Price vs. Production Restrictions: China's Coal Industry

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Motivation: Price versus Quantity Instruments

- Price vs. quantity instruments to regulate externality
  - Congestion pricing vs. driving restrictions: road congestion
  - Emission tax vs. quotas: pollution
- Policy maker chooses a policy instrument before uncertainty realizes
  - Uncertainty about demand, supply or external loss

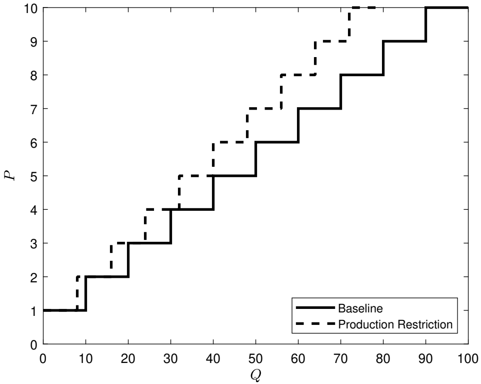
$$\max \mathbb{E} \left(\text{Economic Surplus} - \text{External Loss} \right)$$

- Tax versus **quotas** (Weitzman, 1974): theoretically ambiguous with uncertainty
  - Uncertainty on MC matters for the comparison (locally)
  - The **convexity** of the loss function is the key: the relative slopes of MB and MC

Research Question

- **Externality loss: critical for policy choices but hard to pin down**
  - Arguments: e.g., environmental gain, workplace safety, production push, ...
  - Parameters: e.g., social cost of carbon, slope of the marginal curve
- **Production restrictions: another common quantity tool**
  - Limit production of firms, rotating the industry supply curve inwards
  - Conservation Reserve Program in the US, China's coal reform since 2016

Research Question



- Baseline: 10 firms, each with capacity 10 and marginal costs ranging from 1 to 10
- Production restrictions: reduces every firm's capacity by 20%

Research Question

- Externality loss: critical for policy choices but hard to pin down
  - Arguments: e.g., environmental gain, workplace safety, production push, ...
  - Parameters: e.g., social cost of carbon, slope of the marginal curve
- Production restrictions: another common quantity tool
  - Limit production of firms, rotating the industry supply curve inwards
  - Conservation Reserve Program in the US, China's coal reform since 2016
- **Can we rank tax and production restrictions when we don't know the convexity?**

What We Do In This Paper: Methodology

- Develop a criterion that compares different policies
  - Main assumptions
    1. A model to compute economic surplus
    2. The loss function is monotone in a scalar outcome
  - We do **NOT** make assumptions about the convexity of the loss function
- The criterion's output
  - Given policy A, does there exist policy B that achieves the same economic surplus at lower external loss?
  - B: SND (**s**urplus-**n**eutral **d**ominating) policy

What We Do In This Paper: Empirical Application

- China's coal industry
  - Largest producer and consumer of coal ($>$50% of the world)
  - Energy security, pollution, economic stability
- Coal reform under China's 13th Five-Year Plan (2016–2019)
  - Reduce capacity: close small mines and suspend new approval
  - **Constraints on production**: command-and-control approach
  - 35% YoY price increase in 2016
- Is tax more efficient than production restrictions?
  - Estimate an equilibrium model and quantify the economic cost of the policy
  - Use the criterion to rank tax against the observed policy

Main Findings

- Observed policy
  - Economic surplus $\downarrow$: 0.6% of China's GDP
  - Offset by saved environmental cost
- Our criterion:
  - Consider a general loss function that increases in total Q
    - Beyond environmental costs: mining deaths, leakage, ...
  - A tax would achieve higher welfare
    - Might stop when the government weighs more on producer surplus

Literature Review and Contributions

- A novel criterion to rank policies
  - A large theoretical literature starting with Weitzman (1974) with environmental applications (Pizer, 2002; Muller and Mendelsohn; 2009; Newell and Pizer; 2003; Fell et al., 2012)
  - **Compare tax with production restrictions, rather than quota**
  - **We try to do so without knowing the convexity of the loss function**
- Economic costs of environmental policies (Ryan, 2012; Fowlie et al., 2016; Chen et al., 2025; among many)
  - **An empirical model of China's coal market**
- China's coal industry matters a great deal to the world
  - Prior work often uses older data (Burke and Liao, 2015; Shi et al., 2018; Teng et al., 2019) and take production function approach (Zhou et al., 2019; Zheng, 2024)
  - **New estimates on demand and supply elasticities**

