Unintended Consequences of Coal-fired Power Plant Closures: Evidence from China

Yi Fan[1] Qiuxia Gao[1] Cheng Keat Tang[2]

[1]Department of Real Estate
National University of Singapore

[2]Department of Economics
Nanyang Technological University

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Motivation

A view of Shougang's Qian'an steelworks in Tangshan, China, in 2016. The city has long been known as one of China's smoggiest. (Xiaolu Chu/Getty Images) from The Washinton Post

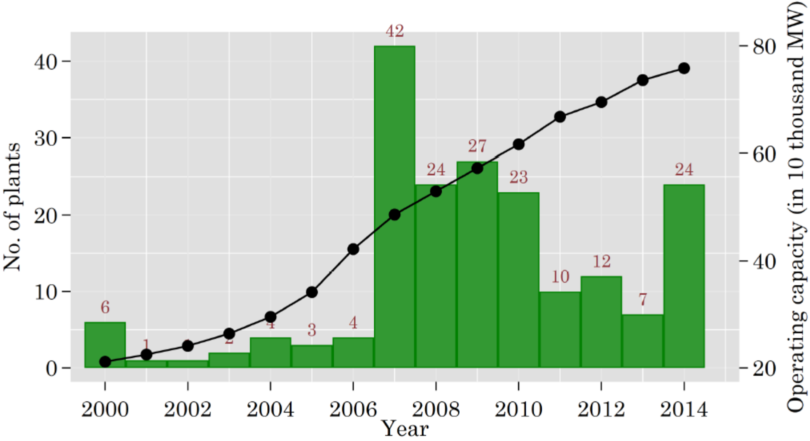
Coal combustion from heavy manufacturing industries and power plants is a major source of air pollution in China, contributing around 79% of SO2, 35% of PM2.5, and 40% of PM10 of the national total emissions

Motivation

To reduce pollution from burning coal and meet Carbon Neutrality & global 1.5$^{\circ}C$ Paris Agreement goals, the government have taken numerous measures:

1. Enforcing stringent emission standards (Karplus *et al.*, 2018)
2. Increasing pollution discharge fees (Gowrisankaran *et al.*, 2020)
3. Conducting inspections (Karplus & Wu, 2023)
4. Increasing reliance on renewable energy and natural gas for electricity production
5. **Retiring old, pollution inefficient coal-fired power plants**

Motivation



more than 180 coal-fired power plants with a total production capacity of more than 70 million megawatts (MW) were retired across China from 2000 to 2014

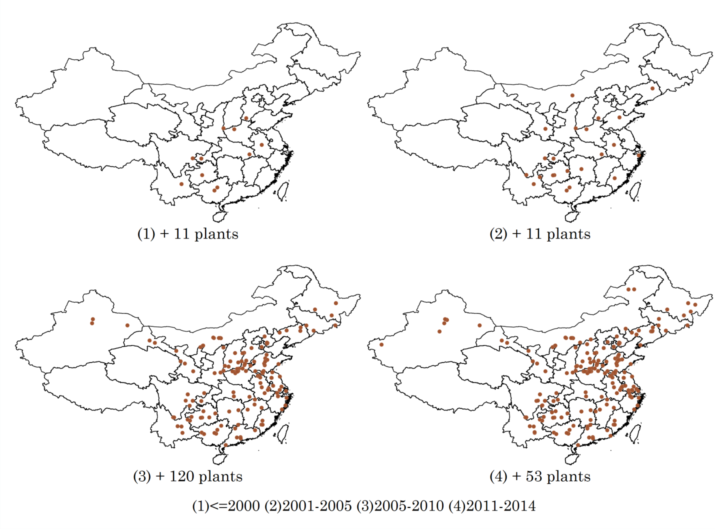


Figure: Spatial distribution of retired coal fired power plants

Motivation

Problem with shutdowns is that, if demand for electricity remains unchanged, other plants must increase production to meet electricity demand

