The Energy Transition, Air Pollution, and Mortality

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March 2025

Abstract

This paper studies the mortality benefits of the transition from coal-fired power generation in the US. Using hourly operational data of every generator from 1999-2019 combined with a high-frequency atmospheric dispersion model, we estimate the contribution of each plant's generation to downwind air quality. We use the reshuffling of generation across plants to estimate the mortality impacts of acute exposure to particulate matter among the elderly population. We find that 25% of U.S. fine particulates (PM2.5) in 1999 came from power plants, and that 40% of the air quality improvement from 1999-2019 was due to changes in electricity generation. We calculate one day of exposure to 1 $\mu g/m^3$ of PM2.5 raises senior mortality by 0.12%, and that one month of exposure raises total mortality by 0.5%. Using an empirical dispatch model to estimate counterfactual outcomes, we find that the shift away from coal was worth $50B per year in reduced mortality by 2019.

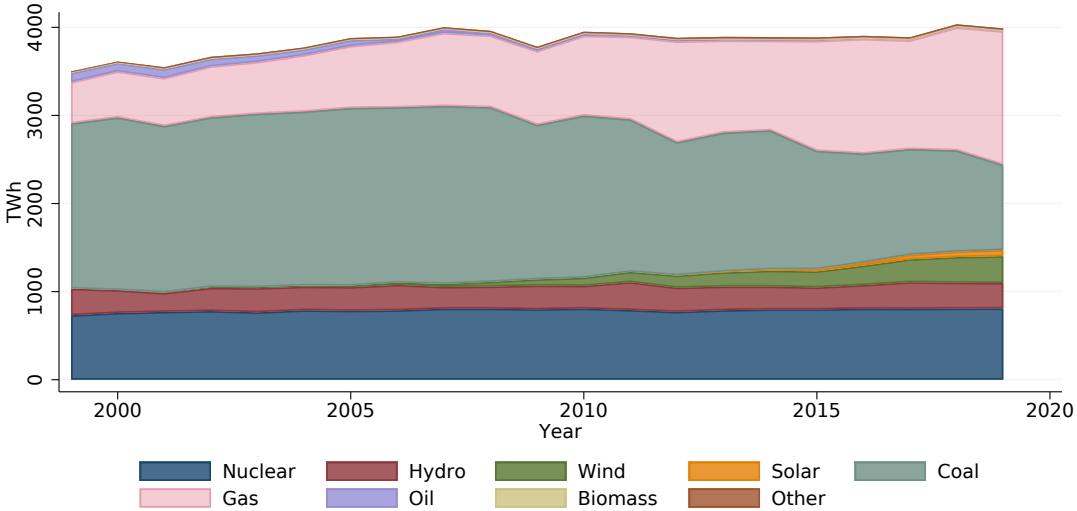
*We are grateful for helpful comments from seminar participants at the University of Zurich, MIT, and Chicago. We thank Daisy Lu, Sifat bin Raquib, Yann Decressin, and Scott Blatte for exceptional research assistance. email: scicala@gmail.com, jgottlieb@uchicago.edu

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The Energy Transition is Underway: U.S. Fuel Mix



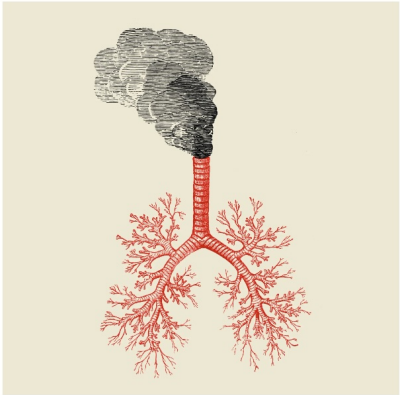
The New York Times

OPINION

BINYAMIN APPELBAUM

Enough About Climate Change. Air Pollution Is Killing Us Now.

April 19, 2022



Research Question

- What was the impact of this changing fuel mix on U.S. air quality?
  - Focus on fine particulate matter ($< 2.5 \mu m$ diameter, PM2.5)
- What was the impact of this changing fuel mix on U.S. mortality?
  - Short-run: daily
  - Medium-run: up to 5 years

Simple Questions, Hard to Answer Well

- Regulatory impact assessments: piecewise analysis
  - Engineering estimates of plant emissions.
  - Source-receptor matrices of annual emissions.
  - Dose-response functions from epidemiology.
- Heavily model dependent, minimal endogeneity concerns.
- Refinements generally follow one of two paths:
  - Engineering side: Improved atmospheric chemistry & dispersion.
  - Economics side: Quasi-experimental, but sourceless variation in exposure.

This Paper: A Fully-Integrated Estimation of the Grid's Mortality Impacts

- Use dispersion model outputs as part of a credible research design.
- Estimate each plant's contributions to ambient air quality.
- Use reshuffling of generation across plants as an instrument for downwind air quality.
- Estimate impacts of particulate matter on U.S. mortality, both immediate & eventual.
- Estimate counterfactual outcomes holding grid fixed.

Summary of Findings

- 25% of U.S. fine particulates (PM2.5) in 1999 came from power plants.
- 40% of air quality improvement from 1999-2019 due to grid operations.
- 1 $\mu g/m^3$ causes:
  - 1 day of exposure: 0.12% increase in senior mortality.
  - 1 month of exposure: 0.54% increase in overall mortality within 3 months.
  - 1 month of exposure: 0.45% increase in overall mortality within 5 years.
- 2019 grid versus counterfactual holding grid fixed:
  - 50,000 fewer deaths per year.
  - \$50B in annual mortality cost savings.

Outline

1. Background
2. Estimation Strategy
3. Data
4. Results
5. Conclusion

Measuring the Health Costs of Polluting Activities

$$\underbrace{\underbrace{A_{jt'}}_{\text{Activity}} \cdot \underbrace{e_{jt'}}_{\text{Emissions rate}} \cdot \underbrace{D_{jt'it}}_{\text{Dispersion}}}_{\Delta \text{PM2.5}_{it}} \cdot \underbrace{\tau}_{\text{Dose-Response}} \cdot VSL$$

- Outcome y_{it} in county i due to activity $A_{jt'}$ from plant j.
- Want to measure external costs $\frac{\$}{\text{MWh}}$ for activity $A_{jt'}$.
- Mass of emissions per unit activity: $= e_{jt'}$ (units: $\frac{\mu g \text{ of PM2.5}}{MWh}$).
- Dispersion of mass per volume of air: $D_{jt'it}$ (units: $\frac{\text{share of mass}}{m^3}$).
- Dose-response estimate: τ (units: $\frac{\text{deaths}}{\mu g/m^3}$).
- Value of a statistical life(year): VSL (units: $\frac{\$}{\text{death}}$).

Approaches to Measuring Health Impacts of Pollution I:

$$\underbrace{A_{jt'}}_{\text{Activity}} \cdot \underbrace{e_{jt'}}_{\text{Emissions rate}} \cdot \underbrace{D_{jt'it}}_{\text{Dispersion}} \cdot \underbrace{\tau}_{\text{Dose-Response}} \cdot VSL$$

- Just estimate τ:
  - Wind: Deryugina et al. (2019), Deryugina & Reif (2023).
  - Wildfires: Miller, Molitor & Zou (2024), Dodier (2024), Cabral & Dillinder (2024).
- Immediate proximity: $A_{jt'} \to y_{j+\epsilon,t'}$:
  - Recessions: Chay & Greenstone (2003) Finkelstein et al. (2024).
  - Planes: Schlenker & Walker (2016).
  - Automobiles: Anderson (2020), Knittel et. al (2016), Currie & Walker (2011).
  - Fracking: Currie et al. (2017), Hill (2018).

