The Economics of the Global Energy Challenge

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Climate Change has Arrived

Extreme Heat

Climate Change has Arrived

Extreme Heat

More Powerful Storms

Climate Change has Arrived

Extreme Heat

More Powerful Storms

More Frequent Wildfires

The Global Energy Challenge

A Better Way to Think About This Challenge

The real problem is the **Global Energy Challenge**.

To exclusively focus on climate change misses that when choosing our energy sources, we are choosing:

- Energy prices
- Air pollution
- Climate change

−→ All three things affect human well-being, not just climate change.

−→ No single energy choice is the cheapest, is the least polluting, and contributes the least to climate change...

... and this defines what is perhaps the challenge of the century, the **Global Energy Challenge.**

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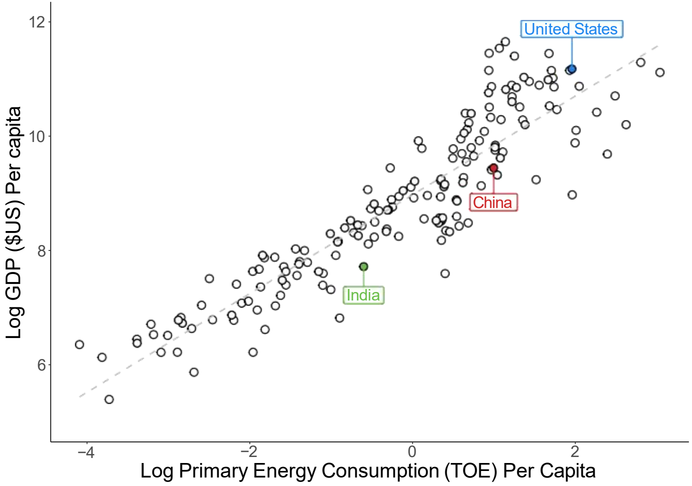
I. Seven Facts that Define the Global Energy Challenge

II. Actions to Address the Global Energy Challenge

III. Conclusion

Fact 1: Energy Consumption is Critical for Living Standards

Primary Energy Consumption and GDP (2021)



- There is no economic growth without energy.
- Continued growth in energy demand is critical for improving quality of life in emerging economies.

EIA (2024), World Bank (2024)

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   1. Energy Consumption is Critical for Living Standards
   2. Energy Consumption is Low in Many Highly Populated Areas
   3. Energy Consumption in Emerging Countries is Projected to Grow
   4. Fossil Fuels Are Expected to Remain the Dominant Source of Energy
   5. Fossil Fuels Increase Air Pollution Which Shortens Lives
   6. Impacts of Climate Change are Large and Unequal
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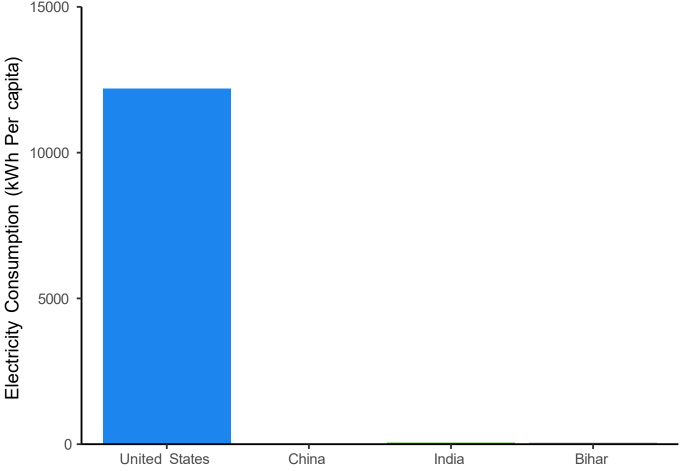
Fact 2: Energy Consumption is Low in Many Highly Populated Areas



- Nearly 750 million people globally lack access to reliable electricity (IEA 2023).
- Bihar had per capita electricity consumption of 350 kWh in 2023.
- It takes 131 kWh to use a 60-watt light bulb for 6 hrs/day for a year.