Previous literature has documented the possibility of displacement when plants (mostly nuclear) are taken off the grid (Davis & Hausman, 2016; Severnini, 2017; Jarvis *et al.*, 2022; Burney, 2020)

Existing papers focus on the localized "partial" equilibrium effects of air quality & health from small-scale plant retirements (Russell *et al.*, 2017; Jaffe & Reidmiller, 2009; Komisarow & Pakhtigian, 2022, 2021b; Strasert *et al.*, 2019)

Does this mean that closures simply redistribute, rather than reduce net exposure? What is the general equilibrium effect of power plant closures on air quality?

Motivation

Conceptually, if a planner can identify the most inefficient power plants (pollution per kilowatt of electricity generated) and retire them, and transfer electricity generation to the most pollution efficient plants, net emissions should reduce

However, the actual scenario could depart from the ideal if:

1. the most inefficient coal fired power plants are not retired;
2. production capacity is not given to the most pollution efficient power plants (e.g renewable power plants & $\downarrow$ coal reliance, larger more efficient generators);
3. quota is allocated to operating plants around densely populated human settlements

Are there good reasons to believe that these dispatch distortions exist in China?

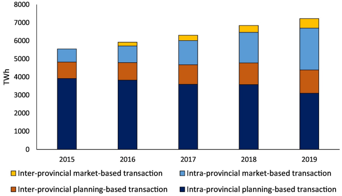
How are Plants Selected for Closure?

Closed plants are smaller in capacity, older, and are around more polluted areas that are more densely populated.

	(1) Completely close	(2) Partly close w/o new units	(3) Partly close with new units	(4) Fully operating
Average capacity	407.518	1345.926	1491.986	963.34
	(1.779)	(2.158)	(2.471)	(.711)
Age	28.964	32.304	40.646	13.312
	(0.021)	(0.027)	(0.03)	(0.008)
Monthly SO2 (DU)	0.436	0.427	0.36	0.363
	(0.001)	(0.001)	(0.001)	(0.000)
GDP (thousand)	3581.074	3330.338	2155.008	2594.82
	(11.927)	(15.086)	(16.615)	(4.718)
GDP of secondary industry (thousand)	1776.715	1725.023	1113.573	1371.213
	(6.693)	(8.447)	(9.423)	(2.655)
Employment in secondary industry (%)	12.997	12.305	10.223	9.387
	(0.045)	(0.055)	(0.062)	(0.017)
Population (thousand)	5098.86	4411.813	3097.913	2881.829
	(6.371)	(7.726)	(8.847)	(2.546)
Number of plants	167	115	85	1,061

Equal Shares System and Limited Cross-province Trading

- **Equal shares system:** Operating hours were evenly allocated to all plants instead of a "merit" order based → Quota not given to the most efficient plants (lowest production & social cost/ unit of electricity)
- **Reforms from 2007:** Differentiated Generation Quota Scheme → more utilization hours to larger, more efficient, and less polluting generator units
- Generation Rights Trading allowed decommissioned units to transfer quotas to operating units → limited in scope geographically (only a few piloting areas) & not nationwide
- **Between province dispatch** of electricity is limited before reforms in 2015
- Provinces do not import electricity from other provinces, unless facing a shortage; provincial leaders are reluctant to reduce utilization hours of their generators to maintain profitability



Continued Reliance of Coal for Power

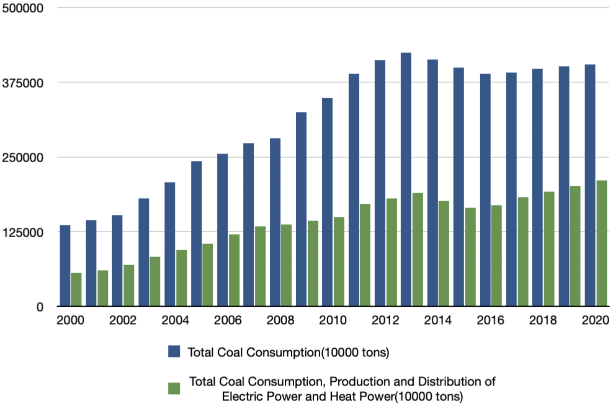


Figure: Coal consumption in China from 2000-2020 (Source: National Bureau of Statistics)