Approaches to Measuring Health Impacts of Pollution II:

$$\underbrace{A_{jt'}}_{\text{Activity}} \cdot \underbrace{e_{jt'}}_{\text{Emissions rate}} \cdot \underbrace{D_{jt'it}}_{\text{Dispersion}} \cdot \underbrace{\tau}_{\text{Dose-Response}} \cdot VSL$$

- Measure $A_{jt'}$, time-invariant D_{ji}:
  - others' τ:
    - Trains: Clay et al. (2019).
    - Power: Holland et al. (2020), Jarvis et al. (2022).
    - EVs: Holland et al. (2016).
  - estimate τ:
    - SO_2: Barreca, Neidell & Sanders (2021).
- Various permutations, without addressing endogeneity: Henneman et al. (2023).

Why Do We Need a Fully-Integrated Approach?

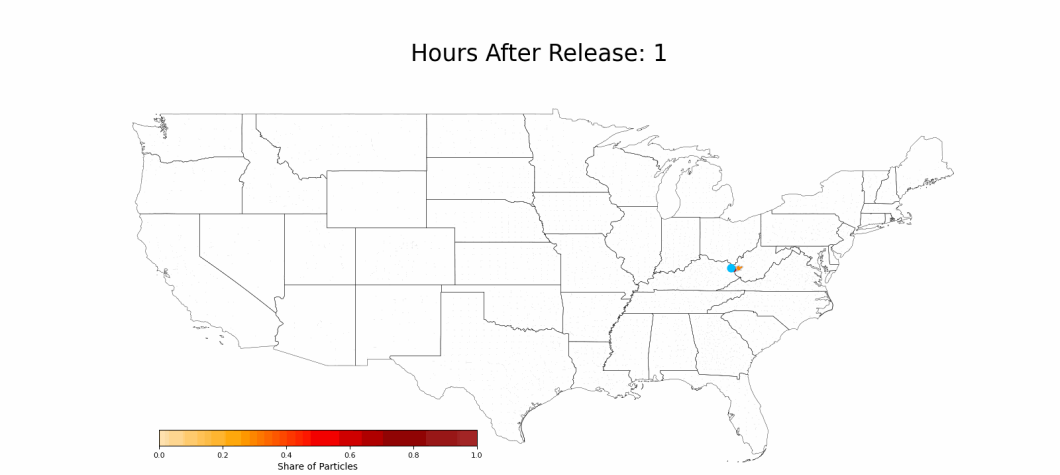
$$\underbrace{A_{jt'}}_{\text{Activity}} \cdot \underbrace{e_{jt'}}_{\text{Emissions rate}} \cdot \underbrace{D_{jt'it}}_{\text{Dispersion}} \cdot \underbrace{\tau}_{\text{Dose-Response}} \cdot VSL$$

- $A_{jt'}$: Emissions are highly variable, correlated with load.
- $\mathbf{D}_{jt'it}$: Emissions are dispersed across space and time.
- $D_{\mathbf{jt'it}}$: Exposure is highly variable.
- τ: Generation correlated with other mortality determinants, LATE.

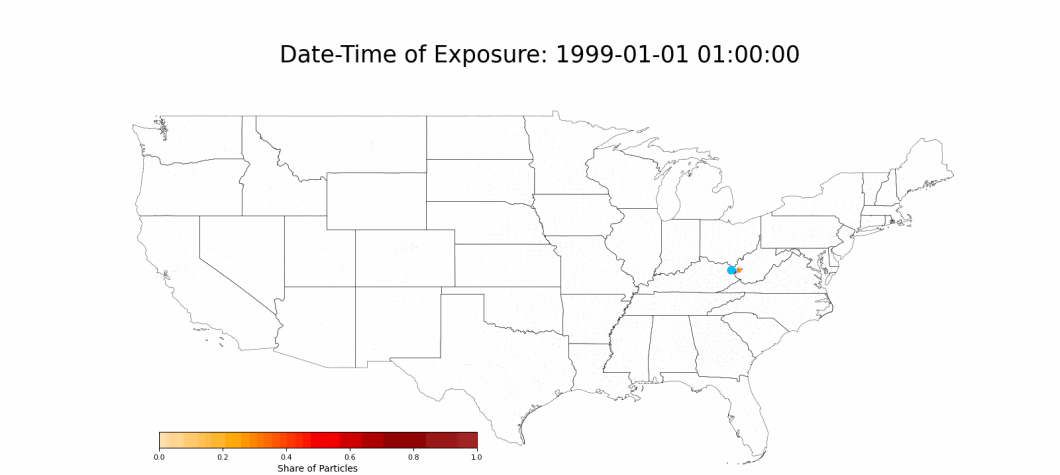
HYSPLIT Forward-Simulation of Pollutant Dispersion

- Coordinates, date, time, and stack height.
- Parameters of emissions.
- Pull meteorological data throughout air column.
- Simulate locations in hour $t + 1$ based on locations & meteorology in hour t.

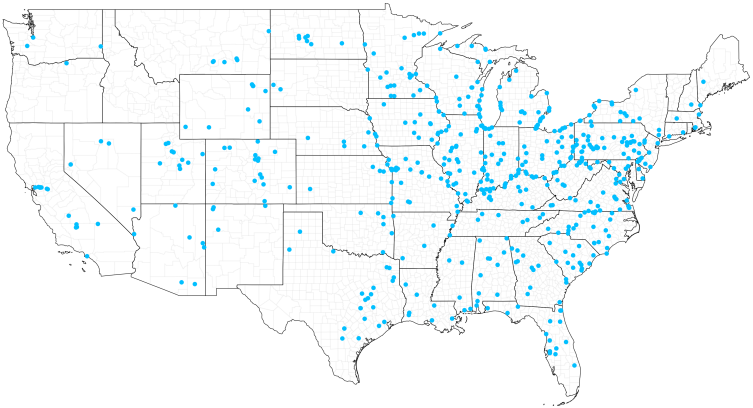
Forward-Simulation of Dispersion from Big Sandy: Single Release



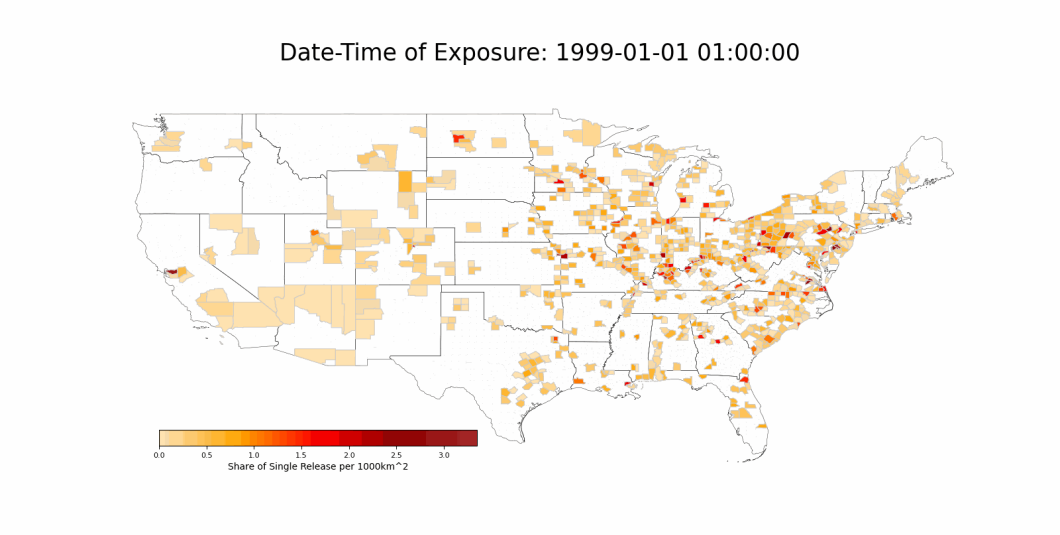
Forward-Simulation of Dispersion from Big Sandy: 4 Daily Releases



