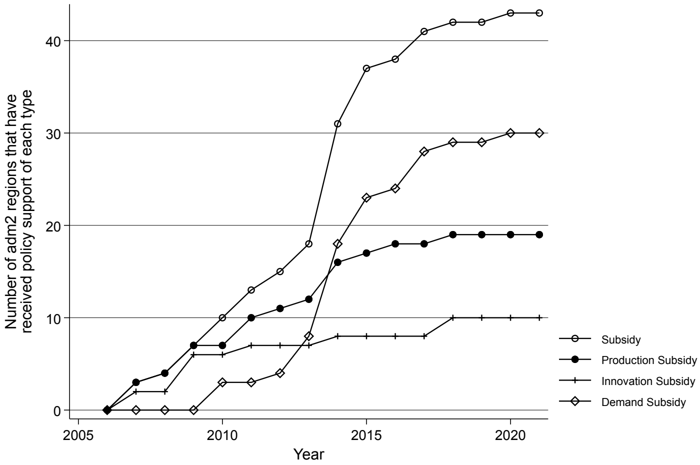
Table: City-level solar policies

Type of policy	*Number*	*key feature*	*Example*
Subsidy	78	Policy text contains precise information on the size of the subsidy	
1. Production subsidy	27	Subsidises solar production	*"The cost of a new solar production line built in Hefei will be subsidized by 12% (2018)"*
2. Innovation subsidy	12	Subsidises solar innovation	*"Firms will be awarded 10,000 RMB if they earn provincial level R&D center certification (Guilin, 2011)"*
3. Demand subsidy	61	Subsidises the installation of solar panels	*"1 RMB per watt for the electricity generated by solar projects installed in Beijing (2010)"*

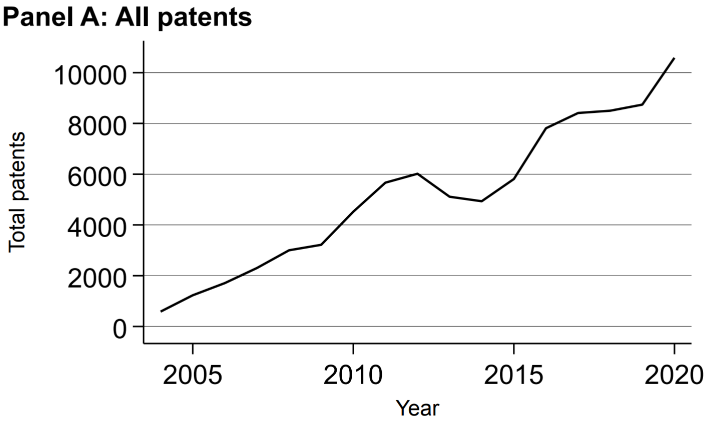
Source: Way, Ives, Mealy and Farmer (2021) "Empirically grounded technology forecasts and the energy transition"

Measuring solar industrial policy

Figure: Number of cities treated with supply & demand subsidies

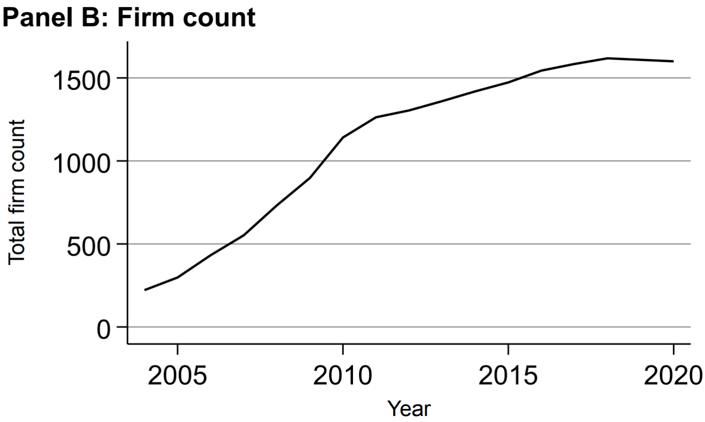


Chinese Solar industry evolution: Patents



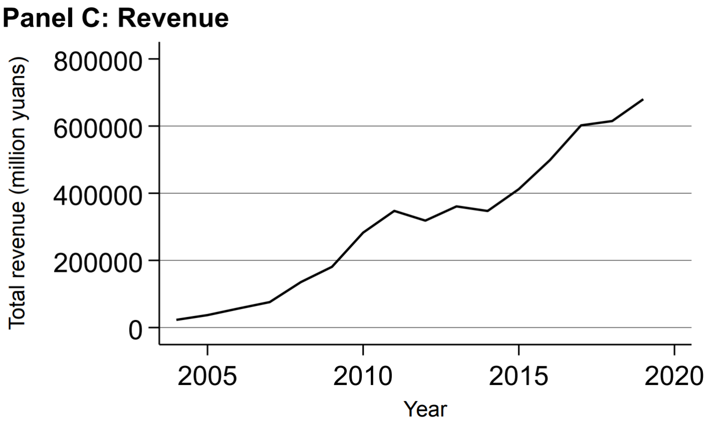
Notes: Total patent filings by Solar firms in SIPO.

Chinese Solar industry evolution: Firm Numbers



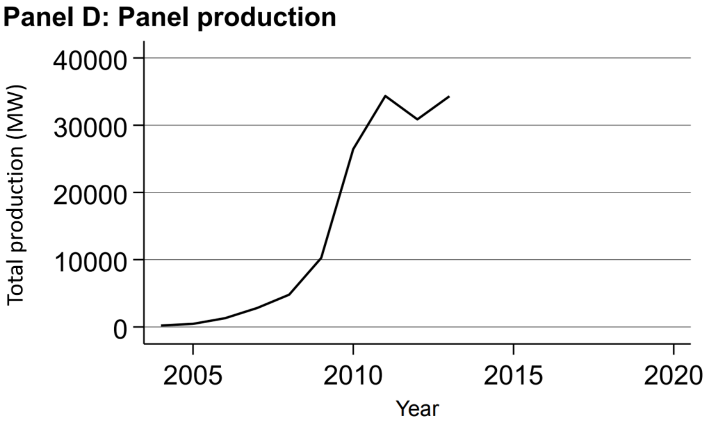
Source: ENF firm registration database

Chinese Solar industry evolution: Revenue



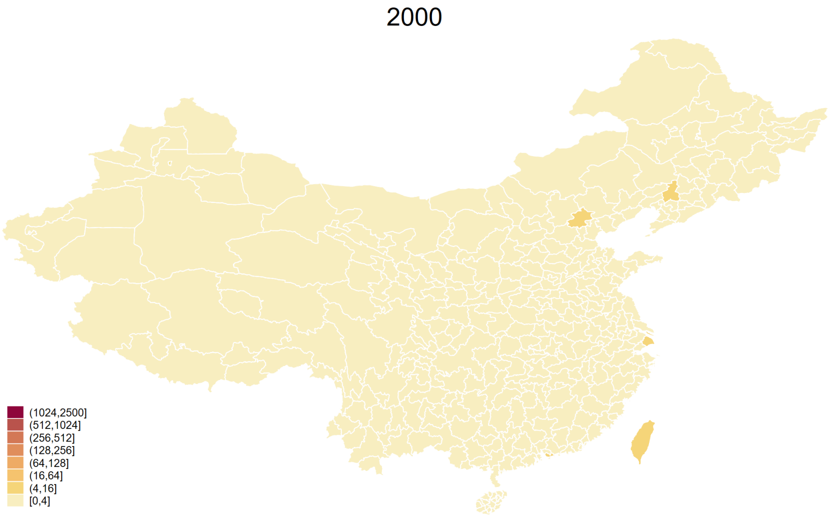
Source: ENF firm registration data and Orbis