Research Questions

1. **Closure**: Does closing coal-fired power plants improve ambient (or local) air quality?
2. **Displacement**: Do we observe air quality worsening around neighboring coal-fired power plants that remained open?
3. **Exposure**: If there is pollution displacement, what is the net exposure effect of plant closures and what are the determinants of displacement?
4. **Health**: What is the overall effects on health outcomes due to coal fired power plant closures?

Effects of Closure on Environment & Health

- Localized improvement in air quality following the closure of power plants (Russell *et al.*, 2017; Jaffe & Reidmiller, 2009; Brown & Tousey, 2020; Strasert *et al.*, 2019)
- In China,
  - concentrations of SO2 declined by 13.9% following the July 2014 deadline for implementing tighter emissions standards in China (Karplus *et al.*, 2018)
  - reduce SO2 emission and PM pollution using Flue Gas Desulfurization (FGD) facility and installation of Selective Catalytic Reduction system (SCR) in power plants (Hao *et al.*, 2007)
- Shutdown of plants on birth weight, fetal and child growth (Tang *et al.*, 2014; Yang & Chou, 2017; Kalia *et al.*, 2017): Reduce mortality rates by 0.6 percent (Brown & Tousey, 2020)
- Shutdown on respiratory health of children (Chen *et al.*, 2018; Komisarow & Pakhtigian, 2021a,b)

Existing literature focuses on localized (environmental & health) benefits surrounding coal fired power plant closures → but not general equilibrium overall effects

Displacement Effects of Plant Shutdowns

Previous literature indicate that cuts in electricity production from plant retirements contribute to displacement in production & pollution:

- Jarvis *et al.* (2022): substantial increase in coal-fired electricity production and import of electricity after many nuclear power plants in Germany were closed in 2011 post Fukushima
- Davis & Hausman (2016): shutting down nuclear power plants in the United States led generation displacement to natural gas plants that increase carbon footprint
- Severnini (2017): closure of two large nuclear power plants in Tennessee Valley Authority due to the Three Mile Island accident in 1979 attributed to one-to-one shift of electricity generation to coal-fired power plants, deteriorating ambient air quality and reducing infant birth weight
- Burney (2020): document ↑ in PM2.5, NO2 and O3 around operational power plants after neighbouring coal-fired power plants are retired.

The environmental benefits of plant retirements are unclear → especially when there are allocation distortions!

Overview of Strategy and Results

- Manually collected information on more than 1,500 power plants and more than 6,000 renewable energy plants across China in 2004-2014, combined with NASA satellite data on SO2
- Exploit staggered coal fired power plants closures using quasi-experimental DiD estimation to identify the effects of closure and displacement on environment and health outcomes
- SO2 emission in treatment group (within 35km of retired plants) decreases by around 2.5% 👍
- Displacement effects of the open plants near the retire plants increase SO2 within 35km of open plants by 1.9% 👎
- After accounting for population density around coal-fired power plants, net exposure effects are about 11.6% of the closure effects after accounting for displacement 👉👈
- Negligible effects on health outcomes measured at county level 👉👈

Contributions

1. Improve understanding on the "overall" environment and health outcomes from plant closures
   - Previous papers mainly focus on the "partial equilibrium" localized impact of a singular large power plant closure on air quality & health outcomes
   - Draw inferences from a massive wave of plant closures across China from 2004-2014
   - Account for both closure and displacement effects on air quality from retired and operating plants to compute net exposure
2. Overcome potential data bias by using satellite measures instead of monitoring stations (Brombal, 2017; Chen *et al.*, 2012)
3. Examine these questions in a setting with dispatch distortions; Provide some insights on how to mitigate displacement effects