U.S. Coal-Fired Power Plants in 1999



Forward-Simulation of Dispersion from U.S. Coal Plants



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A Canonical Distributed Lag Model of Pollution and Health

$$y_{it} = \mathbf{P}_{it}\tau + \mathbf{X}_{it}\beta + f(L_{it}) + \phi_i + \lambda_{ym} + \eta_{sm} + u_{it}$$

- y_{it}: Mortality in county i on day t.
- $\mathbf{P}_{it}$: Distributed lag of exposure to pollution.
- $\mathbf{X}_{it}$: Controls for weather, economic activity, etc.
- $f(L_{it})$: Spline of local electricity load.
- ϕ_i, λ_{ym}, η_{sm}: County, year-month, and state-month fixed effects.

Instrumenting for Pollution

$$y_{it} = \mathbf{P}_{it}\tau + \mathbf{X}_{it}\beta + f(L_{it}) + \phi_i + \lambda_{ym} + \eta_{sm} + u_{it}$$

- Endogeneity concern: $E(\mathbf{P}_{it}u_{it}|\mathbf{X}_{it}) \neq 0$.
- Measurement error: single stations represent entire counties.
- LATE is policy-relevant.
- Instrument: Daily simulated receipt of pollution:

$$\sum_{j \notin i} A_{jt'} \cdot e_{jt'} \cdot D_{jt'it}$$

- Only use plants in other counties.

One Complication: PM2.5 Emissions Rates are Unobserved

$$e_{jt'} = \mathbf{K}_{jt'}\theta + \delta_{jt'}$$

- Generation unit characteristics, $\mathbf{K}_{jt'}$.
  - Fuel, generator type, vintage, abatement equipment.
- Instrument: Daily simulated receipt of heat-characteristics.

$$\mathbf{Z}_{it} = \sum_{j \notin i} A_{jt'} \cdot \mathbf{K}_{jt'} \cdot D_{jt'it}$$

- Units: 1 day of full exposure to 1 MMBTU from unit with characteristics $\mathbf{K}_{jt'}$ for an average-sized county.

First Stage

$$\mathbf{P}_{it} = \mathbf{Z}_{it}\gamma + \mathbf{X}_{it}\zeta + f(L_{it}) + \phi_i + \eta_{sm} + \nu_{it}$$

- γ converts simulated exposure to heat & characteristics into ambient pollution.
- Unobserved component of plant emissions orthogonal to Z_{it} by construction.
- Predicted pollution from power generation: $\sum_j A_{jt'} \cdot \mathbf{K}_{jt'}\hat{\gamma} \cdot D_{jt'it}$.
  - Includes $j \in i$.
  - Can be calculated for counties without pollution monitors.
- Predicted pollution from fuel f: $\sum_j A_{fjt'} \cdot \mathbf{K}_{fjt'}\hat{\gamma}_f \cdot D_{fjt'it}$.
- Predicted pollution from full exposure to plant j: $\mathbf{K}_{jt}\hat{\gamma}$.

Limitations & Interpretations

- Omitted variables bias from serially-correlated exposure.
- Inference:
  - OLS with predicted pollution not adjusted for generated regressors.

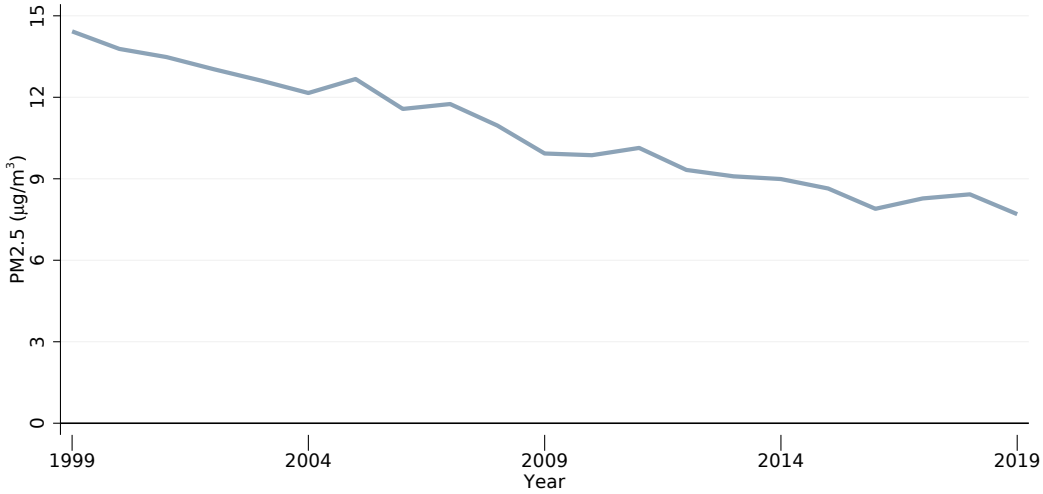
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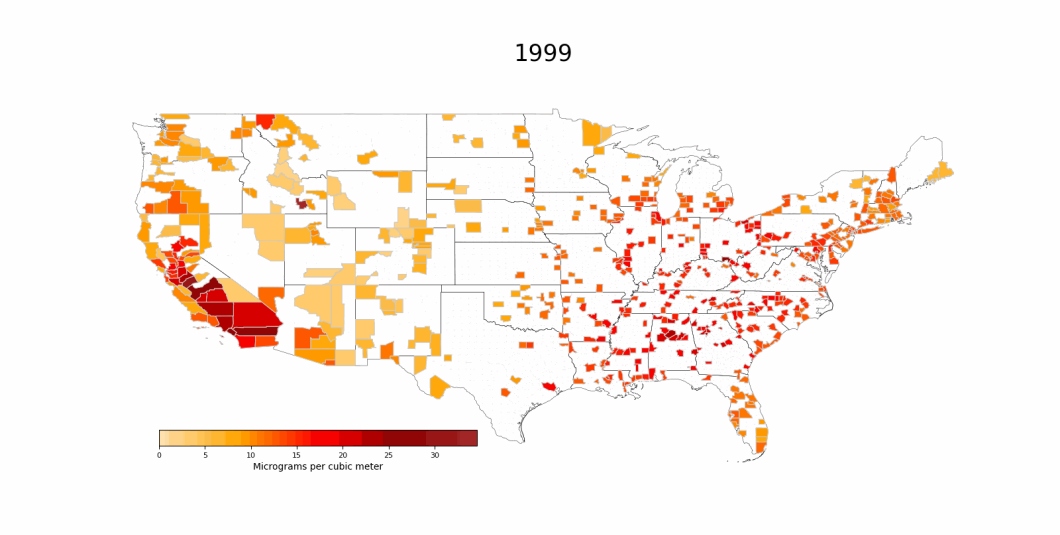
Data

- Generation:
  - Hourly operations of every generator in the U.S. electricity grid: 1999-2019.
  - Characteristics of units: fuel, generator type, vintage, abatement equipment.
  - Plant coordinates and stack heights.
- Dispersion: HYSPLIT
  - Simulate emissions for each plant-fuel type: 1999-2019.
  - Coarsen to 4 releases per day.
  - Track each release to counties for 48 hours.
- Pollution & Weather: 1999-2019.
  - EPA AQS daily PM2.5 measurements by county.
  - ERA5 daily mean wet bulb temperature and precipitation.
- Health: Daily Deaths, Medicare (65+) beneficiaries: 1999-2013.
  - Monthly deaths, CDC National Vital Statistics (all ages): 1999-2019.