Chinese solar industry evolution: Production



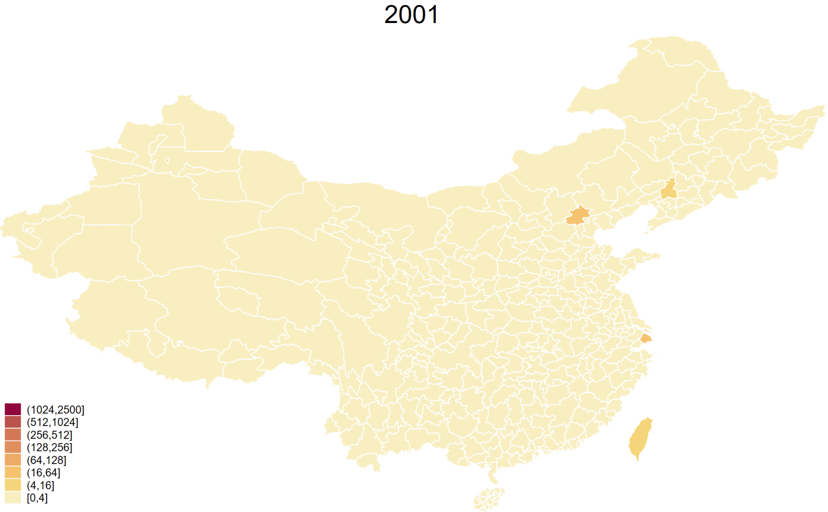
Source: ENF Production Data

Patent distribution at city level and policy implementation: 2000



Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2001



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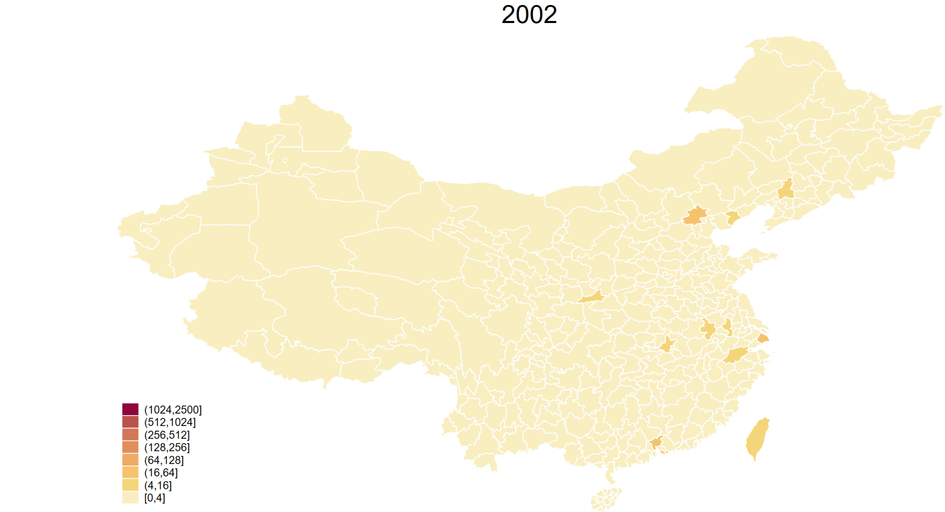
Patent distribution at city level and policy implementation: 2002



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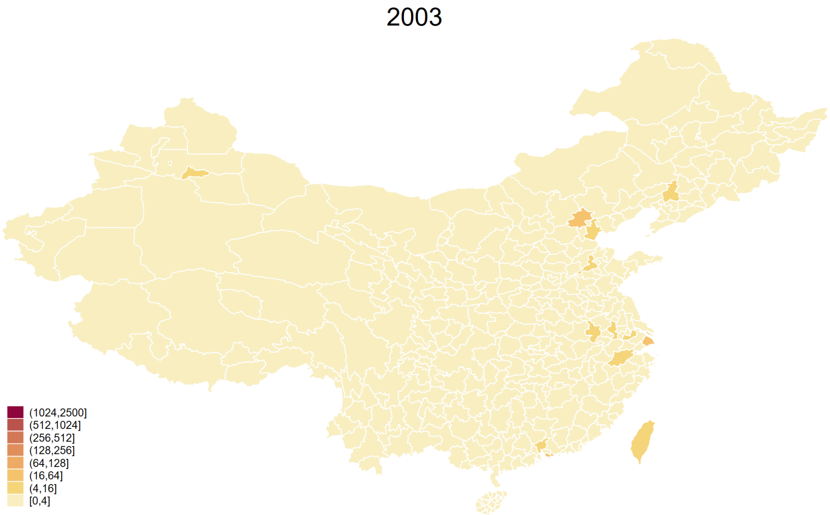
Patent distribution at city level and policy implementation: 2003



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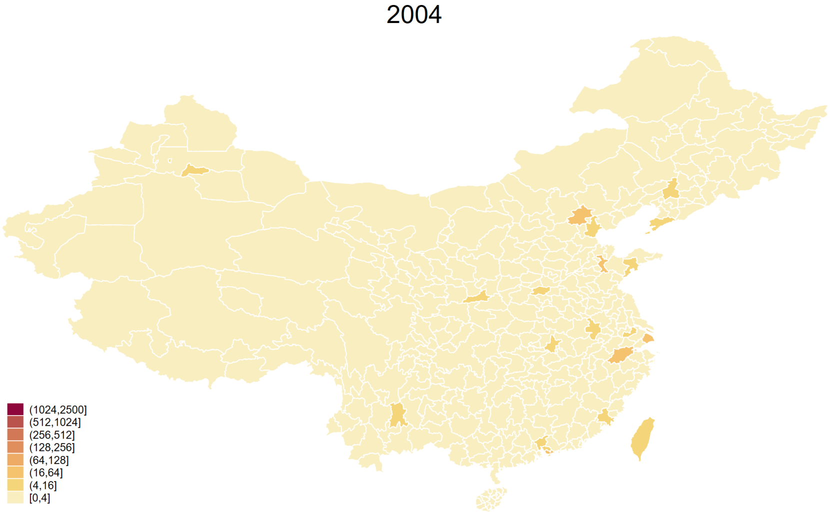
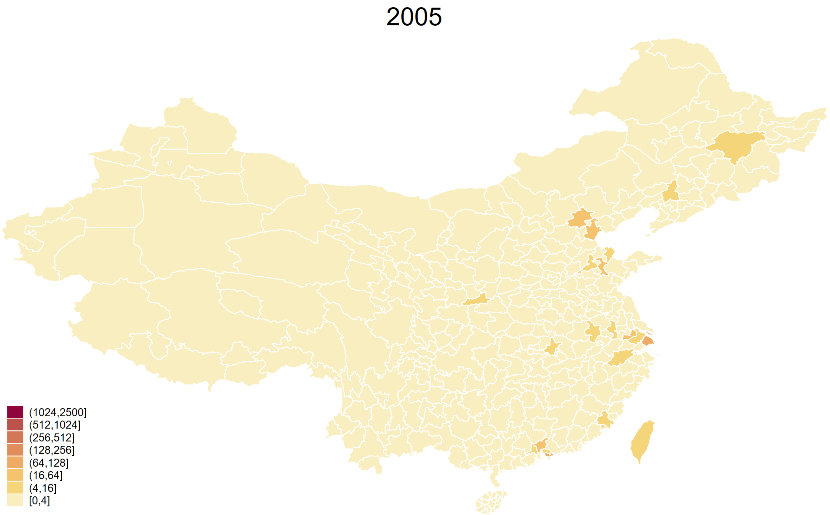
Patent distribution at city level and policy implementation: 2004



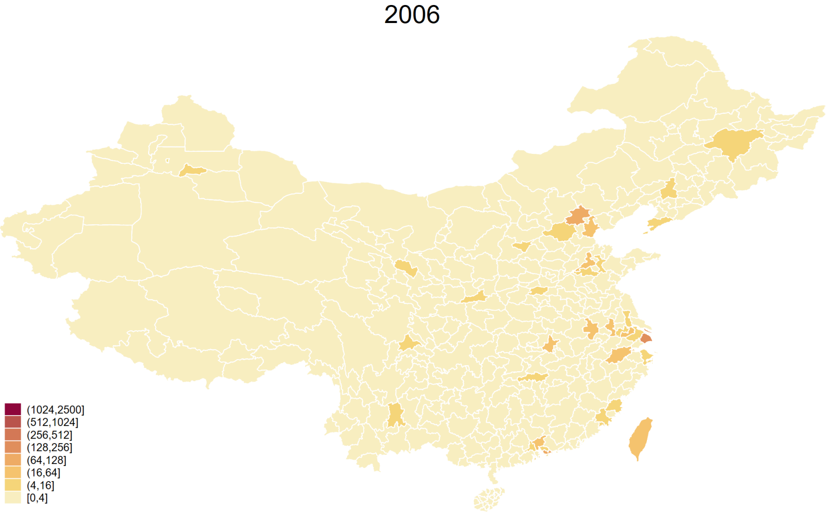
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2005