Road Map

1. An Illustrative Model
   (a) Efficiency trade-off between **tax** and command-and-control **production restriction**
   (b) An SND tax exists for production restriction
2. Background and Data
3. Estimation of Supply and Demand
4. Counterfactual Simulations
   (a) Welfare relative to no policy
   (b) Efficient production restriction (cap-and-trade)
   (c) **Welfare ranking between production restriction and tax**

Illustrative Model

Model Setup

- **Supply function**: $P^S = a_0 + a_1 Q, a_1 > 0$
- **Demand function**: $P^D = b_0 + b_1 Q + \varepsilon, b_1 < 0$
- **Uncertainty**: $\mathbb{E}[\varepsilon] = 0$ and $\mathbb{V}\text{ar}[\varepsilon] = \sigma^2$
- **External marginal loss** $MD = r_0 + r_1 Q, r_1 > 0$
- **Welfare**

$$W = E\left(\int_0^{\max(Q^\star,0)} \left(P^D(q) - P^S(q) - MD(q)\right) dq\right)$$

  - $Q^\star$: equilibrium quantity

Tax vs. Production Restriction

- **Tax**: choose τ

$$\max_{\tau} W\left(Q^{\star}(\tau)\right)$$

where

$$Q^{\star} = \max\left(0, \frac{b_0 + \varepsilon - a_0 - \tau}{a_1 - b_1}\right)$$

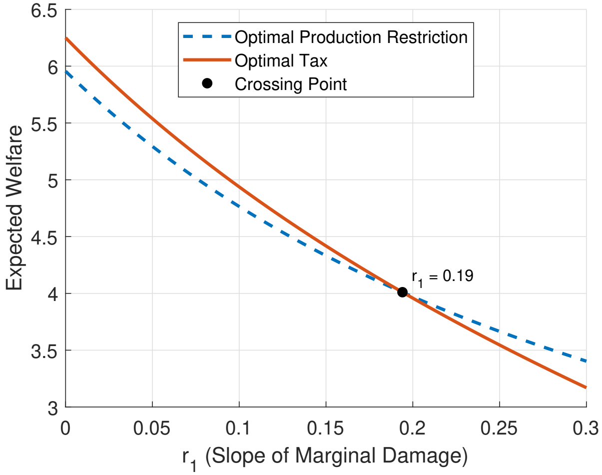
- **Production restriction**: choose a rotation $\alpha_1 > a_1$

$$\max_{\alpha_1} W\left(Q^{\star}(\alpha_1)\right)$$

where

$$P^S = a_0 + \alpha_1 Q, \text{ and } Q^{\star} = \max\left(0, \frac{b_0 + \varepsilon - a_0}{\alpha_1 - b_1}\right)$$

Production Restriction More Efficient When Loss Function is More Convex



Our Ranking Criterion: A Motivation

- What happens if we do not know (much about) the loss function?
  - Environmental impact, forcing coal users to switch to renewables, reducing coal mining deaths, ...

$$W = \underbrace{E\left(\int_0^{\max(Q^\star,0)} \left(P_D\left(q\right) - P_S\left(q\right)\right) dq\right)}_{E(S)} - \underbrace{E\left(\int_0^{\max(Q^\star,0)} MD\left(q\right) dq\right)}_{E\left(L(Q^\star)\right)}$$

- Given a production restriction policy α_1, is there a tax τ that
  - matches the economic surplus $E\left(S\right)$
  - has a smaller $E\left(L\left(Q^\star\right)\right)$?