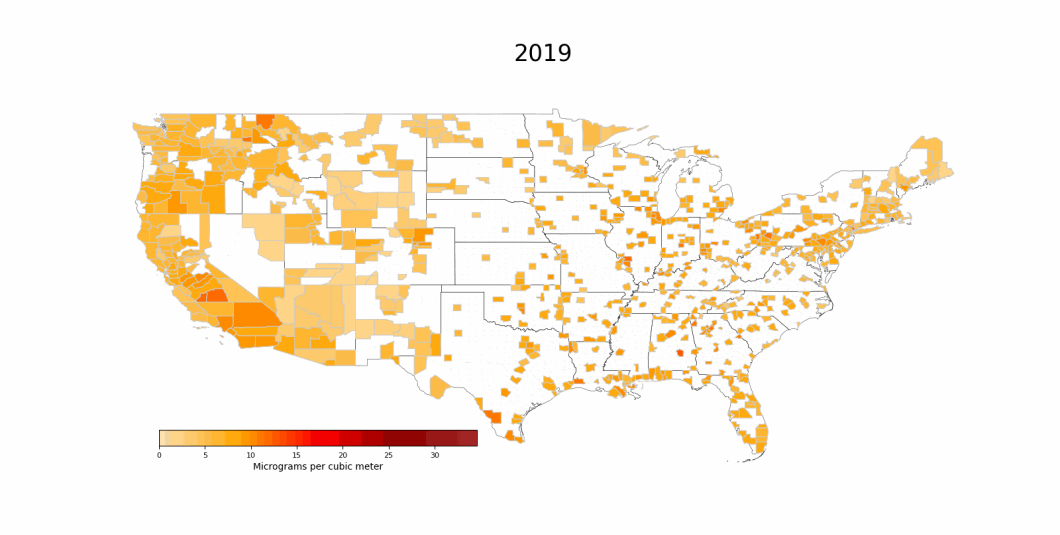
Mean Ambient PM2.5 in the US: 1999-2019 (population-weighted)



Mean Ambient PM2.5 in the US: 1999



Mean Ambient PM2.5 in the US: 2019



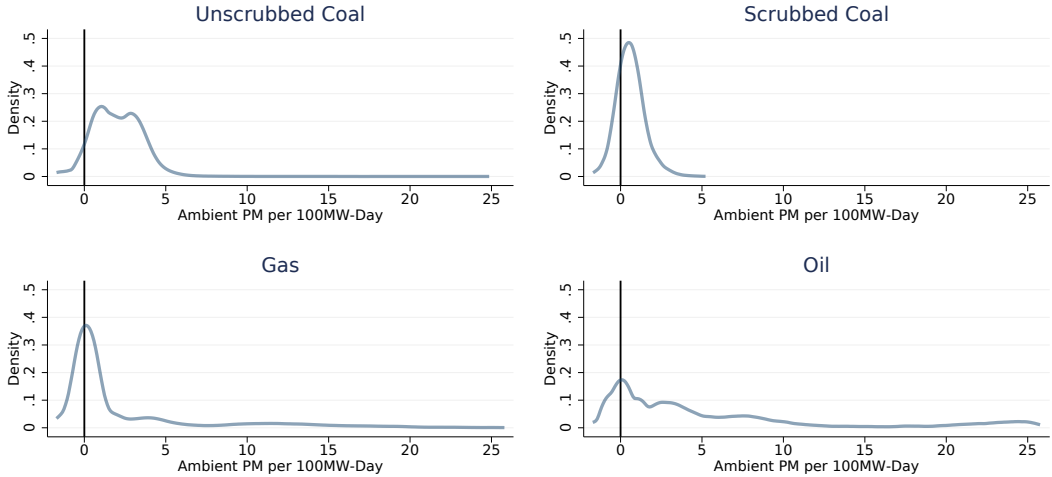
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Outline of Results Presentation

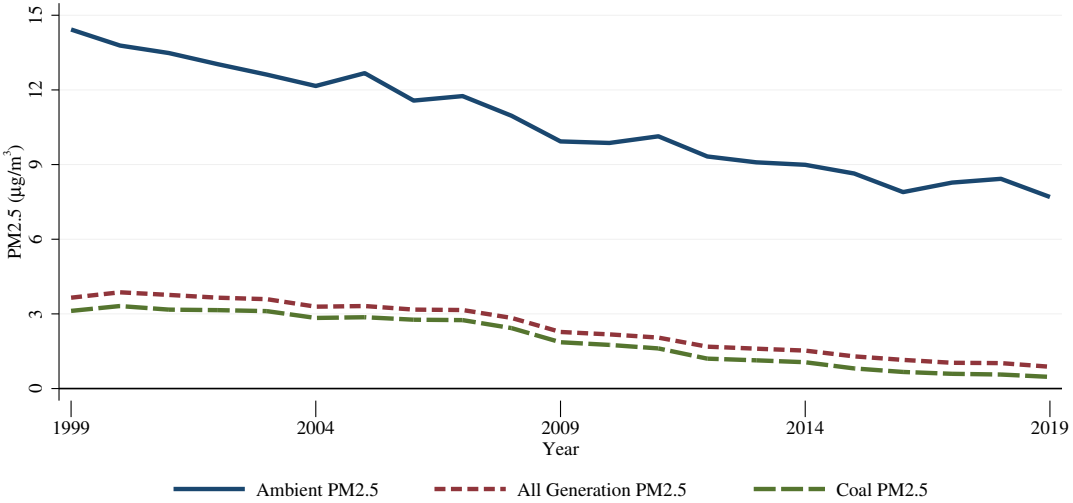
- First stage: How much PM2.5 comes from power plants?
- Daily IV estimates: Seniors, 1999-2013.
- Monthly IV estimates: All ages, 1999-2019.
- Counterfactual estimates: Hold grid fixed in 2003.

Plant-Fuel Densities of First Stage Coefficients: Heat Rate$_{jt} \cdot \mathbf{K}_{jt}\hat{\gamma}$

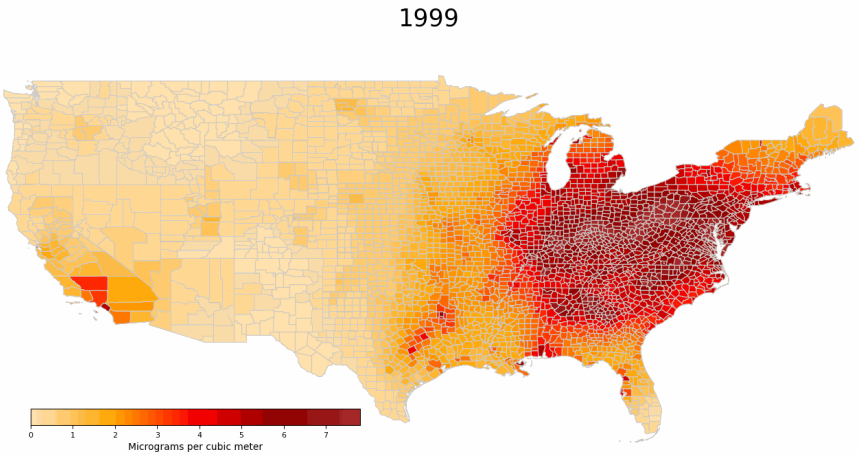


Note: Domain trimmed by the 1st and 99th percentiles.