EIA (2023), India Climate & Energy Dashboard (2023)

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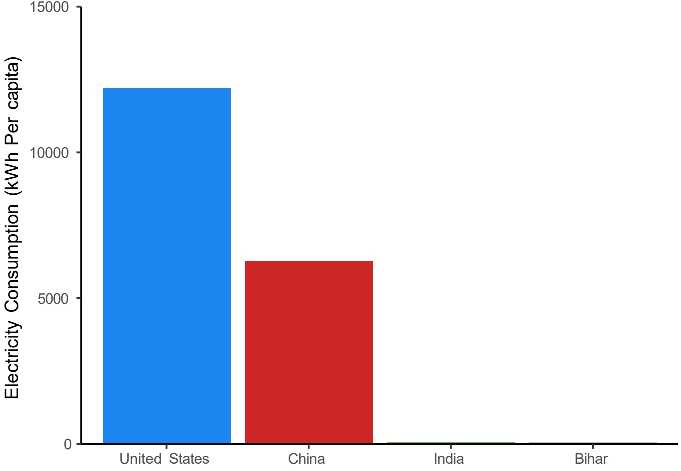

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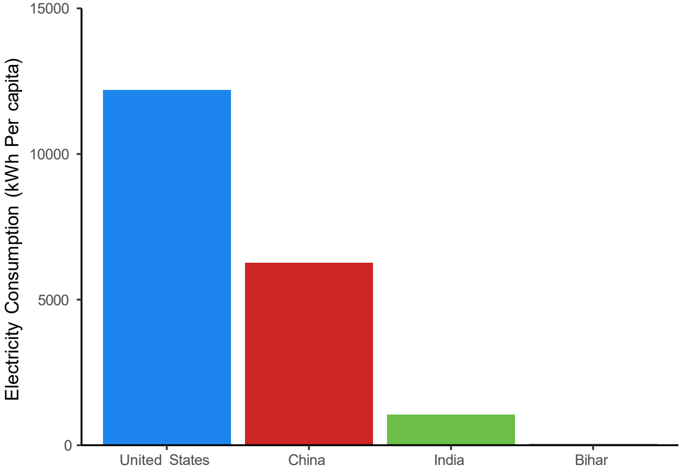

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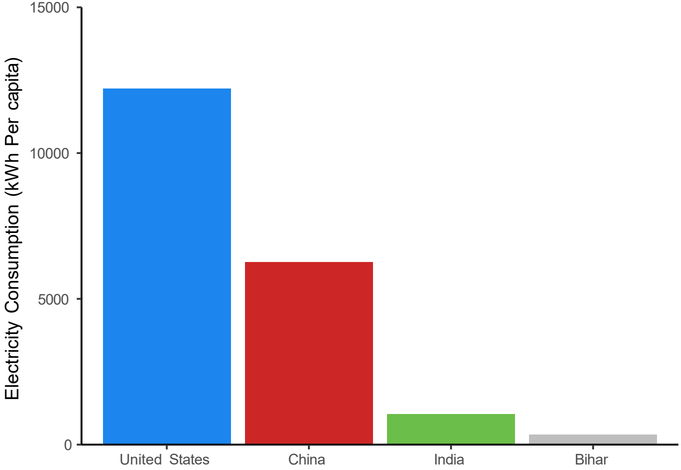

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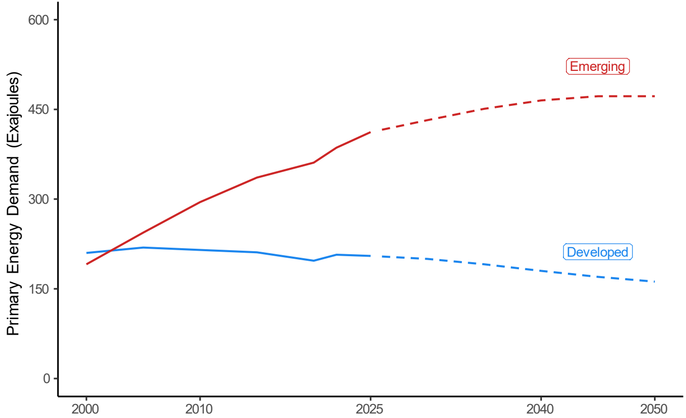