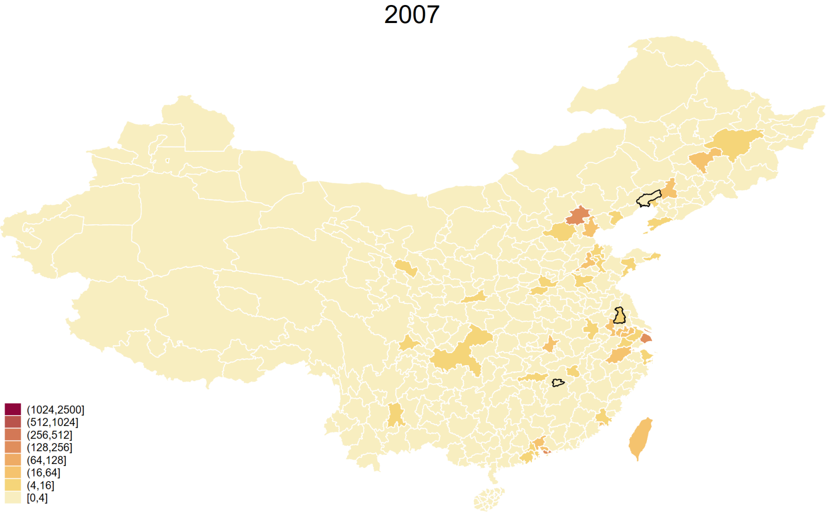
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2006



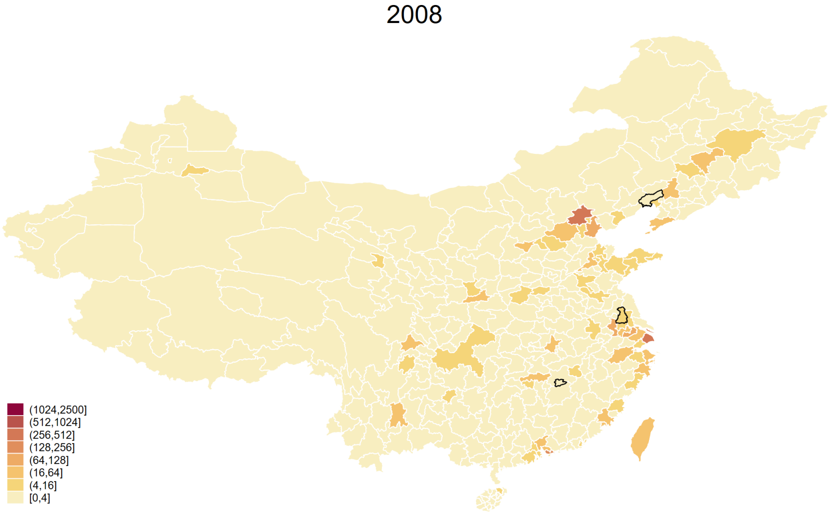
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2007



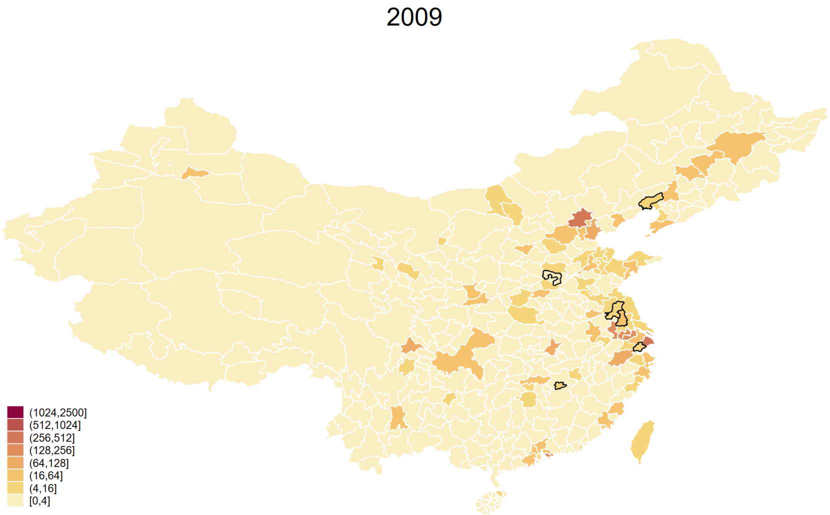
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2008



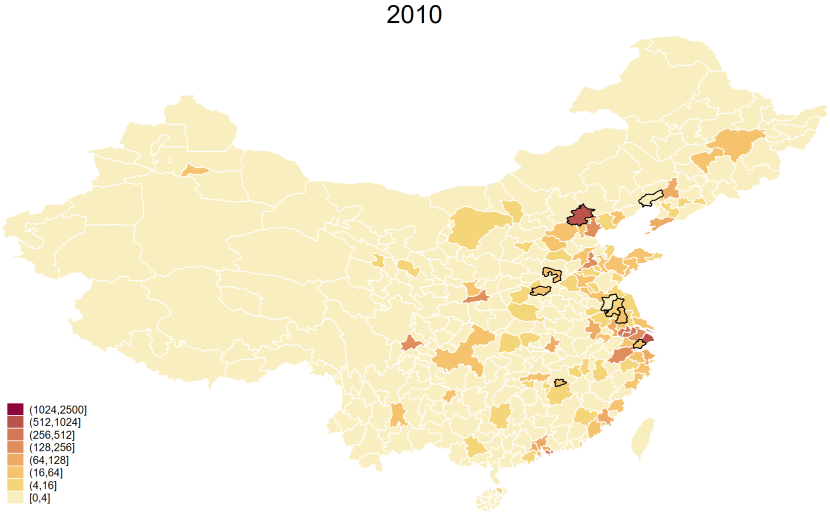
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2009



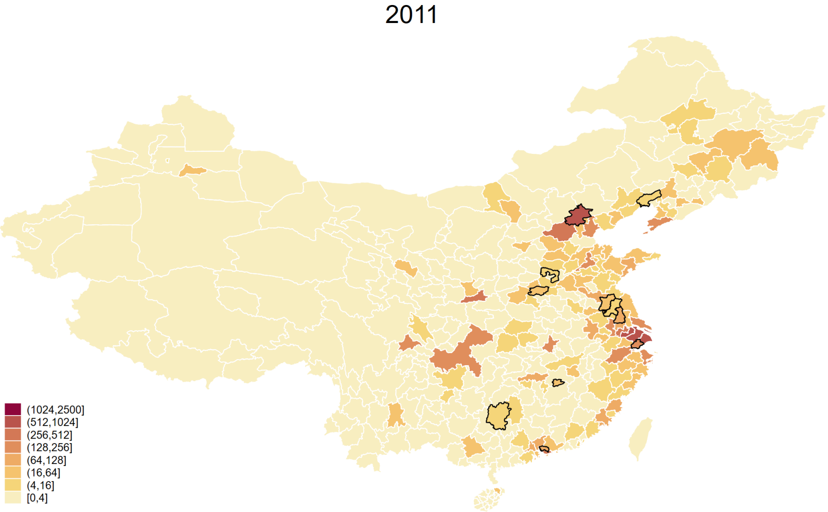
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2010



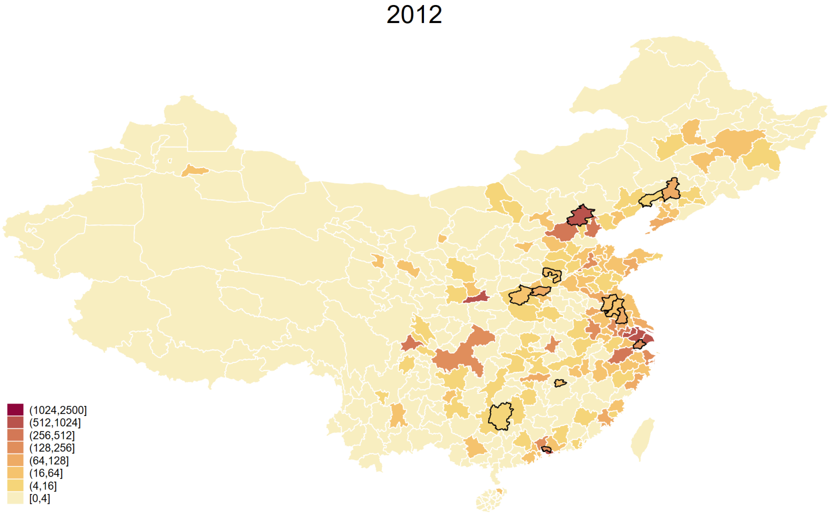
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2011