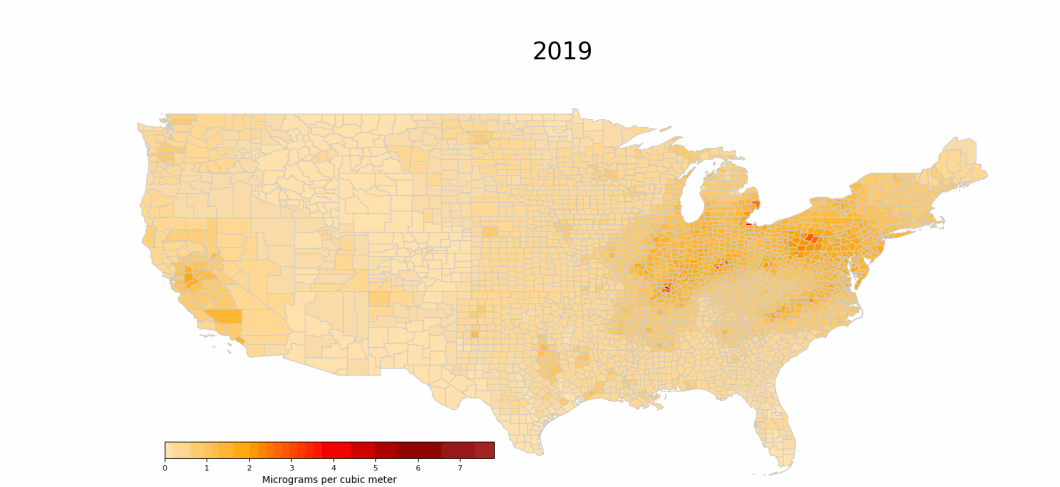
Predicted PM2.5 from Generation vs. Observed PM2.5



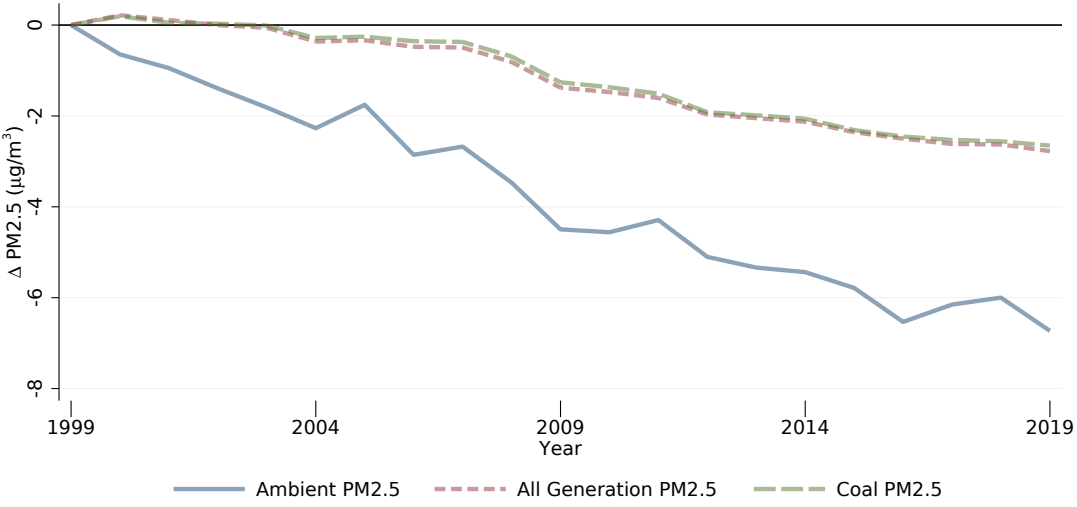
Annual Average Predicted PM from Generation: 1999



Annual Average Predicted PM from Generation: 2019



Change in Predicted PM2.5 from Generation vs. Observed PM2.5



Same-Day Mortality (Deaths per Million): OLS Sensitivity, 85+

	(1)	(2)	(3)	(4)
PM 2.5	0.287***	0.356***	0.346***	0.333***
	(0.046)	(0.046)	(0.050)	(0.049)
Dependent Variable Mean	377	377	377	377
Estimate Relative to Mean, Percent	0.076	0.094	0.092	0.088
State-Month, DOW FE		✓	✓	✓
Weather Controls			✓	✓
Econ Controls				✓
Observations	2,173,632	2,173,632	2,173,632	2,173,632

Note: All specifications include county and year-month fixed effects. Standard errors clustered by county in parentheses. * p<0.1, ** p<0.05, *** p<0.01

Same-Day Mortality (Deaths per Million): IV Sensitivity, 85+

	(1)	(2)	(3)	(4)
PM 2.5	0.493***	0.680***	0.548***	0.511***
	(0.099)	(0.088)	(0.098)	(0.101)
Dependent Variable Weighted Mean	377	377	377	377
Effect relative to mean, percent	0.131	0.180	0.145	0.135
F-statistic, PM 2.5	3,033.2	2,863.2	2,460.7	2,274.5
State-Month, DOW FE		✓	✓	✓
Weather Controls			✓	✓
Econ Controls				✓
Observations	2,173,632	2,173,632	2,173,632	2,173,632

Note: All specifications include county and year-month fixed effects. Standard errors clustered by county in parentheses. * $p<0.1$, ** $p<0.05$, *** $p<0.01$

Same-Day Mortality by Age Group (Deaths per Million): IV

	65-69 (1)	70-74 (2)	75-79 (3)	80-84 (4)	85+ (5)
PM 2.5	0.052**	0.088***	0.161***	0.197***	0.511***
	(0.023)	(0.028)	(0.037)	(0.045)	(0.101)
Dependent Variable Mean	44	66	105	170	377
Effect relative to mean, percent	0.119	0.133	0.153	0.116	0.135
F-statistic, PM 2.5	2,086.2	2,152.7	2,211.9	2,244.9	2,274.5
Observations	2,173,632	2,173,632	2,173,632	2,173,632	2,173,632

Note: All specifications include county, year-month, state-month and day of week fixed effects, as well as controls for weather, load, and employment. Standard errors clustered by county in parentheses. * $p<0.1$, ** $p<0.05$, *** $p<0.01$

Same-Day Mortality by Age Group: Predicted PM2.5 from Generation

	65-69	70-74	75-79	80-84	85+
	(1)	(2)	(3)	(4)	(5)
Predicted PM2.5	0.088***	0.157***	0.271***	0.362***	1.06***
	(0.016)	(0.021)	(0.031)	(0.041)	(0.092)
Dependent Variable Weighted Mean	46	69	109	177	388
Effect relative to mean, percent	0.191	0.227	0.249	0.204	0.274
Observations	17,015,969	17,015,969	17,015,969	17,015,969	17,015,969