Data on Power Plants

- Manually collect information on: coordinates, start year, cancel year, retired year and capacity of coal fired generators from Global Energy Monitor website
- Identify 180 retired plants from 2004 to 2014 and calculate number of retired generator units and retired capacity
- Specify the earliest retired year of generators as the retired year of the plants
- Match grids (and SO2 data) with the closest retired plants

Data on Environment

- Use satellite observations from NASA's dataset OMSO2 and calculate the average daily SO2 emissions at 0.25 deg $\times$ 0.25 deg grid (27km $\times$ 27km)

- Aggregate the monthly SO2 data of each grid from daily data: replace negative values with zero following Karplus *et al.* (2018)

- Final sample includes 220,765 obs for closure effect and 559,401 obs for displacement effect

Data on Climate Controls

- Climate data from National Oceanic and Atmospheric Administration; matched with SO2 data by Inverse Distance Weighting (IDW)
  - containing temperature, dew point, air pressure relative to mean sea level, visibility, wind speed and precipitation
  - IDW: d is the distance between grids and 5 nearest climate points

$$x* = \frac{\omega_1 x_1 + \omega_2 x_2 + ... + \omega_5 x_5}{\omega_1 + \omega_2 + ... + \omega_5}, \omega_n = \frac{1}{d}$$

Closure & Displacement Effects on Air Quality

Descriptive

$$ln(SO2_{it}) = \alpha_i + \beta Close_i \times Post_t + X'_{it}\phi + \tau_t + \epsilon_{it}$$

$$ln(SO2_{it}) = \alpha_i + \delta Near_i \times Post_t + X'_{it}\phi + \tau_t + \varepsilon_{it}$$

- $Close_i$ is a dummy variable, =1 when grid i is within 35 km of retired plants
- $Post_t$ is a dummy variable, =1 after the power plant is retired, 0 otherwise
- $Near_i$ is a dummy variable, =1 when grid i is within 35 km of open plants & within 100km from the retired power plant is less than 100 km, but not within 35 km of retired plants
- α_i is the grid fixed effects
- τ_t is Year-month fixed effects
- X'_{it} is a vector of climatic controls (at 2nd polynomial)
- SE Cluster at grid level

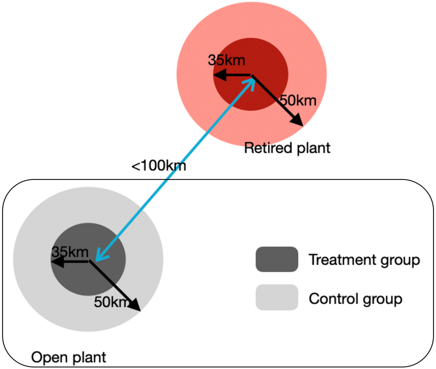
Visualizing Empirical Strategy

Closure

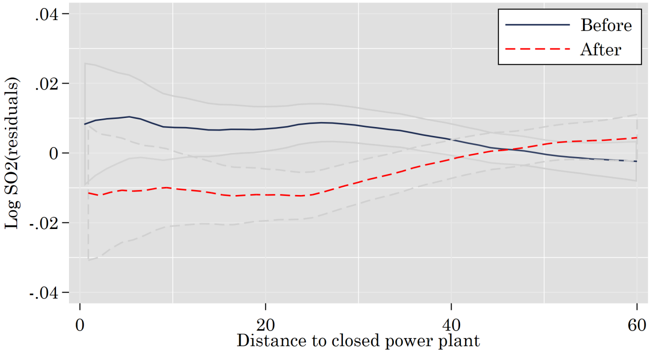
- 180 retired power plants from 2004-2014
- Treatment: areas within 35 km of retired plants; Control: areas within 35-50 km of retired plants

Displacement

- 554 operating plants within 100 km from retired plants
- Treatment: areas within 35 km of open plants; Control: areas within 35-50 km of open plants