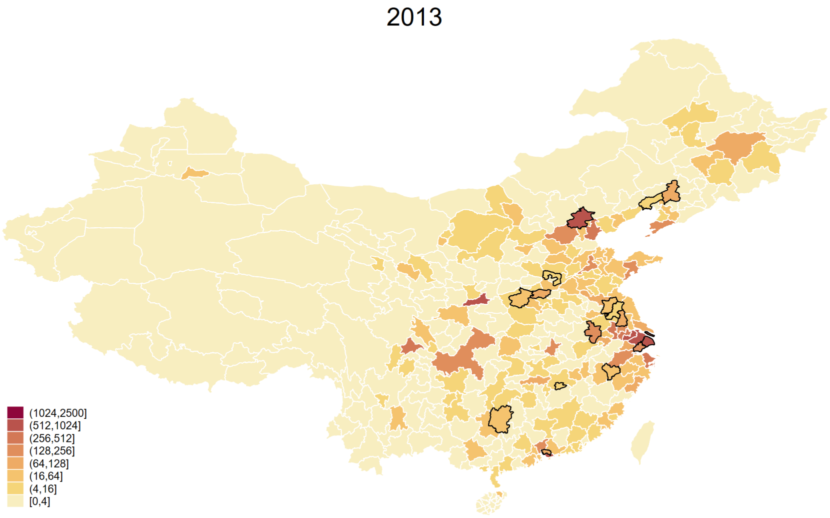
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2012



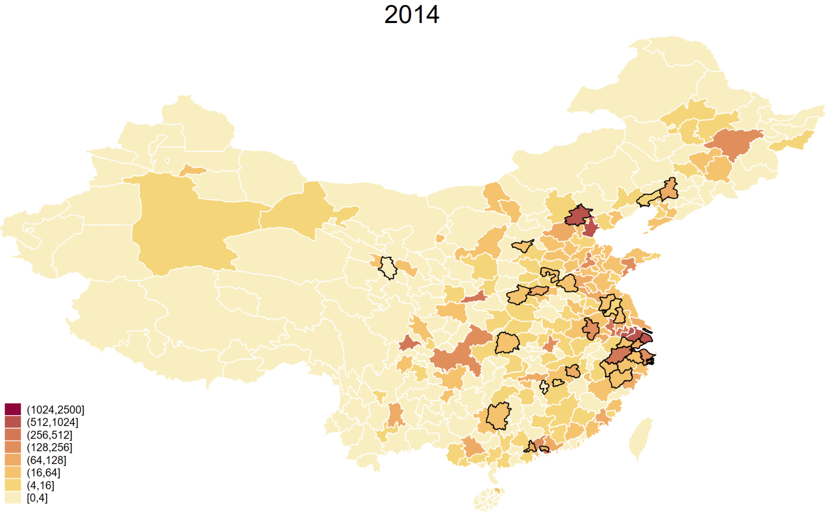
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2013



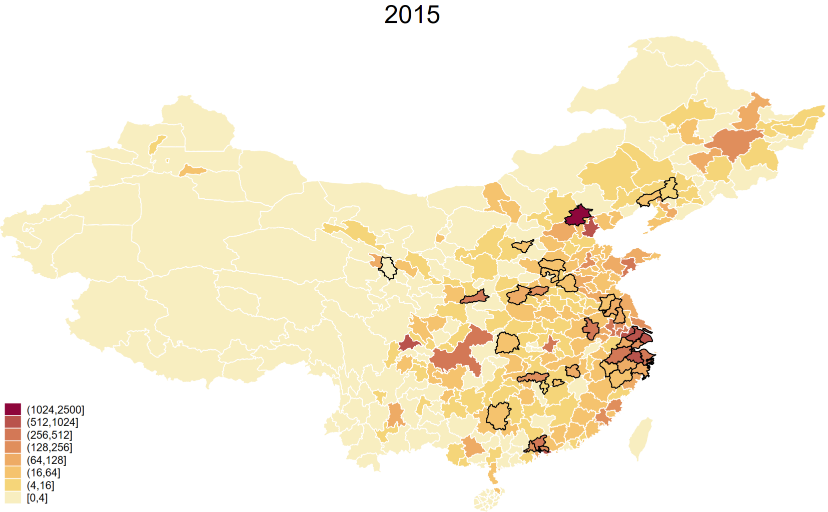
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2014



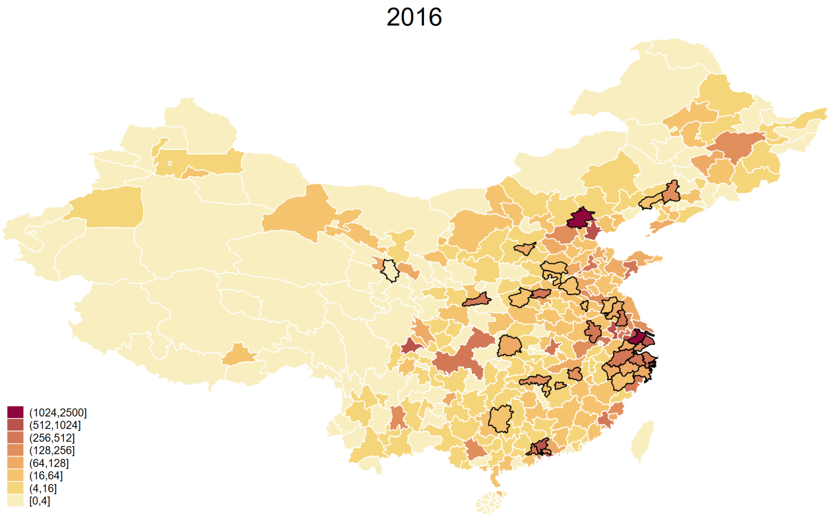
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2015



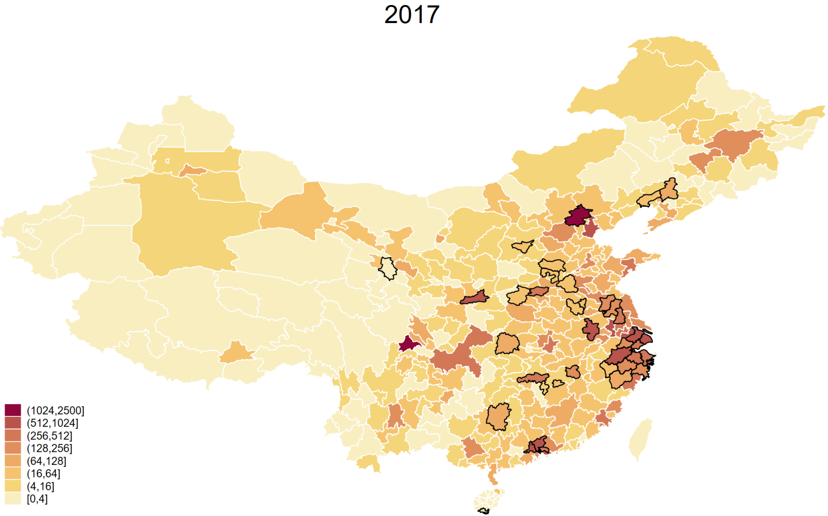
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2016



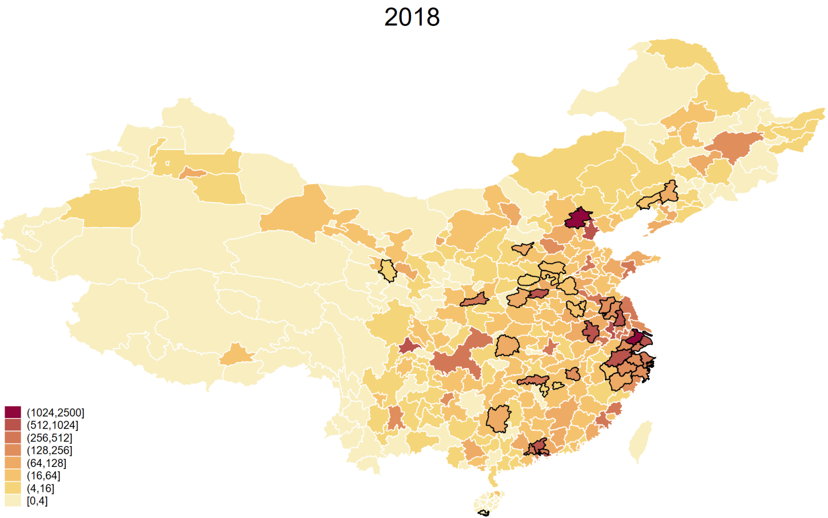
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2017



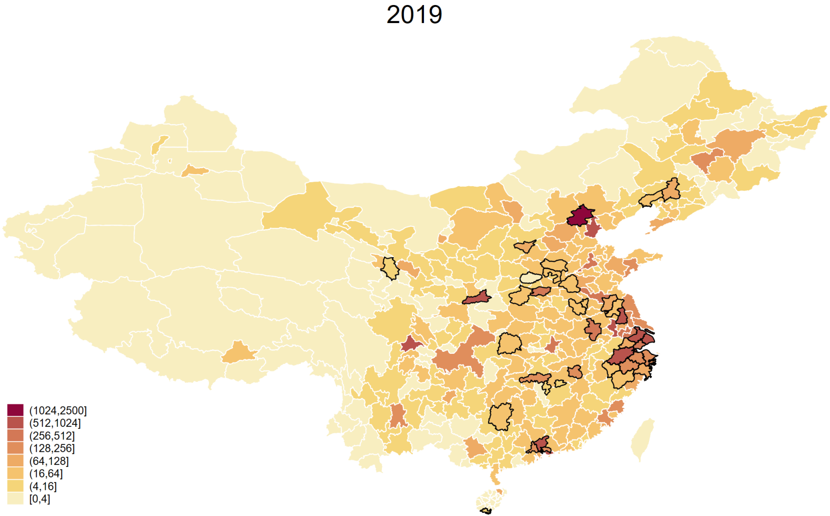
Note: black circled cities are treated by any subsidy policy