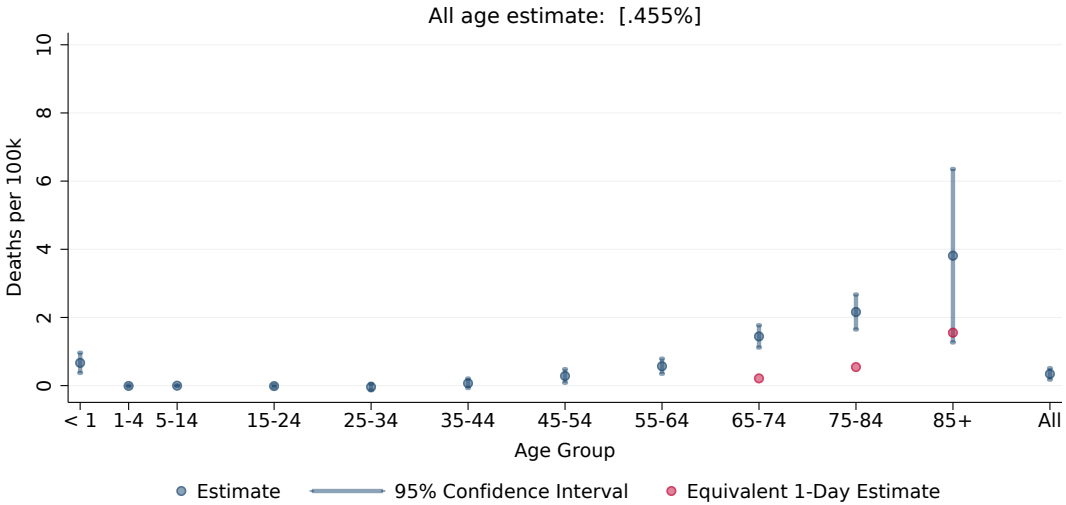
Note: All specifications include county, year-month, state-month and day of week fixed effects, as well as controls for weather, load, and employment. Standard errors clustered by county in parentheses. * $p<0.1$, ** $p<0.05$, *** $p<0.01$

Cumulative Mortality Impacts

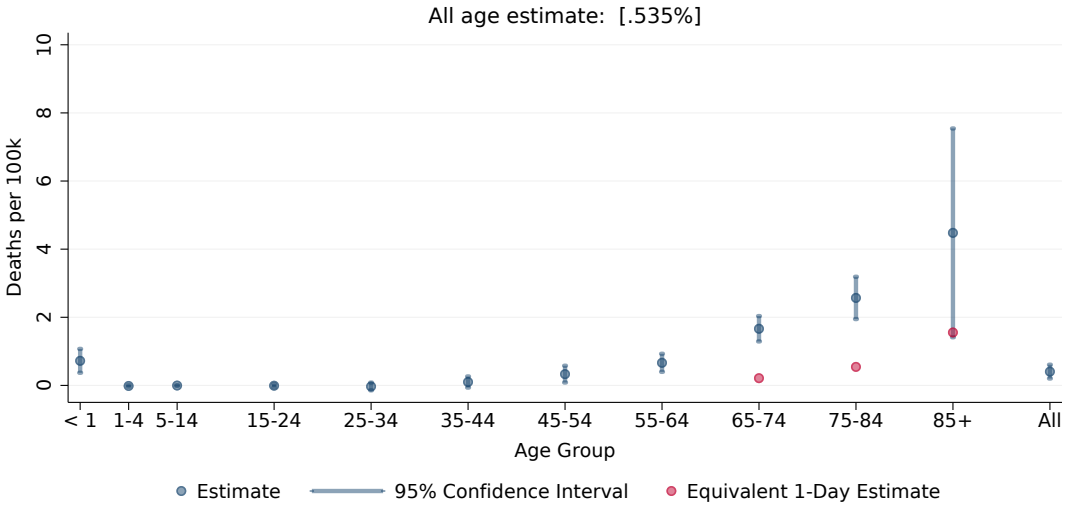
$$y_{it} = \sum_d P_{i,t-d}\tau_d + \mathbf{X}_{it}\beta + \phi_i + \lambda_{ym} + \eta_{sm} + u_{it}$$

- τ_d: "How will $P_{i,t}$ affect $y_{i,t+d}$?"
- Same-day mortality estimate $\neq$ impact of 1 day of exposure.
  - Autocorrelation: 0.65 for $t-1$, 0.4 for $t-2$, etc.
  - Omitted Variables Bias: narrow horizon, differing lagged controls.
- Longer horizon impacts may be $\gtrless$ than short term.
  - Delayed impacts.
  - Mortality displacement.

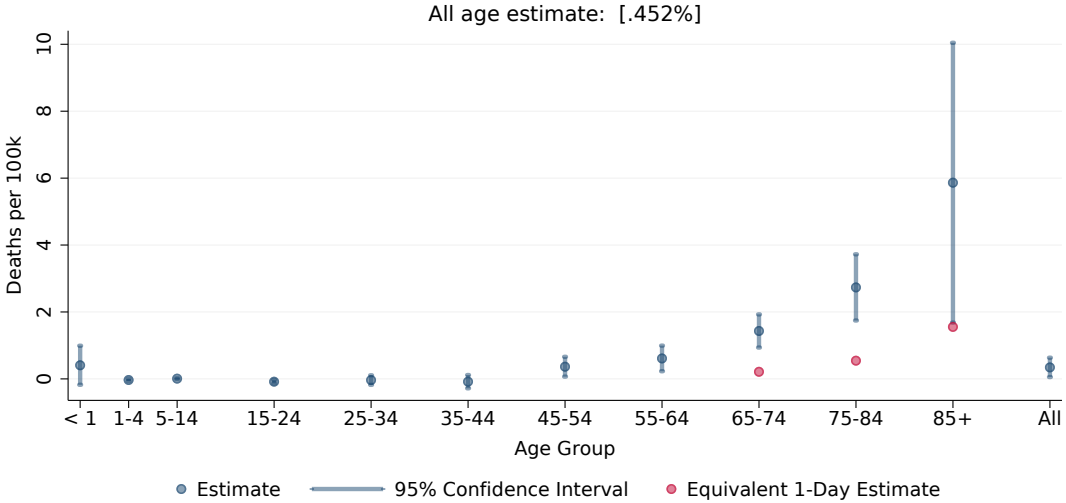
Contemporaneous Mortality: 1 Month of Exposure to 1 μg/m^3