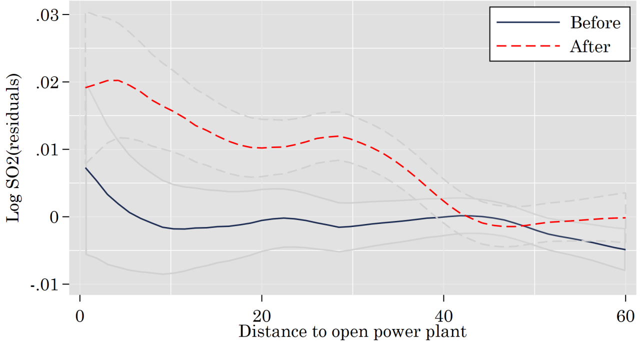


Graphical Evidences: Closure



SO2 emission across distance to plants before and after closure. Log SO2 residuals are obtained from regressing ln(SO2) on all sets of control variables with grid, year-month fixed effect and province-by-year fixed effects, clustering standard errors at grid level. Observations of 5 years before and after the plant closure are used.

Graphical Evidences: Displacement



SO2 emission across distances to plants before and after displacement. Log SO2 residuals are obtained from regressing ln(SO2) on all sets of control variables with grid, year-month fixed effect and province-by-year fixed effects, clustering standard errors at grid level. Observations of 5 years before and after the plant closure are used.

Baseline Results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
			Panel A: Closure Effect				
Close ∗ Post	-0.026**	-0.028***	-0.033***	-0.033***	-0.029***	-0.029***	-0.025***
	(0.013)	(0.010)	(0.009)	(0.007)	(0.006)	(0.006)	(0.008)
Observations	848563	848563	848563	848563	848563	484667	220765
R2	0.37	0.43	0.46	0.48	0.49	0.49	0.50
Mean Dep Variable	0.44	0.44	0.44	0.44	0.44	0.45	0.48
			Panel B: Displacement Effect				
Near ∗ Post	0.035***	0.025**	0.016*	0.006	0.010*	0.015***	0.019***
	(0.012)	(0.010)	(0.009)	(0.007)	(0.006)	(0.006)	(0.006)
Observations	2795840	2795840	2795840	2795840	2795840	1434559	559401
R2	0.33	0.39	0.42	0.44	0.45	0.45	0.45
Mean Dep Variable	0.37	0.37	0.37	0.37	0.37	0.39	0.40
Year month FE	Y	Y	Y	Y	Y	Y	Y
Province FE	Y						
City FE		Y					
County FE			Y				
Grid FE				Y	Y	Y	Y
Province*Year FE					Y	Y	Y

*P $<$ 0.10; **P $<$ 0.05; ***P $<$ 0.01. Dependent variable is natural log of monthly SO2 after replacing negative values with missing values. Regression sample includes observations of 5 years before and after plant closure from 2004 to June 2014. Treat $=$ 1 for grids that are $\leq$ 35km from the power plants, and Post $=$ 1 for time periods 0-5 after power plant is closed. Column (1)-(5) use grids within 100 km of retired plants. Column (6) restricts the sample to be within 75 km and column (7) restricts the sample to be within 50 km. All regressions include various climate controls at 2nd polynomials. Standard errors are clustered at grid level.