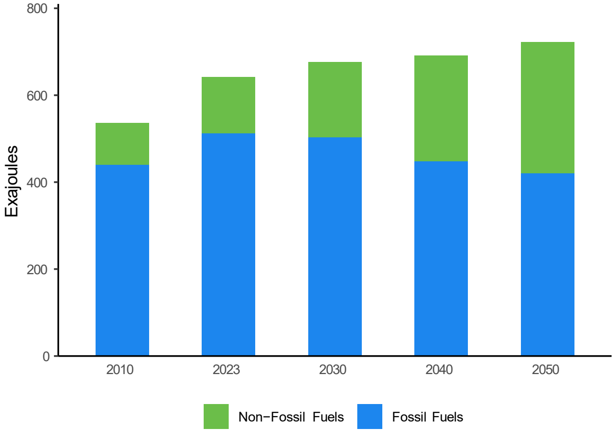
BP Energy Outlook (2024) Current Trajectory Scenario

- Global energy demand is set to grow 15% by 2050.
- 100% of expected growth will occur in emerging markets (esp. Asia).

Fossil Fuels Will Meet Much of This Growth

Fact 4: Fossil Fuels Are Expected to Remain the Dominant Source of Energy

Fossil Fuel Historical and Projected Energy Supply



- 2023 Fossil Share: 80%
- 2050 Fossil Share: 58%

IEA World Energy Outlook (2024) Stated Policies Scenario

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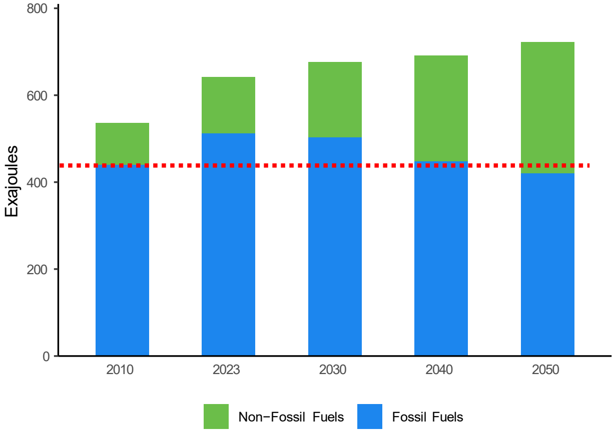

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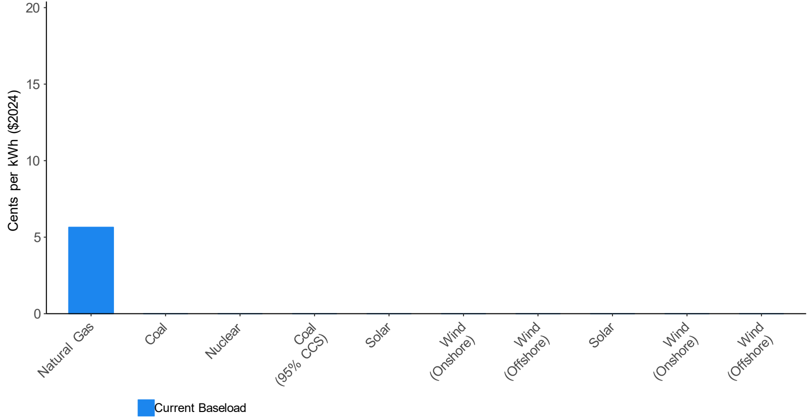
Fossil Fuels Are Inexpensive in the Power Sector

Fact 4: [Fossil Fuels Are Expected to Remain the Dominant Source of Energy]

Levelized Cost of Energy, United States



EIA AEO (2025) inputs, EPIC calculation

- Coal is 46% more expensive than natural gas. Nuclear, 96% more.
- Renewables with NGCT backups, almost 50% more expensive.
- Renewables with battery backups, >100% more expensive.