Ranking Criterion

- **Proposition 6.D.1 (MWG)** On a bounded support, if L is increasing and differentiable, and Q_1 stochastically dominates Q_2, then
$$E\left(L\left(Q_1\right)\right) \geq E\left(L\left(Q_2\right)\right)$$
- We can claim a tax is better, if:
  1. For a given restriction α_1, compute $E(S)$ (e.g., based on estimated model)
  2. Find a tax $\tau^\star$ that matches $E(S)$
  3. Verify that the quantity distribution under the restriction stochastically dominates that under $\tau^\star$
- We call $\tau^\star$ an **SND** (Surplus-Neutral Dominating) tax.
  - SND tax typically exists due to the superiority of tax in efficiency
  - Failure to find an SND tax does *not* say which one is better

Background and Data

Coal Industry in China

- Anthracite (high purity coal): 23%; bituminous: 70%
  - Majority use: electricity, coking, cement
  - Power plants in China adapt to mixed grades
- Reforms in 2013 create a national coal market connected by rails, rivers and sea
- Long-term contracts
  - Promised delivery quantity
  - Allow prices to move based on the spot market

Economic Policies

- 13^{rd} five-year plan in 2016: limit production to
  - Improve coal industry profitability
  - Improve worker welfare and safety
  - Reduce environmental impact
- Alternative: resource tax
  - Started in 2014; low rates (2–8%)
  - Not selected for the reform

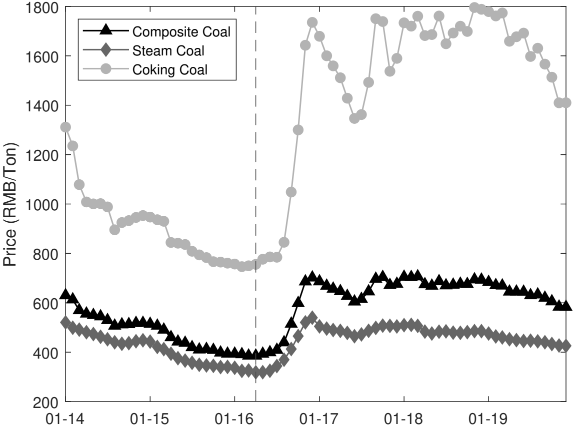
Main Data Sources

- Cross-province shipment 2012–2016: China Coal Transportation and Distribution Association (CCTDA)*
- Mining capacity 2014–2018: National Energy Administration
- Monthly consumption 2014–2017: China Coal Resources* and imputation
- Monthly production 2014–2019: CCTDA* and National Bureau of Statistics (NBS)
- Monthly provincial coal prices: National Development and Reform Council
- High frequency station level air quality 2014–2017: Ministry of Environmental Protection

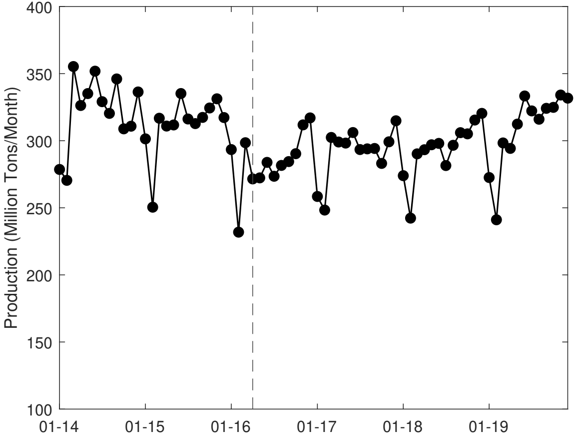
*: commercial data vendors

Price and Production

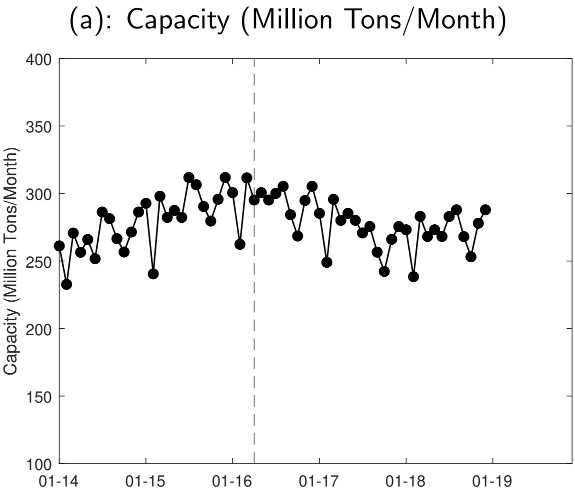
(a): Price (RMB/Ton)