Patent distribution at city level and policy implementation: 2018



Note: black circled cities are treated by any subsidy policy

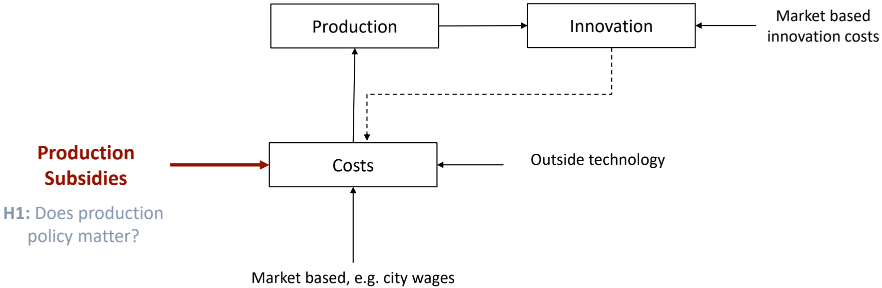
Patent distribution at city level and policy implementation: 2019



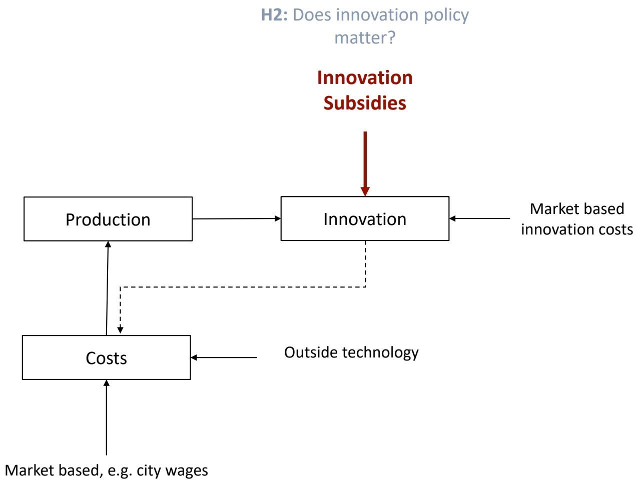
Note: black circled cities are treated by any subsidy policy

Theory

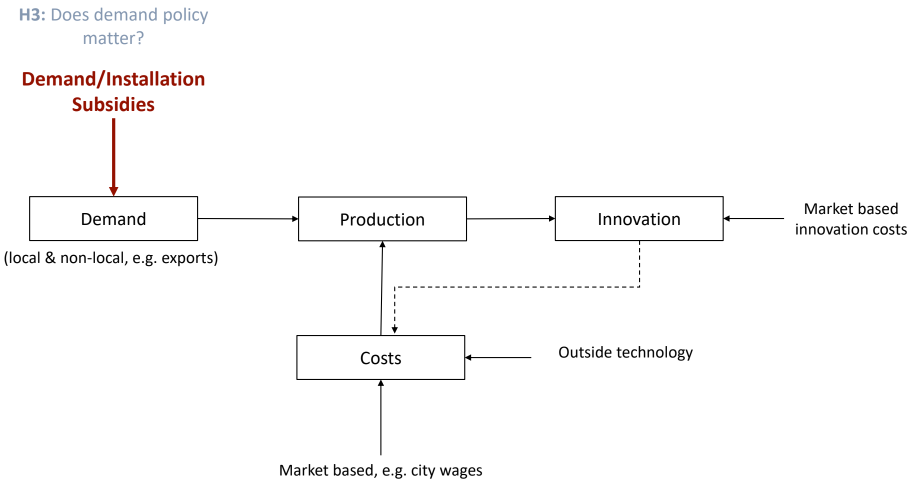
Heuristic Causal Graph (Domestic)



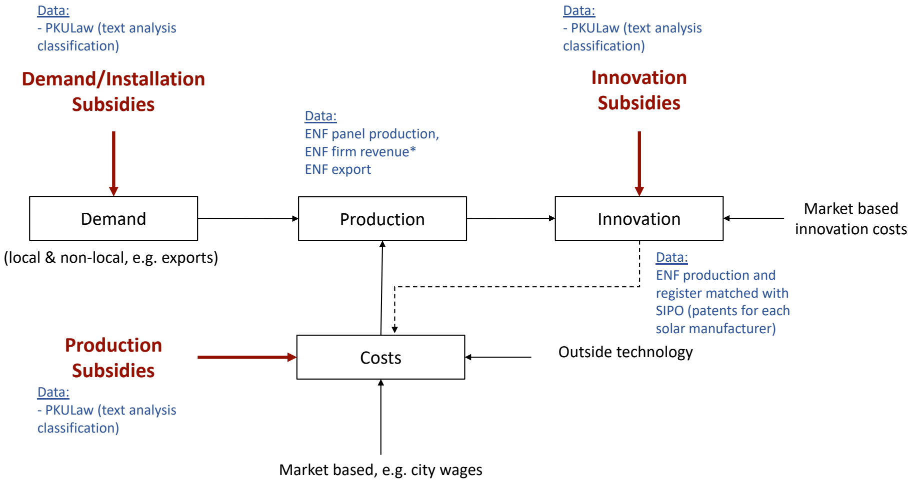
Heuristic Causal Graph



Heuristic Causal Graph



Heuristic Causal Graph with Data



Firm count: ENF register matched with Chinese firm registration platform (firm entry and exit dates for each solar manufacturer)
*ENF firm revenue: ENF register matched with Orbis platform

Model

Summary

- Demand for electricity decided locally ("Grid Planner") who builds power plants (e.g. solar vs. coal) using components (e.g. solar panels) sourced across **multiple** Chinese cities (subject to transport costs). Nested CES.
- Local solar PV manufacturers have heterogeneous productivity. Make endogenous entry, exit, production, exporting, and technology upgrading (innovation) decisions
- Provide intuition for differential impact of place-based subsidies (installation/demand, production, and innovation) on these multiple outcomes

Timing of Decisions

1. Entrepreneurs enter, draw productivity and decide whether to (i) produce; (ii) produce and export overseas; (iii) produce, export and innovate
2. Three fixed costs (& associated productivity cut-offs): (i) production, (ii) exporting and (iii) innovation. Innovation generates reduction in marginal cost.
3. Producing firms in city o serve multiple destination cities d paying iceberg trade costs
4. Demand for intermediates across all Chinese cities from different grid planners (and overseas) influences solar manufacturer decisions.

Demand for energy sources

- In each destination city d, representative consumer utility from electricity services e_d (e.g. from solar farms):

$$U_d = u\left(e_d\right) \tag{1}$$

- Electricity services installed in each city-region by Grid Planner, who builds power plants combining output from a clean and dirty energy sector, s and s' (e.g. solar vs. coal):

$$e_d = \left(\kappa_{d,s} e_{d,s}^{\rho} + \kappa_{d,s'} e_{d,s'}^{\rho}\right)^{1/\rho} \tag{2}$$

Demand for energy sector manufactured inputs

(e.g. solar panels)

- To generate output for each energy sector, Grid Planner in city d combines intermediate inputs, $q_{od,s}(\omega)$ = quantity of variety ω manufactured in city o supplied to d using CES:

$$e_{d,s} = \left(\sum_{o} \int_{\omega \in \Omega_{o,s}} q_{od,s}(\omega)^{\frac{\sigma_s - 1}{\sigma_s}} d\omega \right)^{\frac{\sigma_s}{\sigma_s - 1}} \tag{3}$$

Demand for energy sector manufactured inputs

(e.g. solar panels)

- To generate output for each energy sector, Grid Planner in city d combines intermediate inputs, $q_{od,s}(\omega)$ = quantity of variety ω manufactured in city o supplied to d using CES:

$$e_{d,s} = \left(\sum_{o} \int_{\omega \in \Omega_{o,s}} q_{od,s}(\omega)^{\frac{\sigma_s - 1}{\sigma_s}} d\omega \right)^{\frac{\sigma_s}{\sigma_s - 1}} \tag{3}$$