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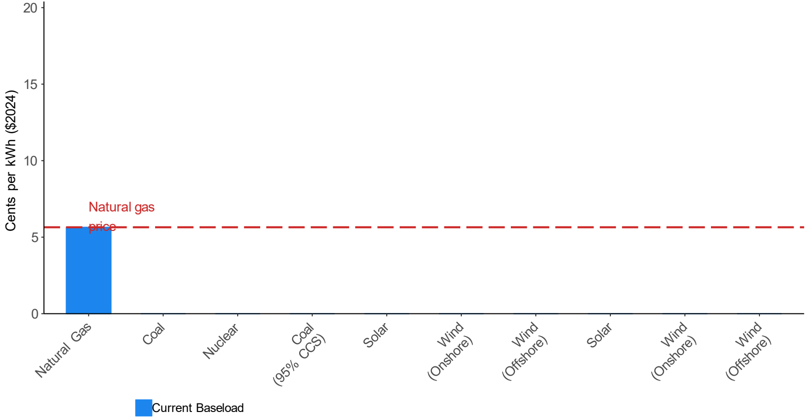

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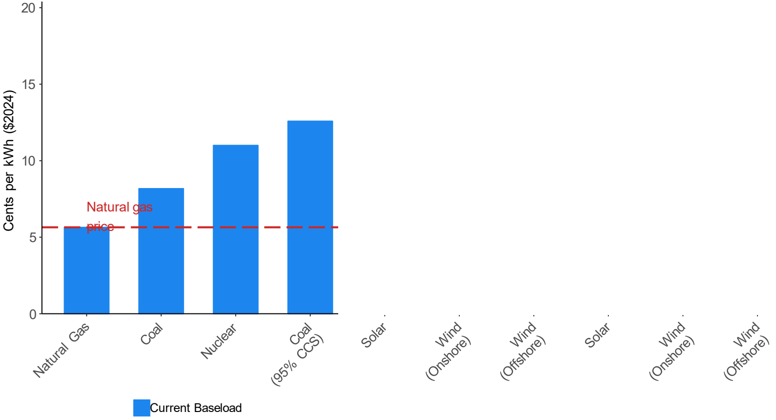

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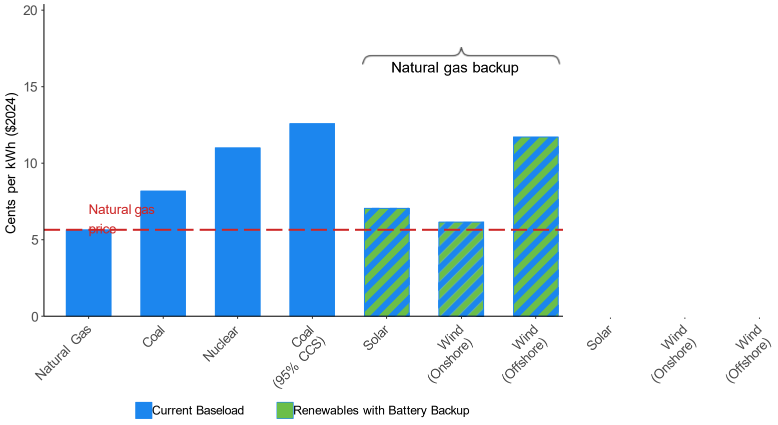

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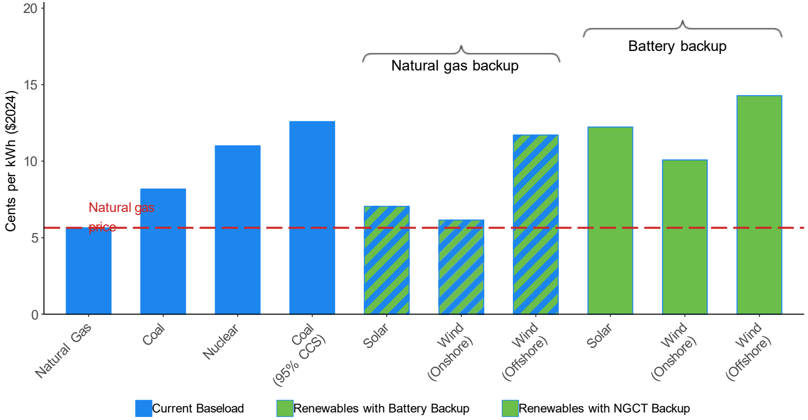