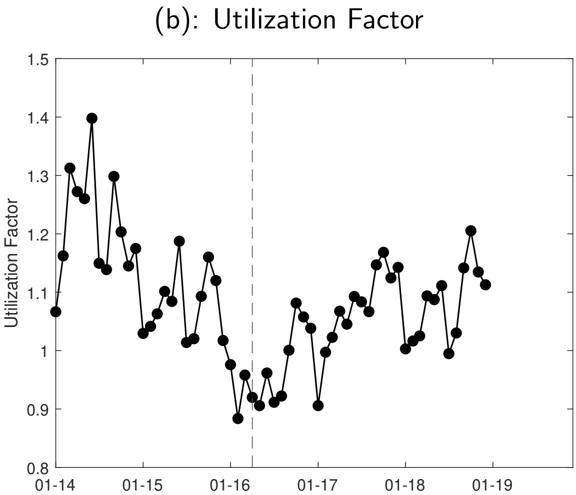


(b): Production (Million Tons/Month)



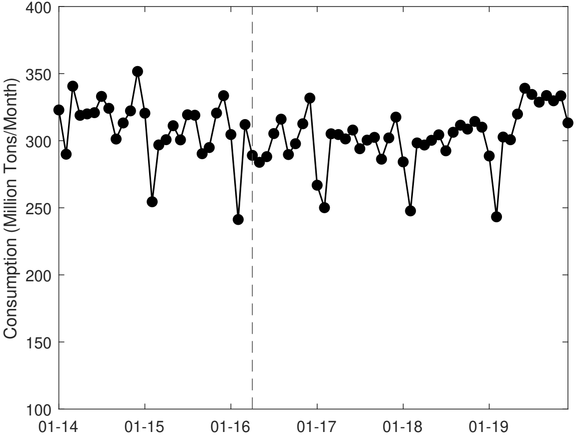
Capacity and Utilization Factor



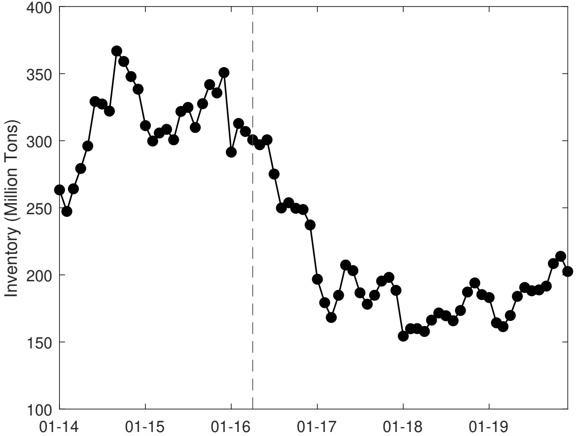


Consumption and Inventory

(a): Consumption (Million Tons/Month)

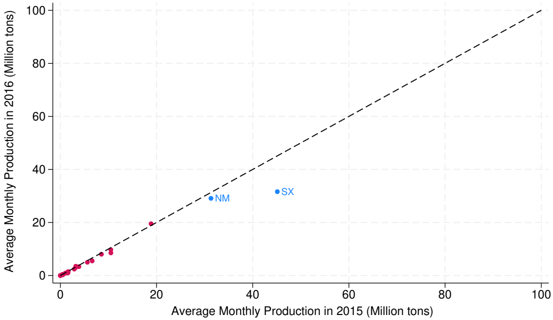


(b): Inventory (Million Tons)