- Grid planner supplies as much energy as possible in the minimal cost way given income of representative consumer, I_d

$$\max_{e_{d,s}, e_{d,s'}} \left(\kappa_{d,s'} e_{d,s'}^{\rho} + \kappa_{d,s} e_{d,s}^{\rho} \right)^{1/\rho}$$

$$\text{s.t. } P_{d,s} e_{d,s} + P_{d,s'} e_{d,s'} = I_d$$

Demand for energy sector manufactured inputs

(e.g. solar panels)

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$$\text{s.t. } P_{d,s} e_{d,s} + P_{d,s'} e_{d,s'} = I_d$$

- Which yields our solar installation demand function, e_s^*:

$$e_{d,s}^* \left(P_{d,s}, P_{d,s'}, I_d \right) = \left(\frac{\kappa_{d,s}}{P_{d,s}} \right)^{\sigma} \frac{I_d}{\kappa_{d,s'}^{\sigma} P_{d,s'}^{1-\sigma} + \kappa_{d,s}^{\sigma} P_{d,s}^{1-\sigma}} \quad (4)$$

Demand for Energy manufactured inputs (e.g. solar PV modules)

- To meet the optimal energy demand, grid planner chooses solar modules from all cities given their prices, $p_{od,s}$. This will determine price indices $P_{d,s}$ and $P_{d,s'}$.
- Solving this constrained optimization problem gives a demand for each variety:

$$q_{od,s}(\omega) = \left(\frac{p_{od,s}(\omega)}{P_{d,s}}\right)^{-\sigma_s} \left(\frac{\kappa_{d,s}}{P_{d,s}}\right)^{\sigma} \frac{I_d}{\kappa_{d,s'}^{\sigma} P_{d,s'}^{1-\sigma} + \kappa_{d,s}^{\sigma} P_{d,s}^{1-\sigma}} \tag{5}$$

Solar Panel manufacturing technology

Production decision:

- Firms use a composite factor of production $L_{o,s}$ with unit cost $w_{o,s}$
- They need to pay a sunk cost $w_{o,s}f^{e}_{o,s}$ to operate
- After paying this cost, they draw productivity φ, from Pareto distribution
- To produce $q_{o,s}(\varphi)$ units of a variety, firm needs $f_{o,s} + \frac{q_{o,s}}{\varphi}$, where $f_{o,s}$ is fixed cost and $\frac{1}{\varphi}$ is marginal cost of production

Innovation decision:

- Upon observing its initial productivity φ, a firm can upgrade its technology (innovate)
- By incurring a fixed cost: $\eta_{o,s}f_{o,s}$, with $\eta_{o,s} > 1$, it reduces marginal cost to: $\frac{1}{\xi_{o,s}\varphi}$, with $\xi_{o,s} > 1$

Exporting and Prices

- Firms can sell to grid planners in China and overseas: both are subject to iceberg trade costs:
  - In order to serve a market d, firm in o needs to produce $\tau_{od,s} q_{od,s}(\varphi)$ of variety, $\tau_{od,s} \geq 1$.
- There is a market access fixed cost for selling overseas (but not within China)
  - In order to serve overseas firm in o pays fixed cost $w_{o,s} f^{x}_{od,s}$
- Manufacturers' optimal prices are a constant markup over marginal costs

$$p_{od,s}(\varphi) = \frac{\sigma_s}{\sigma_s - 1} \frac{w_{o,s} \tau_{od,s}}{\xi_{o,s} \varphi} \tag{6}$$

Optimization and Equilibrium

- We can characterize solution in terms of three productivity cut-offs
  - Least productive firms exit
  - Next most productive firms sell only in China and do not innovate
  - Next most productive firms also export
  - Highest productivity firms export and innovate optimal profits
- Equilibrium involves solving for vector of price indices for clean and dirty energy in each city
- NB: We take general level of city level prices and wages as given (not GE as solar only one sector)

Solar industrial policy

1. **Production subsidies**
   - We model production subsidies s, as a reduction in input costs for manufacturers, whose marginal cost becomes $\frac{1-s}{\varphi}$.
2. **Innovation subsidies**
   - We model innovation subsidies, ϕ as a reduction in the fixed costs of technological upgrading, which becomes $\phi(\eta_{o,s} f_{o,s})$, with $\phi < 1$
3. **Demand/Installation subsidies**
   - We model solar demand subsidies as θ_d, shifting $e_d = \left(\kappa_{d,s'} e_{d,s'}^{\rho} + \theta_d \kappa_{d,s} e_{d,s}^{\rho}\right)^{1/\rho}$

Model Predictions

- All outcome variables and subsidy policies measured in origin city o

	Demand Subsidy, θ_o	*Production Subsidy,* s_o	*Innovation Subsidy,* ϕ_o	*Production & Innov. Subsidy,* $s_o + \phi_o$
Innovation$_o$	+ / 0	+	++	+++
Firm count$_o$	+ / 0	++	+/0	++
Revenue$_o$	+ / 0	++	+	+++
Panel production$_o$	+ / 0	++	+	+++
Exports$_o$	+ / 0	++	+	+++

Notes: A "+" denotes the strength of a relationship, so "+++" is strongest and "+/0" the weakest (positive) relationship.

Empirical Strategy

Empirical Strategy

- Effectiveness of solar industrial policy
  - Look at dynamics: does the effect persist over long time period?
- Challenges in evaluating industrial policy
  - Allocation of solar industrial subsidies across firms non-random
  - So focus on introduction of city level subsidy **policies**
  - These are staggered over time - first ones in 2007 (encouraged by Eleventh Five Year Plan)
  - But policies could also be correlated with future outcomes, even controlling for observable covariates
- We follow the **synthetic-difference-in-differences (SDID)** methodology (Arkhangelsky, Athey, Hirshberg, Imbens and Wager, 2021)

Synthetic-difference-in-differences (SDID)

- Outcomes: revenue, production, number of firms, exports, and patents
- Treatments: subsidy policies (demand, production, innovation)
- Variation: Exploit city-level variation in solar policies and their timing

- SDID: Two-way FE regression with time and unit weights

$$\left(\hat{\tau}^{\text{sdid}}, \hat{\mu}, \hat{\alpha}, \hat{\beta}\right) = \underset{\tau,\mu,\alpha,\beta}{\arg\min} \left\{ \sum_{i=1}^{N} \sum_{t=1}^{T} \left(Y_{it} - \mu - \alpha_i - \beta_t - W_{it}\tau^{\text{sdid}} \right)^2 \hat{\omega}_i^{\text{sdid}} \, \hat{\lambda}_t^{\text{sdid}} \right\}$$

- Unit weights ω_i: chosen so that average pre-treatment outcome for control units is $\approx$ parallel to pre-treament outcome for treated units
- Time weights λ_t: more weight on time periods which better predict post-treatment outcomes for control

SDID Intuition

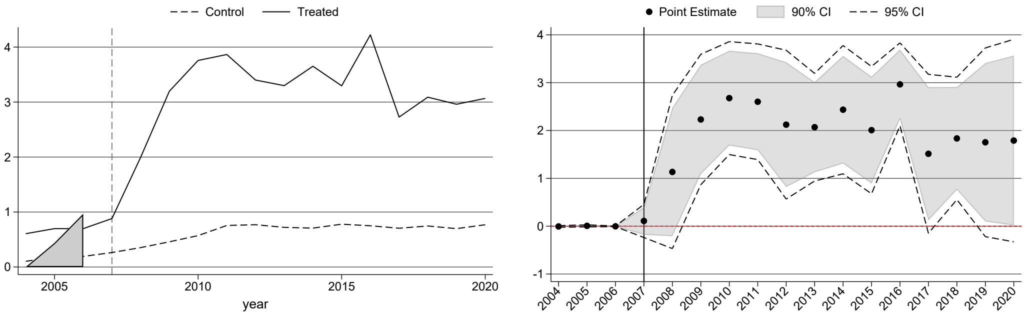
1. Construct synthetic control group such that pre-trends are approximately parallel
2. Compute treatment effect using diff-in-diff between treatment and synthetic control

- Allows us to relax the parallel trends assumption
- Comparison with TWFE
  - SDID as a generalization of TWFE that allows for weighting the control group to construct a better counterfactual
  - We use cohort-by-cohort estimation approach, with never treated as control group
  - We aggregate all these cohort estimates to obtain one aggregate ATT for each type of policy