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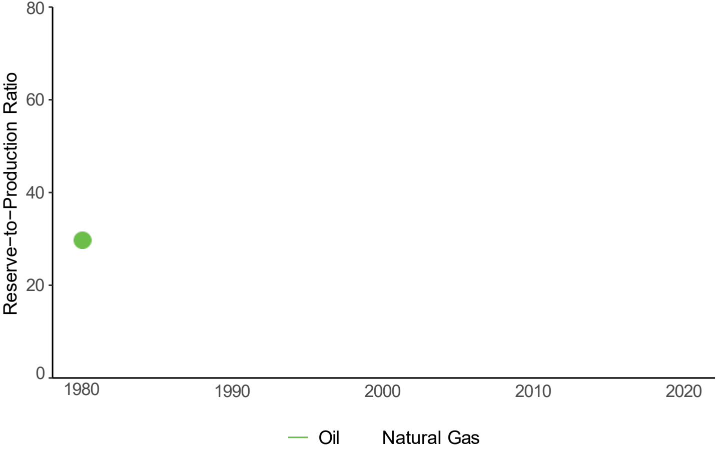
Fossil Fuels Remain Abundant

Fact 4: **Fossil Fuels Are Expected to Remain the Dominant Source of Energy**

Fossil Fuel Reserves-to-Production Ratio



- Oil reserves have grown significantly over the past 30 years.
- Natural gas reserves have roughly equaled production.

Energy Institute (2025)

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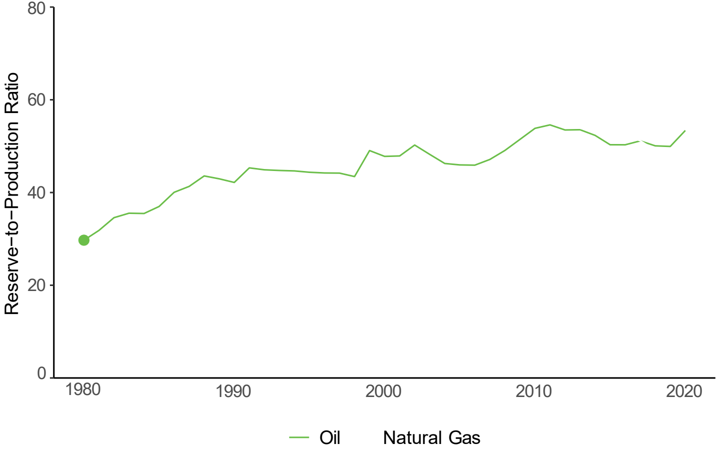

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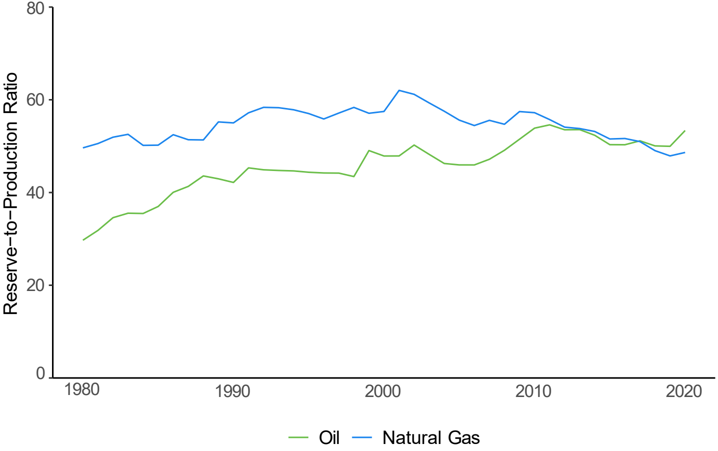