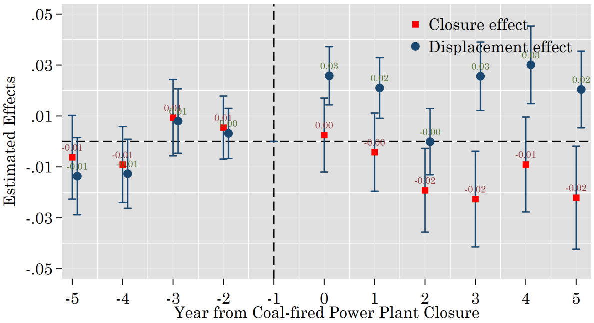
Robustness Tests

	(1) Baseline	(2) Replace negative SO2 with missing	(3) Remove outliers	(4) Cluster county	(5) Cluster province	(6) Sub-sample	(7) CSDID
Panel A: Closure Effect							
Close ∗ Post	-0.025***	-0.016***	-0.026***	-0.025***	-0.025***	-0.021**	-0.013***
	(0.008)	(0.006)	(0.007)	(0.008)	(0.007)	(0.010)	(0.003)
Observations	220765	220765	215185	220765	220765	139871	19871
R2	0.50	0.50	0.51	0.50	0.50	0.50	
Mean Dep Variable	0.48	0.48	0.46	0.48	0.48	0.52	
Panel B: Displacement Effect							
Near ∗ Post	0.019***	0.012**	0.017***	0.019***	0.019***	0.028**	0.016***
	(0.006)	(0.005)	(0.006)	(0.007)	(0.006)	(0.012)	(0.002)
Observations	559401	559401	550406	559401	559401	199053	24826
R2	0.45	0.46	0.47	0.45	0.45	0.41	
Mean Dep Variable	0.40	0.40	0.39	0.40	0.40	0.31	

Notes: *p < 0.10; **p < 0.05; ***p < 0.01. Dependent variable is natural log of monthly SO2 from 2004 to 2014. Coefficients in panel A and B are derived from equation (1) and (2), respectively. Control group is defined as between 35 and 50 km from the retired or operating plants. In Column (6), we use retired plants without new-built units after closure to analyze the sub-sample closure effects; we remove the open plant with overlapped treatment period to estimate displacement effects. All regressions include various climate controls at 2nd polynomials. Standard errors are clustered at grid level.

Robustness Checks: Pre-Trends

▸ TWFE Pre-trend



A full set of controls, grid, year-month and province by year fixed effects are included. Standard errors are clustered at grid level. The effect $\theta^{event}(e) = \frac{\sum \omega_{g,t} ATT(g,t)}{\sum \omega_{g,t}}$ where $\omega_{g,t}$ are based on the number of treated observations of t-g=e, which is average effect of participating in the treatment for the group of units that have been exposed to the treatment for exactly e time periods

Computing Net Exposure

Pop Density

We compute the net exposure using the following formula:

$$\text{Net Exposure} = \overbrace{\left[\beta \times \sum_{i=1}^{n} \left(Popsize_i^{d<=35km} \times \overline{SO2_i} \right) \right]}^{\text{Closure reductions}} - \overbrace{\left[\delta \times \sum_{j=1}^{n} \left(Popsize_j^{d<=35km} \times \overline{SO2_j} \right) \right]}^{\text{Displacement increments}}$$

- β and δ: preferred estimates of the closure effect and displacement effect
- $Popsize_i$ and $Popsize_j$: average population within the 35km vicinity of retired plant i and operational plant j after the closure of plant i
- $\overline{SO2_i}$ and $\overline{SO2_j}$: average SO2 levels in the respective vicinity

Computing Net Exposure

Panel A - Closure		Panel B - Displacement	
Estimated effects	-2.5%	Estimated effects	1.9%
SO2 levels (DU)	0.528	SO2 levels (DU)	0.384
Total Population size (<=35km)	1,250,000,000	Total Population size (<=35km)	2,000,000,000
Net Closure exposure [A]	- 16,500,000	Net Displacement exposure [B]	14,592,000
Panel C - Overall			
Net exposure [A + B]	≈-1,908,000		
Net exposure/Net closure [A]	≈ 11.6%		

Determinants of Displacement

Two questions: (1) Is displacement driven by trading distortion? (2) Can "cleaner" technology minimize displacement?