Results

Results

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

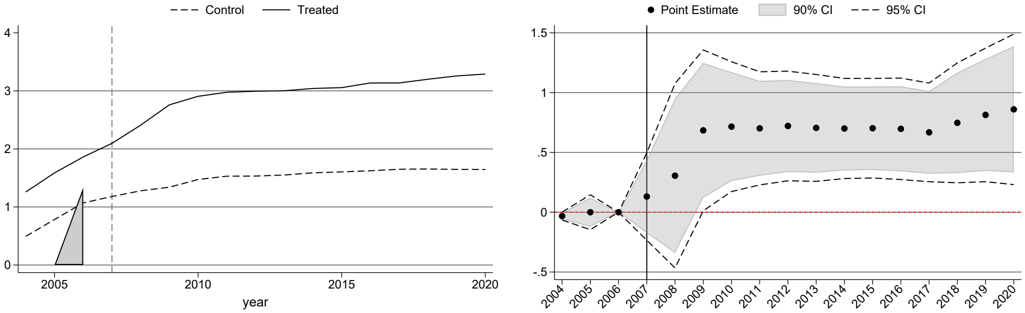
Table: Patents (Aggregate ATT)

	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 estimates on 358 cities 2004-2020. Outcome is IHS of all patents by solar firms in a city-year pair. Mean patents=13.1

Results

Figure: Firm Count - Number of Solar Firms (2007 Cohort)



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

Results

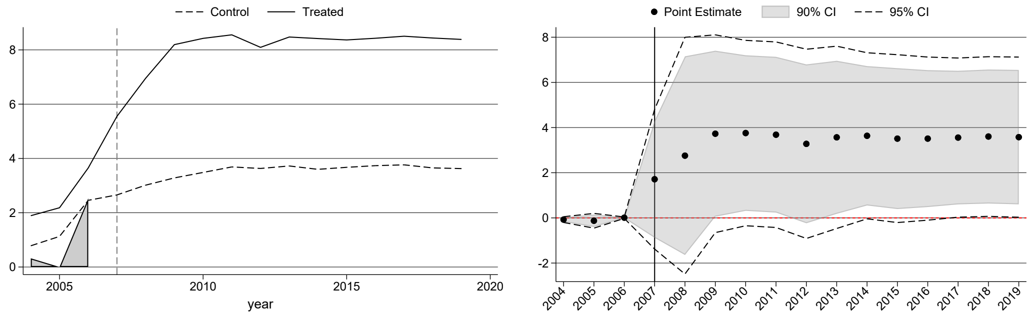
Table: Firm Count - Number of Solar Firms (Aggregate ATT)

	Any subsidy	*Demand subsidy*	*Production subsidy*	*Innovation subsidy*
Firm count	0.186***	0.060	0.288***	0.381***
	(0.064)	(0.043)	(0.090)	(0.135)
Observations	6,086	6,086	6,086	6,086

Notes: * 0.1 ** 0.05 *** 0.01. SDID estimates on 358 cities 2004-2020. Outcome is IHS of count of solar firms in a city-year pair.

Results

Figure: Revenue (2007 Cohort)



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

Results

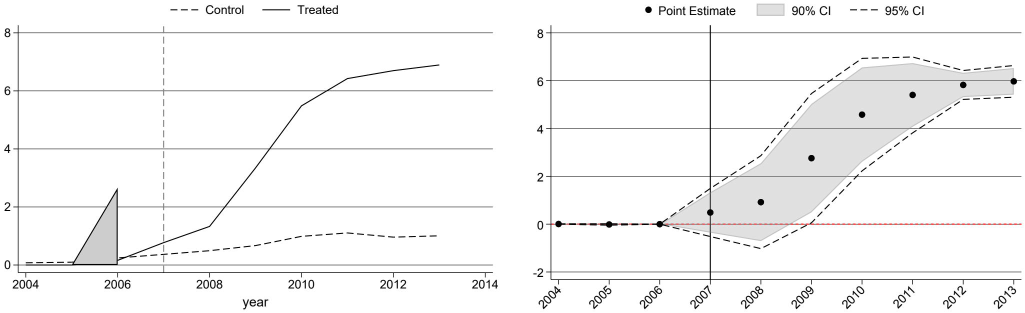
Table: Revenue (Aggregate ATT)

	Any subsidy	*Demand subsidy*	*Production subsidy*	*Innovation subsidy*
Revenue	1.100**	0.192	1.887**	2.670**
	(0.456)	(0.199)	(0.767)	(1.193)
Observations	5,728	5,728	5,728	5,728

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

Results

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

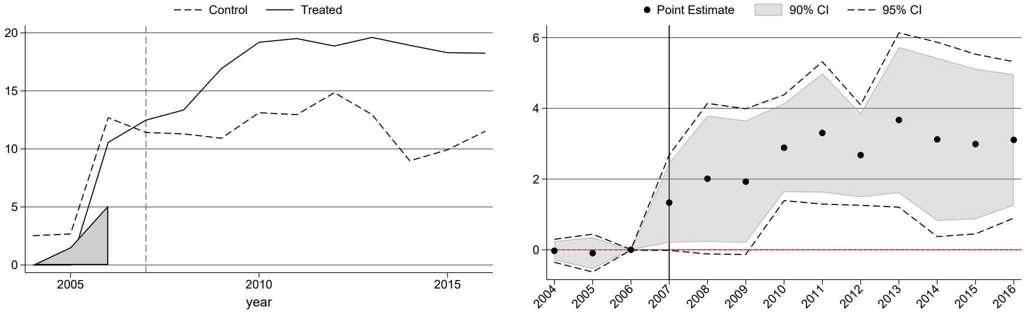
Table: Solar Panel Production Capacity (Aggregate ATT)

	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

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

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.

Summary of Baseline Results

- Subsidy policies significantly raise solar production, revenue, innovation, exports and number of firms.
- Demand subsidies effects are small and insignificant. Production plus innovation subsidies have the largest impact
- Consistent with our simple model of multi-location demand, solar PV supply with endogenous innovation and trade

Extensions

- Types of patents (how innovative? Learning by Doing?)
- Productivity
- Business Stealing vs. agglomeration
- Adding other Controls (GDP, population, income,..)

Results

Table: Examining different types of 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)
□ Design patents	0.186	0.277	0.237	0.151
	(0.138)	(0.216)	(0.173)	(0.253)
□ invention/utility model patents	0.529***	0.201	0.937***	1.097**
	(0.201)	(0.274)	(0.232)	(0.373)
• Solar patents	0.515***	0.189	0.857***	1.090**
	(0.168)	(0.210)	(0.216)	(0.358)
• Non-solar patents	0.247	−0.034	0.732***	0.809**
	(0.168)	(0.196)	(0.203)	(0.320)

Notes: * 0.1 ** 0.05 *** 0.01. Solar patents are classified according to IPC codes

Results

Table: Productivity (Aggregate ATT)

Panel A	(1)	(2)	(3)	(4)
Period: 2004-2019	*Any subsidy*	*Demand subsidy*	*Production subsidy*	*Innovation subsidy*
Revenue	1.100**	0.190	1.887**	2.670**
	(0.456)	(0.198)	(0.767)	(1.193)
Labor	0.859**	0.249	1.443**	1.832*
	(0.435)	(0.291)	(0.664)	(1.034)
Capital	0.609	−0.130	1.302*	1.858
	(0.408)	(0.198)	(0.767)	(1.193)
Observations	5,728	5,728	5,728	5,728
Panel B	(1)	(2)	(3)	(4)
Period: 2004-2013	*Any subsidy*	*Demand subsidy*	*Production subsidy*	*Innovation subsidy*
Revenue	1.926**	0.285	2.392**	3.058**
	(0.767)	(0.193)	(0.944)	(1.517)
Panel production capacity	2.098***	0.587	2.496***	2.930***
	(0.532)	(0.467)	(0.575)	(0.773)
Labor	1.382**	0.523	1.581*	1.773
	(0.677)	(0.442)	(0.848)	(1.188)
Capital	1.470**	0.310	1.784**	2.307
	(0.711)	(0.282)	(0.905)	(1.426)
Observations	3,580	3,580	3,580	3,580

Notes: * 0.1 ** 0.05 *** 0.01. Revenue, Capital and Labor are from Orbis and Productive Capacity from ENF.

Results

Table: Positive Spillovers, not Business Stealing

	(1) All patents	(2) Firm count	(3) Revenue	(4) Panel capacity
Any subsidy in an adjacent city	0.373^{***}	0.099	0.485^{***}	0.385
	(0.096)	(0.055)	(0.177)	(0.263)
Observations	5,049	5,049	4,768	3,210

Notes: * 0.1 ** 0.05 *** 0.01. Treated cities are those contiguous to those introducing a policy. SDID estimates.