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5.9 billion people currently live in areas that exceed the 2020 WHO safe guideline for small particulate pollution
Population Living in Areas Exceeding WHO Limit (millions)
China 1382
India 1297
Indonesia 244
Pakistan 208
Bangladesh 160
Nigeria 140
Japan 113
Russia 106
Ethiopia 103
US 36
Chile 12

China's Huai River Heating Policy

Fact 5: Fossil Fuels Increase Air Pollution Which Shortens Lives

PNAS

New evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River Policy

Avraham Ebenstein[a,1], Maoyong Fan[b,1], Michael Greenstone[c,d,1,2], Guojun He[e,f,g,1], and Maigeng Zhou[h,1]

[a]Department of Environmental Economics and Management, Hebrew University of Jerusalem, Rehovot 76100, Israel; [b]Department of Economics, Ball State University, Muncie, IN 47304; [c]Department of Economics, University of Chicago, Chicago, IL 60637; [d]National Bureau of Economic Research, Cambridge, MA 02138; [e]Division of Social Science, The Hong Kong University of Science and Technology, Hong Kong; [f]Division of Environment and Sustainability, The Hong Kong University of Science and Technology, Hong Kong; [g]Department of Economics, The Hong Kong University of Science and Technology, Hong Kong; and [h]National Center for Chronic and Non-Communicable Disease Control and Prevention, Chinese Center for Disease Control and Prevention, Beijing 100050, China

Ebenstein et al. (2017)

China's Huai River Winter Heating Policy

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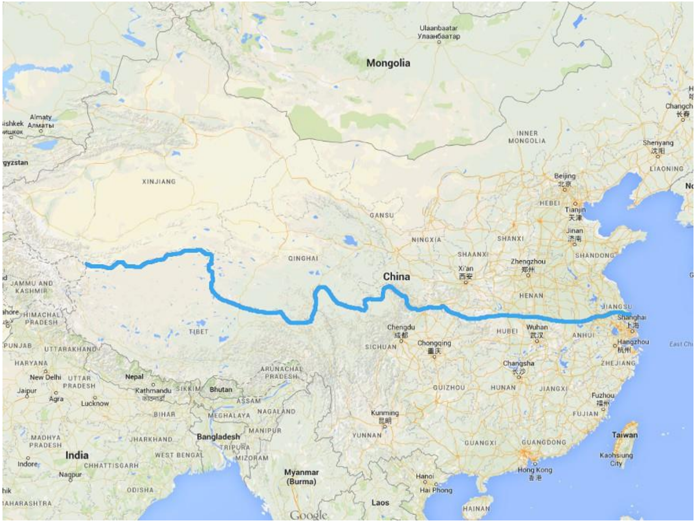

- Municipal coal boilers built in the planning period (1950-80) for subsidized heating, but only in cities north of Huai River-Qinling Mountains line.

The Boiler Heating System

Fact 5: Fossil Fuels Increase Air Pollution Which Shortens Lives

- Subsidized coal is burned to heat water.
- The combusted coal emits high levels of soot and particulate matter.

Pollution is 40% Higher North of the River

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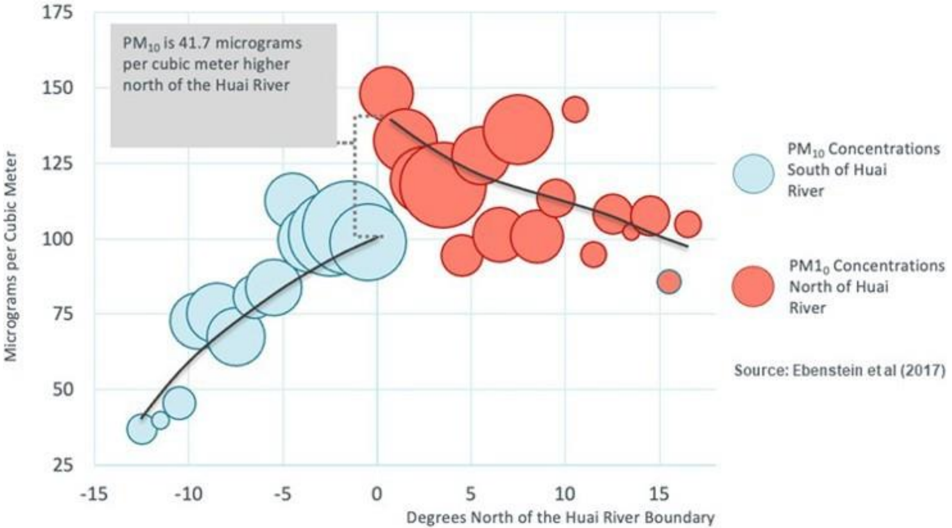