Table: Determinants of pollution displacement effects from plant closures

	(1) Province	(2) City	(3) County	(4) Renewable Energy	(5)
Near × **Post** × **SameArea**	0.019^{***}	0.015^{*}	0.049^{***}		
	(0.006)	(0.008)	(0.016)		
Near × **Post** × **DiffArea**	0.003	0.014^{**}	0.017^{***}		
	(0.010)	(0.007)	(0.006)		
Near × **Post** × **WithRE**				0.014^{**}	
				(0.006)	
Near × **Post** × **W/ORE**				0.025^{*}	
				(0.013)	
Near × **Post** × **AboveMeanRE**					0.005
					(0.009)
Near × **Post** × **BelowMeanRE**					0.020^{***}
					(0.007)
Observations	559401	559401	559401	559401	559401
R2	0.45	0.45	0.45	0.45	0.45
Mean Dep Variable	0.40	0.40	0.40	0.40	0.40

Data on Infant Mortality

- County-level infant mortality rate from manual collection from Yearbook of Health in the P.R.China
- Match with the power plant data collapsed by county level
- Cumulative number of retired plants and retired capacities of counties in each year are calculated

Plant Closure Effect on Health Outcomes

$$ln(Y_{ct}) = \gamma Plant_{c,t-1} + X'_{ct}\phi + \lambda_c + I_t + \epsilon_{ct}$$

Y_{ct} is infant mortality rate at county c in year t

$Plant_{c,t-1}$ is either the (1) count of retired plants at county c in year t-1 or (2) the cumulative number of retired plants at county c from the beginning till year t-1

λ_c is the county fixed effects; I_t is year fixed effect

X'_{ct} are control variables: GDP, population, number of maternal and child health hospitals, birth rate, average income, female illiteracy rate, and female employment rate

SE Cluster at county level

Closure Effect: Infant Mortality Outcome

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Levels				**Cumulative**			
	Number		Capacity		Number		Capacity	
	ln(infant)	ln(infant)trim	ln(infant)	ln(infant)trim	ln(infant)	ln(infant)trim	ln(infant)	ln(infant)trim
L.Yearly_retireplant	0.074	0.083						
	(0.098)	(0.098)						
L.Yearly_retirecapacity			-0.053*	-0.054*				
			(0.028)	(0.029)				
L.Cumulative_retireplant					-0.057	-0.037		
					(0.080)	(0.077)		
L.Cumulative_retirecapacity							-0.020	-0.023
							(0.034)	(0.035)
Observations	2934	2880	2934	2880	2934	2880	2934	2880
R2	0.79	0.82	0.79	0.82	0.79	0.82	0.79	0.82

Standard errors are clustered at the county level. *P $<$ 0.10; **P $<$ 0.05; ***P $<$ 0.01; All columns includes county and year fixed effects; Year_retired plants is the number of retired plants each year, Year_retired capacity is the retired capacities each year, Cum_retired capacity is the cumulative retired capacities of the county divided by 100, Cum_retired plant is the cumulative retired plants of the county; ln(infant)_trim removes the outliers of top 1% and bottom 1%; All regressions contain GDP, population, number of maternal and child health hospital, birth rate, average income, female illiteracy rate and female employment rate controls and restriction of positive number of coal-fired power plants in the province.

Concluding Remarks

- We measure the local and external effects of power plant closures on air quality using high quality granular satellite data
- Although we observe a reduction in SO2 in areas surrounding the close power plants (around 2.5%), we observe areas surrounding neighboring power plants that remained in operation experience a 1.9% spike in SO2 levels
- Net effects is merely 11.6% of the localized reductions around closed power plants by combining with micro population date → negligible effects associated with health outcomes at county level
- **Policy implications** on mitigating displacement effect: (1) develop renewable clean energy and (2) reduce electricity dispatch distortions
- Of paramount importance how these electricity quotas are allocated in the grid after shutting down of "dirty" plants!

Thank You!