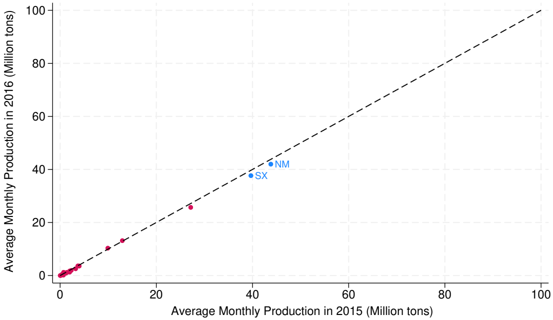


SOEs in the two largest provinces drive quantity reduction

(a): Year-to-Year SOE Production



(b): Year-to-Year Non-SOE Production



Key Data Patterns

A province's share of coal shipped to another province has remained stable

	Inner Mongolia	Shanxi	Shandong	Hebei	Jiangsu	Shaanxi	Henan	Liaoning	Guizhou	Xinjiang
Inner Mongolia	0.392	0.011	0.049	0.017	0.064	–	0.002	0.082	–	–
	[0.014]	[0.002]	[0.008]	[0.003]	[0.010]	–	[<0.001]	[0.003]	–	–
Shanxi	0.006	0.298	0.104	0.231	0.103	0.002	0.055	0.017	–	0.001
	[0.002]	[0.013]	[0.007]	[0.029]	[0.012]	[0.001]	[0.012]	[0.002]	–	[0.001]
Shaanxi	0.004	0.148	0.086	0.039	0.101	0.411	0.059	–	0.001	–
	[0.001]	[0.020]	[0.049]	[0.010]	[0.027]	[0.070]	[0.007]	–	[0.001]	–
Guizhou	–	–	–	–	–	–	–	–	0.740	–
	–	–	–	–	–	–	–	–	[0.025]	–
Shandong	–	–	0.857	0.012	0.033	–	0.008	0.002	–	–
	–	–	[0.016]	[0.005]	[<0.001]	–	[0.001]	[<0.001]	–	–

Demand and Supply

Demand

- In province j and month t, coal consumption

$$\ln q_{jt} = \alpha \ln p_{jt} + \alpha_X X_{jt} + FE_j^{\text{demand}} + FE_{m(t)}^{\text{demand}} + \varepsilon_{jt}$$

  - X_{jt}: wind power generation, CDDs, province and month fixed effects

- Instruments (for province j): Shift-share IVs based on different policy timing and exposures
  - Average lagged (2012–13) SOE production in each province
  - Weighted by transportation shares to j
  - Interacted with policy time indicator (Started in Shanxi first, then other provinces)

- Elasticity: -0.635 (F-stat: 37.84)

Supply

- Province i's production in month t

$$\ln MC_{it} = \gamma \frac{q_{it}}{K_{it}} + FE_i^{\text{supply}} + FE_{m(t)}^{\text{supply}} + \text{policy effect}_{it} + \eta_{it}$$

  - K_{it}: approved mining capacity; P_{it}: average destination prices

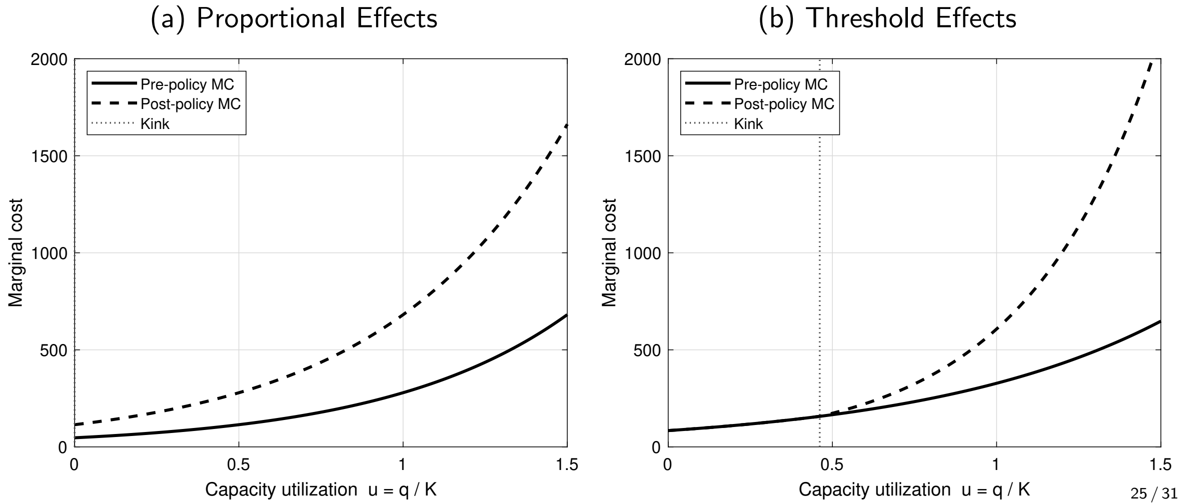
- Policy rotates the MC curve in two ways:
  - Proportional policy effects: province-specific FE_i^{policy}
  - Threshold policy effects: quantity-specific $\alpha^{S,\text{policy}} \cdot \mathbf{1}\left(\text{policy}_{it}\right) \cdot \left(\frac{q_{it}}{K_{it}} - \nu\right)_+$