Results

Table: Including control for GDP per capita

	(1) *Any subsidy*	(2) *Demand subsidy*	(3) *Production subsidy*	(4) *Innovation subsidy*
All patent	0.483**	0.226	0.867***	1.001***
	(0.205)	(0.242)	(0.220)	(0.341)
Firm count	0.210***	0.030	0.380***	0.396***
	(0.081)	(0.031)	(0.125)	(0.138)
Revenue	1.076**	0.170	1.882***	2.557***
	(0.458)	(0.205)	(0.727)	(1.102)
Panel Production capacity	2.025***	0.531	2.415***	2.848***
	(0.466)	(0.428)	(0.470)	(0.705)
Export value	2.409***	0.577	3.210**	4.041**
	(0.886)	(1.009)	(1.292)	(1.992)
Export volume	2.066**	0.038	2.841**	3.726**
	(0.812)	(0.699)	(1.208)	(1.851)

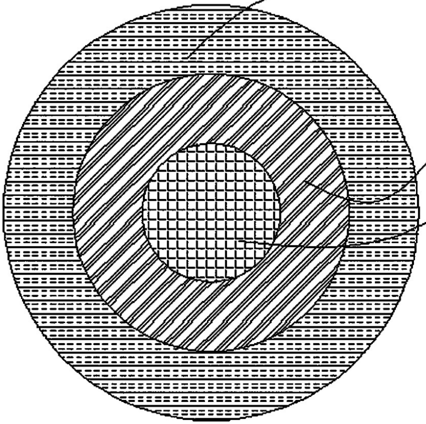
Notes: * 0.1 ** 0.05 *** 0.01. SDID estimates with GDP per capita control.

Conclusion

Conclusions

- Chinese cities that introduced solar subsidies appear to have successfully increased the production, revenue, innovation, exports, and number of solar manufacturers
- Key distinction between effects of supply (production and innovation) vs. demand/installation subsidies
- Supply subsidies, designed to encourage growth of the solar industry within a city, are associated with increases in panel production, increases in revenue, increases in the number of solar firms, increases in exports, and increases in the number of solar patents filed by solar firms within a city
- Demand subsidies, designed to encourage installation of solar electricity within a city, have small or negligible effects on these outcomes locally.
- **Next steps**: Quantitative analysis: welfare; micro-data; other designs; Global version of model to examine how policies in other countries matter

Patent as process innovation: Grid Line Structure for Solar Cell manufacturing



Back

Example Patent: Grid Line Structure for Solar Cell manufacturing

This invention comprises metal wires and conductive silver paste. The grid line is woven from metal wires, with a layer of silver paste applied to the metal wires which ensures excellent adhesion between the silver paste and the metal wires as well as strong ohmic contact between the sub-grid line and the silicon wafer. The silver paste used for the main grid line does not contain glass material, which ensures good adhesion between the main grid line and the silicon wafer and reduces the recombination of minority carriers under the main grid line. **Compared with the prior art, the present invention greatly reduces the amount of (expensive) silver paste used generating big cuts in production costs. It ensures excellent aspect ratios of the grid lines, eliminating the possibility of broken lines and false prints, thereby improving the photovoltaic conversion efficiency of the solar cell, and being suitable for large-scale industrial production.**

Back

National vision for sectoral industrial policies in The Five-Year Plans

- **2001-2005 Tenth Five-Year Plan:**
  - Solar a targeted sector for first time, together with other renewable energies.
  - In 2001 no solar industry.
  - In 2005 considerable growth.
- **2006-2010 Eleventh Five-Year Plan:**
  - Solar industry as an opportunity to attain technological leadership.
  - Included funding for R&D and manufacturing development for the first time.
  - Solar industry witnessed exceptional growth
- **2011-2015 Twelfth Five-Year Plan:**
  - Government kept pushing for solar adoption, supply-chain expansion and indigenous R&D.
  - R&D goals gained in detail and scope
- **2016-2020 Thirteenth Five-Year Plan:**
  - Targeting capacity and R&D expansion, as well as industry-wide cost-reduction.
  - Includes Thirteenth Five Year Plan for Solar Energy Development.

Back

Results

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)
Export price	0.971*	0.094	1.138	1.502
	(0.554)	(0.636)	(0.731)	(1.051)
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)
Solar export price	1.566**	0.197	2.107**	3.383***
	(0.630)	(0.388)	(0.868)	(0.848)

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

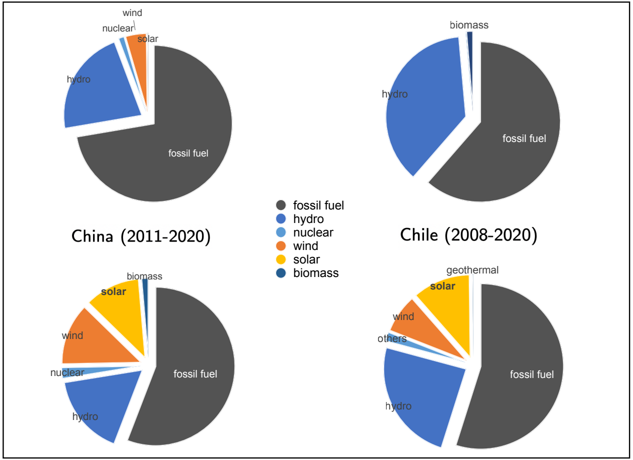
Descriptives

Back

	Mean	Std. Dev.	Sample Size
SIPO, 2004-2020, 358 cities:			
Total patents by solar firms	13.1	111.3	6,086
Orbis and Qichacha, 358 cities:			
Total number of solar firms, 2004-2020	2.9	10.2	6,086
Total revenue of solar firms, RMB, billions, 2004-2019	0.809	5.99	5,728
ENF, 2004-2013, 358 cities:			
Total Solar Panel production capacity, MWh	82.4	483.3	3,580
Customs, 358 cities:			
Total export value of solar firms, millions USD, 2004-2016	24.8	186	4,654
Total export volume of solar firms, millions, 2004-2015	3.18	43.7	4,296
Statistics Yearbook, 2004-2020, 284 cities:			
GDP per capita, RMB	43,497	46,936	4,828

Renewable electricity capacity has grown rapidly in some countries

Figure: Installed Electricity generation capacity in China and Chile by source

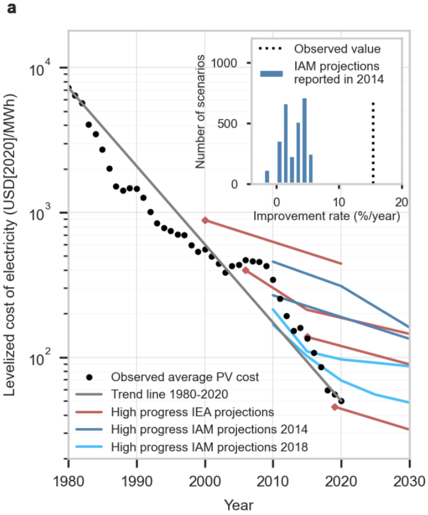


Source: State Grid New Energy Cloud & CNE

- **World, 2011 to 2020**: installed solar capacity went from 0.8% to 6.8%
- **China, 2011 to 2020**: installed solar capacity went from 0.19% to 11.35%
- **Chile, 2008 to 2020**: installed solar capacity went from 0% to 12%

Back

Much faster than forecast (1980-2030)



Back

Source: Way, Ives, Mealy and Farmer (2021) “Empirically grounded technology forecasts and the energy transition”

Optimal Profits

$$\Pi_{o,s}(\varphi) = \max\left\{\sum_{d\neq\tilde{d}}\left\{\frac{(\sigma_s-1)^{\sigma_s-1}}{\sigma_s^{\sigma_s}}\frac{E_{d,s}}{(P_{d,s})^{1-\sigma_s}}\left(\frac{w_{o,s}\tau_{od,s}}{\varphi}\right)^{1-\sigma_s}\right\}-w_{o,s}f_{o,s},\right.$$

$$\sum_{d}\left\{\frac{(\sigma_s-1)^{\sigma_s-1}}{\sigma_s^{\sigma_s}}\frac{E_{d,s}}{(P_{d,s})^{1-\sigma_s}}\left(\frac{w_{o,s}\tau_{od,s}}{\varphi}\right)^{1-\sigma_s}\right\}-w_{o,s}f^{x}_{o,\tilde{d},s}-w_{o,s}f_{o,s},$$

$$\left.\sum_{d}\left\{\frac{(\sigma_s-1)^{\sigma_s-1}}{\sigma_s^{\sigma_s}}\frac{E_{d,s}}{(P_{d,s})^{1-\sigma_s}}\left(\frac{w_{o,s}\tau_{od,s}}{\xi_{o,s}\varphi}\right)^{1-\sigma_s}\right\}-w_{o,s}f^{x}_{o,\tilde{d},s}-w_{o,s}\eta_{o,s}f_{o,s}\right\}$$

back