E-mail: yi.fan@nus.edu.sg

Summary Statistics ▸ Back

	(1) T^{close}	(2) C^{close}	(3) $T^{displace}$	(4) $C^{displace}$
Monthly SO2 (DU)	0.485	0.438	0.403	0.379
	(0.001)	(0.001)	(0.001)	(0.001)
GDP (thousand)	2,493.458	2,177.565	1,568.651	1,289.399
	(15.277)	(14.991)	(3.332)	(3.090)
GDP of secondary industry (thousand)	1,350.060	1,229.835	879.336	680.128
	(9.087)	(8.871)	(2.058)	(1.921)
Employment of secondary industry (%)	12.001	12.461	7.987	8.121
	(0.081)	(0.082)	(0.039)	(0.035)
Population (thousand)	610.796	634.232	610.237	627.035
	(1.586)	(1.608)	(1.211)	(1.163)
Number of grids	1166	1294	2671	3006

T^{close} and C^{close} indicates treatment (within 35km of plants) and control group (35-50km of plants) of retired plants, respectively. $T^{displace}$ and $C^{displace}$ are the treatment (within 35km of plants) and control group (35-50km of plants) of operating plants that are within 100km of retired plants.

TWFE: Pre-Trends

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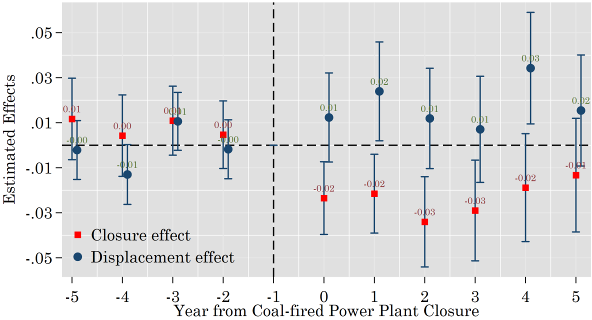
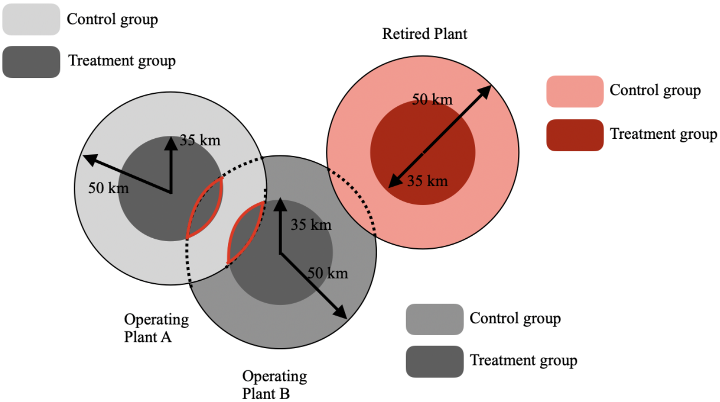


This figure presents the Year × Treatment coefficients for 5 years before and after plant closures. Treatment is defined as within 35 km of retired or operating power plants. To test for the displacement effects, operating plants are restricted to be within 100 km of retired plants. A full set of controls, grid, year-month and province by year fixed effects are included. Standard errors are clustered at grid level.

Overlapping grids removal, noframenumbering



Population Density

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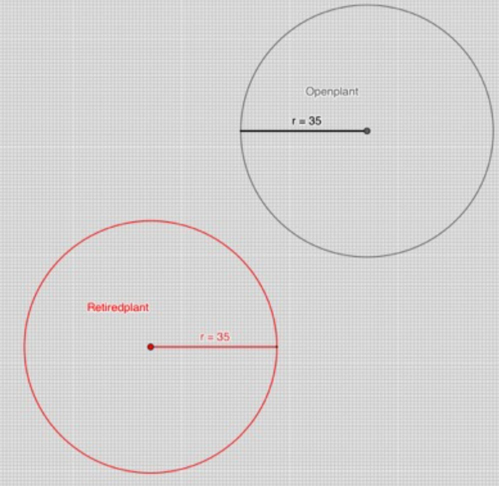

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