- Instruments: Weighted average of wind production in destination provinces; demand residuals

- Elasticities: 0.55 to 0.77

Estimated MC Curves

Shanxi: largest coal-producing province



Welfare Effects and Policy Ranking

Counterfactual Simulations

- Focus on 2017 when the market arrived at a steady state

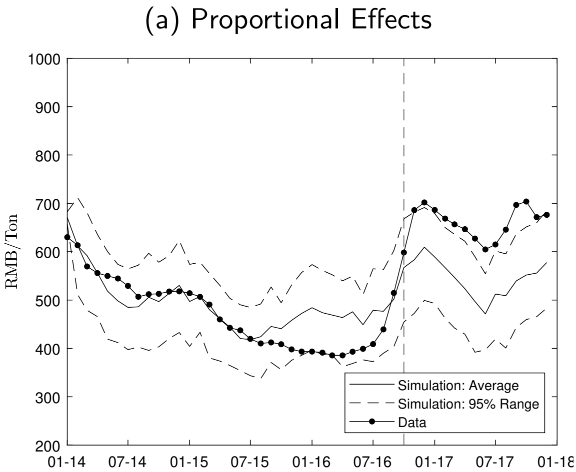
- Assume
  - Policy maker chooses the level of restriction (policy enforcement) before knowing the demand and supply shocks in 2017
  - Capacity (mine entry/closures) are taken as observed in the data
  - Shocks are AR1

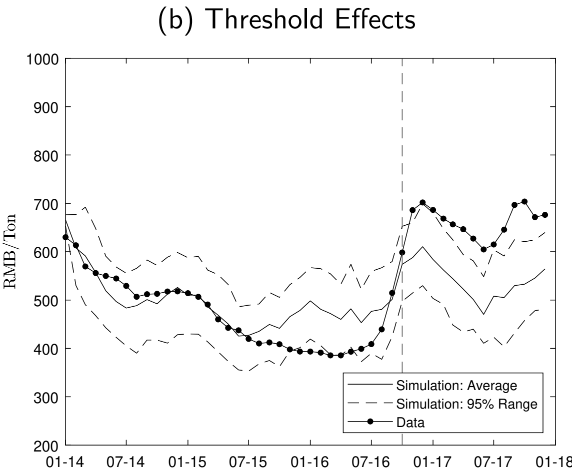
- Main simulations
  - What is the effect of the observed policy relative to a no-policy counterfactual
  - What is the welfare cost of misallocated reduction (from efficient coal mines)?
  - Is tax better under any loss function increasing in domestic production?

Equilibrium Definition

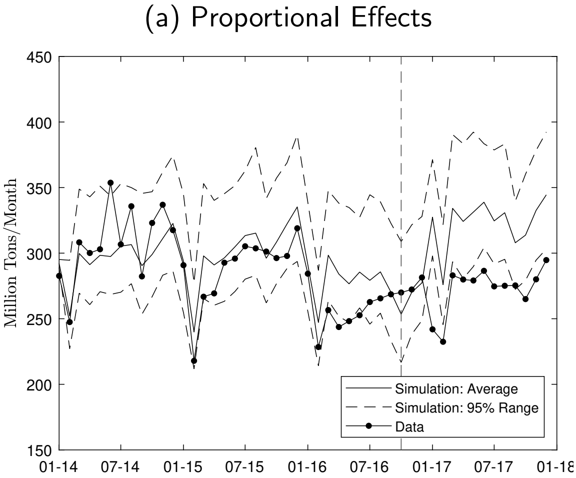
- Let $\mathcal{J}$ denote coal-consuming provinces and $\mathcal{I}$ coal-producing provinces
- In period t, an **equilibrium** given a set of shocks consists of delivery prices $\{p_{jt}\}_{j\in\mathcal{J}}$ and production quantities $\{Q_{it}\}_{i\in\mathcal{I}}$ such that
  - Province j's demand and coal supply shipped to j balance:
  $$q_{jt} = \sum_{i\in\mathcal{I}} s_{ij}\, Q_{it}$$
  for all $j \in \mathcal{J}$
  - The price facing producers in province i is:
  $$P_{it} = \sum_{j\in\mathcal{J}} s_{ij}\left(p_{jt} - \tau_{ij}\right)$$