Cumulative Mortality from 1 Month of Exposure to 1 μg/m^3: 3 Months



Cumulative Mortality from Exposure to 1 Month of 1 $\mu g/m^3$: 5 Years



Calculation of Mortality & Costs

- Predicted Deaths in county i on day t:

$$\sum_g \hat{PM}_{it} \cdot \hat{\tau}_g \cdot \text{population}_{itg}$$

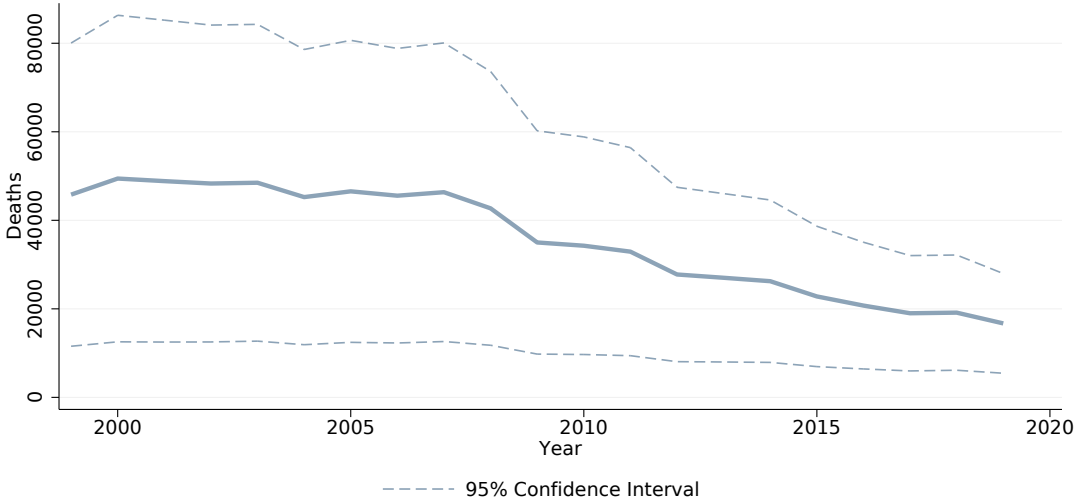
- Life-years lost:

$$\sum_g \hat{PM}_{it} \cdot \hat{\tau}_g \cdot \text{population}_{itg} \cdot \underbrace{\text{Expected Remaining Years}_{sg}}_{\sim 10 \text{ years}}$$

- Value of Life-years lost: ($100k/year)

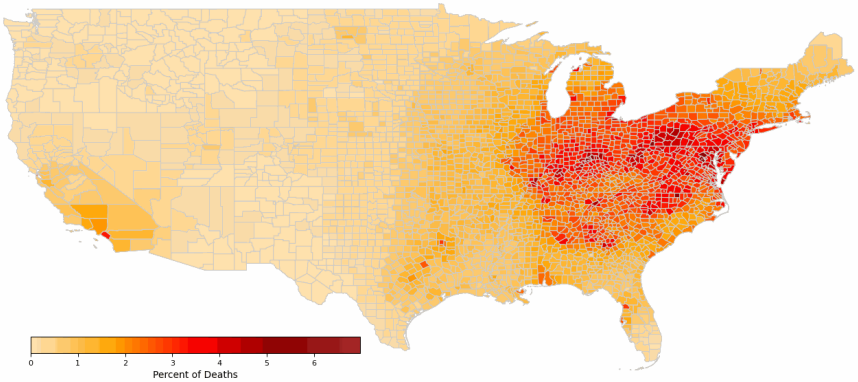
$$\sum_g \hat{PM}_{it} \cdot \hat{\tau}_g \cdot \text{population}_{itg} \cdot \text{Expected Remaining Years}_{sg} \cdot \underbrace{VSLY}_{\$100k/year}$$

Aggregate Mortality from Power Generation by Year



Percent of Total Mortality due to Generation-PM2.5

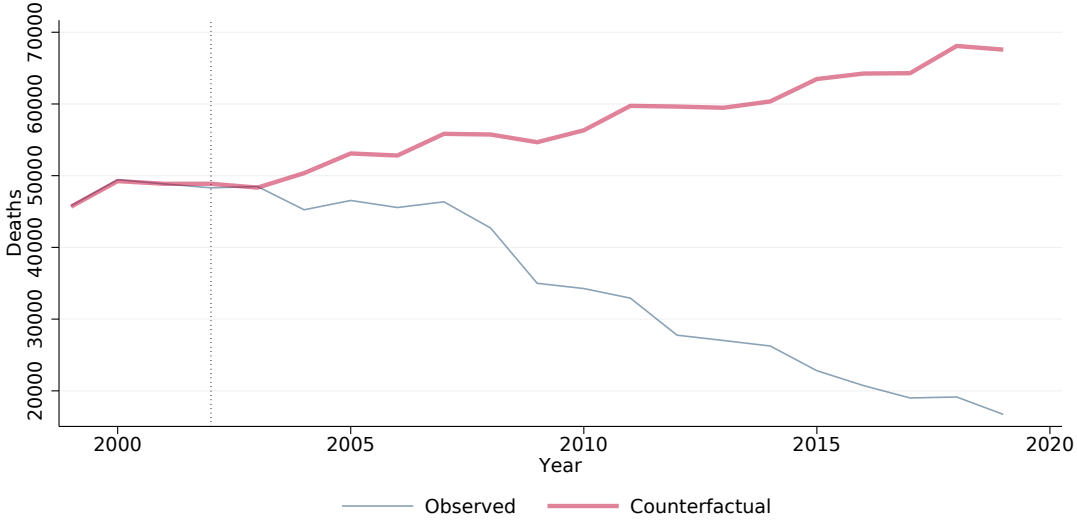
1999



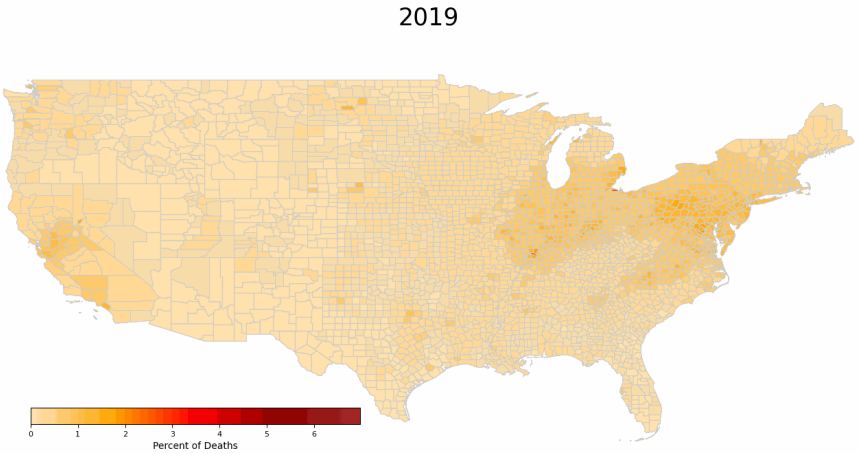
Counterfactual: Holding the Grid Fixed in 2003

- Train separate random forests by power control area: 1999-2002.
  - Hourly unit-level data on generation, load, marginal costs.
- Test models on 2003 data.
- Apply observed loads in 2004-2019 to 2003 grid.
- Estimate counterfactual dispatch using 1999-2002 rules.
- Use HYSPLIT to simulate pollution of counterfactual generation.