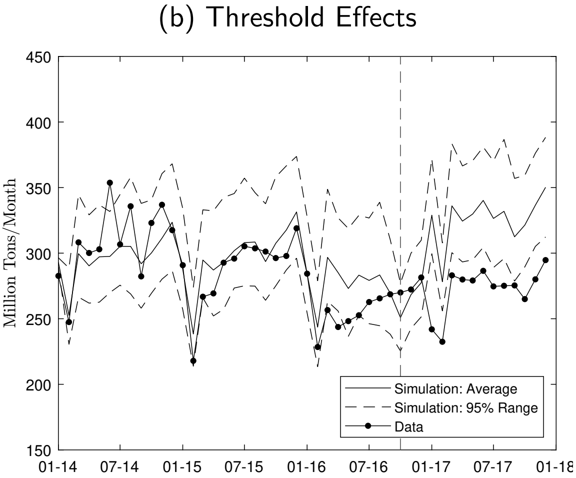
Prices With and Without the Policy





Production With and Without the Policy



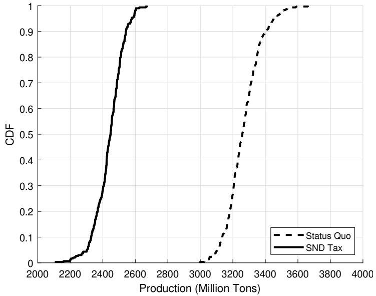


There is an SND Tax

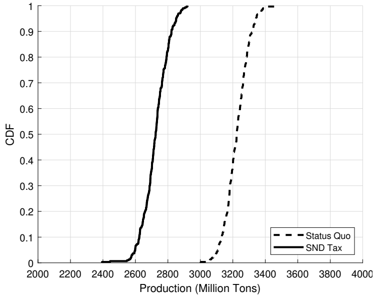
$$W = E\left(CS + \mathbf{weight} \cdot PS + tax - loss\right)$$

If weight $= 1$, SND Tax $= 653/\text{ton}$ (a) or $487/\text{ton}$ (b)

(a) Supply Model of Proportional Effects



(b) Supply Model of Threshold Effects



If weight $= 1.3$: CDFs cross for the threshold-effect model

Conclusion

Conclusion

- SND tax as a ranking criterion to compare the efficiency of a supply reduction and a tax
- Estimate an equilibrium model of China's coal market
- Production restriction significantly increases PS and total welfare
- Existence of SND tax shows that a tax can do better than the observed policy
    - More nuanced if the policy maker weighs PS more
    - Faster and easier to implement restriction than tax
- Hard to rein in coal consumption: China pivots to mass investment in renewables

Appendix

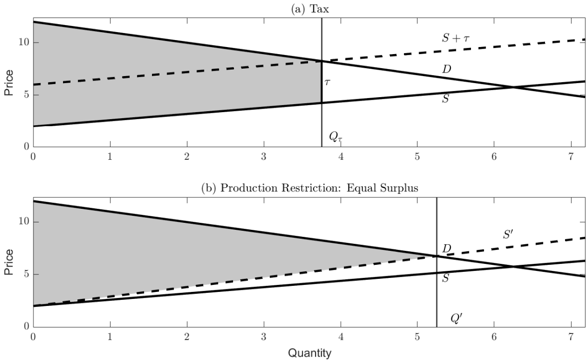
Demand: First-Stage Results

	(1) Timing	(2) SOE	(3) Timing+SOE
Z_{jt}^{Timing}	0.075***		0.017
	(0.014)		(0.029)
Z_{jt}^{SOE}		0.147***	0.117**
		(0.023)	(0.049)
Wind Generation (TWh)	-0.067***	-0.066***	-0.067***
	(0.025)	(0.025)	(0.025)
CDD/1000	0.260***	0.249***	0.249***
	(0.084)	(0.085)	(0.085)
Province FE	YES	YES	YES
Month FE	YES	YES	YES
Kleibergen-Paap F Statistic	25.46	37.84	19.65
N	1440	1440	1440

(Non-)Existence of SND Tax

- Finding an SND tax is a **sufficient condition**
  - SND tax typically exists due to the superiority of tax in efficiency
  - Failure to find an SND tax does *not* say which one is better

Key Intuition: Tax Produces More Surplus For a Given Q



- To generate the same surplus, quantity under the tax is smaller than under a rotated supply

(Non-)Existence of SND Tax

- Finding an SND tax is a **sufficient condition**
  - SND tax typically exists due to the superiority of tax in efficiency
  - Failure to find an SND tax does *not* say which one is better
- Some theoretical results
  - SND tax does not always exist for production restriction
  - No SND production restriction for a tax
  - No SND efficient quota for a tax, and vice versa

Summary Statistics

	Mean	SD	p25	Median	p75
Panel A. Coal-Consuming Provinces					
Consumption (Million Tons/Month/Province)	10.16	7.63	4.62	7.47	13.30
Price (RMB/Ton)	532.01	133.87	430.21	523.03	615.45
Wind Generation (TWh/Month/Province)	0.53	0.73	0.06	0.29	0.70
Cooling Degree Days (°C/Month/Province)	17.77	38.16	0	0	11.12
N=1440; based on 30 coal-consuming provinces in 2014–2017					
Panel B. Coal-Producing Provinces					
Quantity (Million Tons/Month/Province)					
Supply	11.30	19.91	1.20	3.61	9.98
Capacity	11.21	17.85	1.59	5.18	12.40
N=1200; based on 25 coal-producing provinces in 2014–2017					
Panel C. Foreign Import					
Quantity (Million Tons/Month)	18.12	4.97	14.00	17.55	21.82
N=48; 2014–2017					

Welfare Effects of the Observed Policy

	(1) Supply Model of Proportional Effects	(2) Supply Model of Threshold Effects
Δ Economic Surplus and Environmental Costs (RMB bn.)		
Economic Surplus	$\boxed{-478.90}$	$\boxed{-299.94}$
	[-528.58, -429.31]	[-342.91, -262.39]
Consumer	-530.45	-607.16
	[-582.84, -481.98]	[-682.74, -539.24]
Producer	39.48	292.71
	[29.49, 51.44]	[264.42, 322.67]
Resource Tax	12.08	14.51
	[10.80, 13.16]	[12.72, 16.42]
Saved Environmental Cost	$\boxed{453.42}$	$\boxed{516.36}$
	[444.17, 459.22]	[472.33, 559.70]
Air Pollution	203.28	234.92
	[196.20, 208.93]	[219.79, 250.25]
Social Cost of Carbon	167.54	188.94
	[162.26, 172.80]	[170.67, 209.07]
Water Depletion	82.60	92.49
	[80.37, 84.82]	[83.68, 102.12]
Total Surplus	$\boxed{-25.48}$	$\boxed{216.42}$
	[-75.31, 22.86]	[187.32, 256.93]

Welfare Costs of Misallocation

- Total misallocation: within- and across- provinces
  - compared with total quantity-equivalent tax
- Within-province: Production reduction does not target lower marginal cost mines
  - compared with province-specific, production quantity-equivalent quotas
- Across-province: Production reduction does not target lower marginal cost provinces
  - Total misallocation net of within-province misallocation

	Supply Model of Proportional Effects		Supply Model of Threshold Effects	
	Within-Province (1)	Total (2)	Within-Province (3)	Total (4)
Δ Producer Surplus (RMB bn.)	345.57	441.46	155.97	246.35

- 60%-80% of distortions come from within-province misallocation