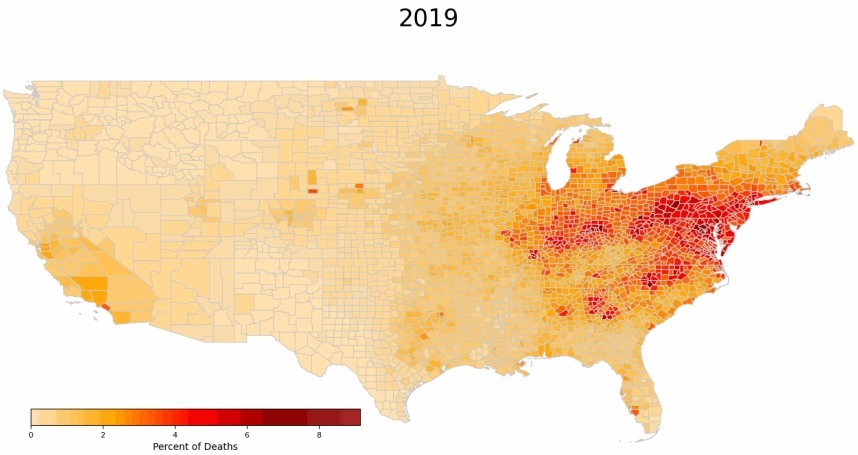
Aggregate Mortality: Observed versus Counterfactual



Percent of Mortality due to Generation-PM2.5: Observed



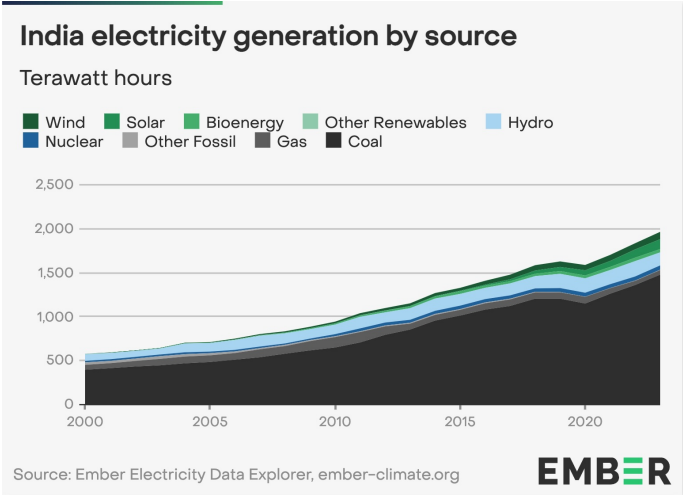
Percent of Mortality due to Generation-PM2.5: Counterfactual



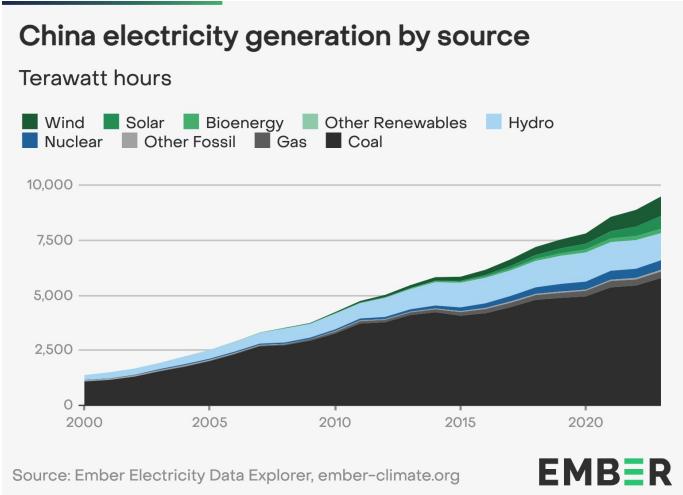
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Generation from Coal is Still Growing



Generation from Coal is Still Growing



Generation from Coal is Making a Comeback?

Bitcoin Miners Are Giving New Life to Old Fossil-Fuel Power Plants

The lofty prices of cryptocurrencies have investors sinking money into electricity generation, risking a backlash

By *Brian Spegele* Follow and *Caitlin Ostroff* Follow

May 21, 2021 7:00 am ET

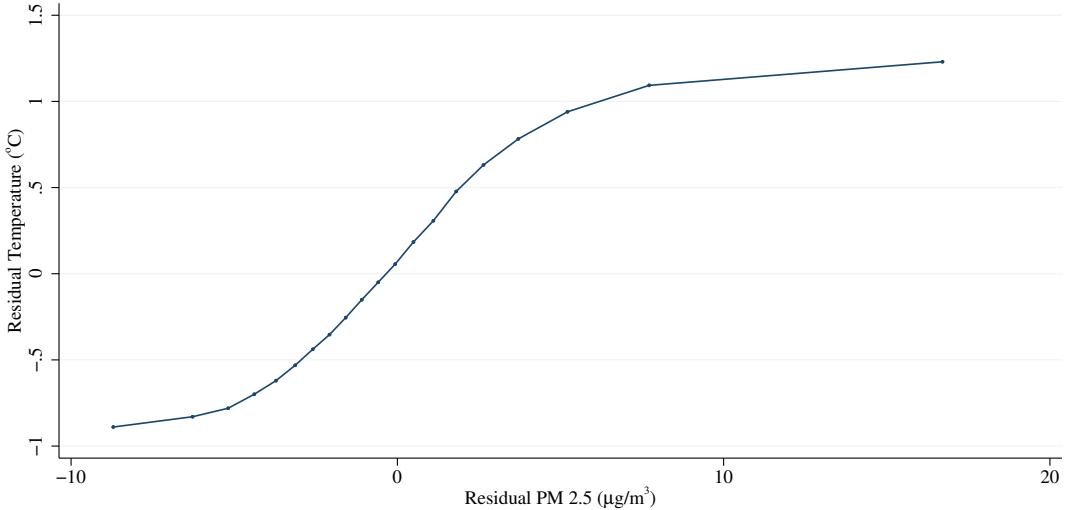
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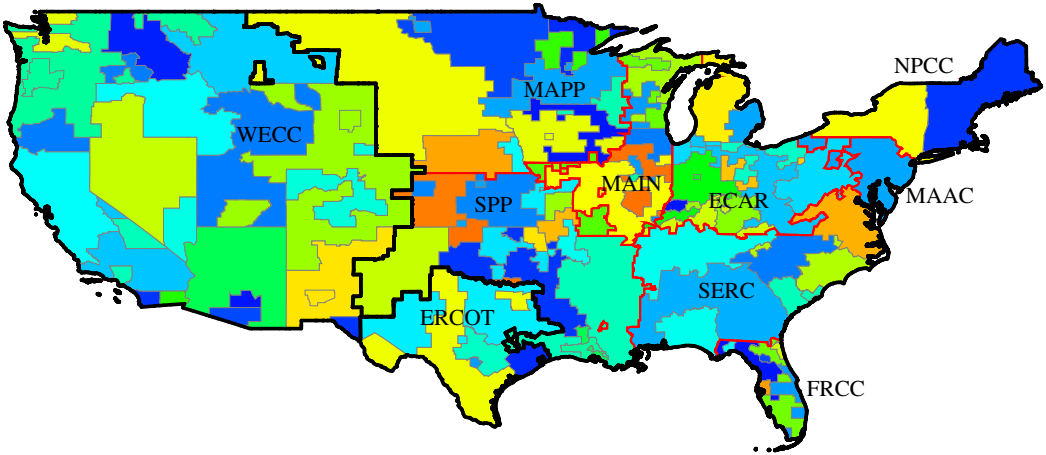
Conclusion

- First fully-integrated, credible, estimates of grid's impact on mortality.
- Next Steps:
  - Include multiple pollutants.
  - Reduced forms.
  - Cause of death and plant-level heterogeneity.
  - Retirement event studies.
  - Alternative counterfactuals (i.e. targeting).

Omitted Variables Bias from Temperature: Residual Binscatter



U.S. Power Control Areas in 1999



Comparison of Estimates

- Henneman et al. (2023): 1.12% for 1 year of exposure to 1 μg/m^3 for seniors.
  - Initial levels match, but only look at SO2, so falls too quickly. Coarser dispersion.
- Dominici et al. (2007): 0.20% for 1 day of exposure to 1 μg/m^3.
- Lepeule et al. (2012) (6 Cities): 1.4% for 1 year of exposure to 1 μg/m^3.
- Deryugina et al. (2019): 0.18% for 1 day of exposure to 1 μg/m^3 for seniors.