Life Expectancy is about 3 Years Lower North of the River

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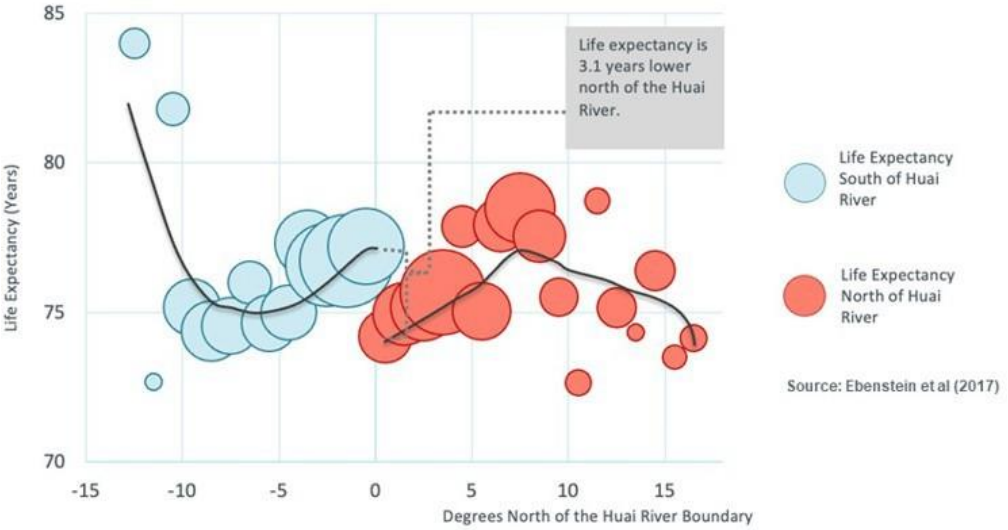

Estimating Decrease in Life Expectancy: AQLI

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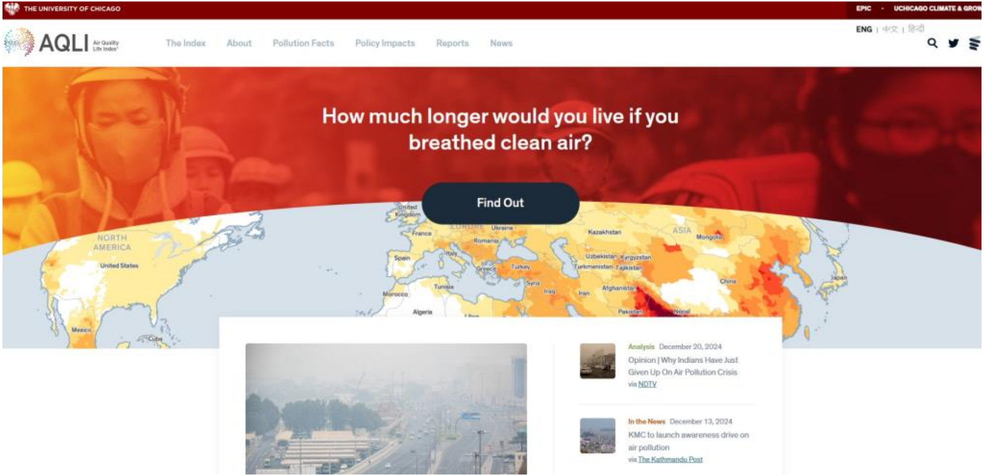

https://aqli.epic.uchicago.edu/

PM Level is Unequal

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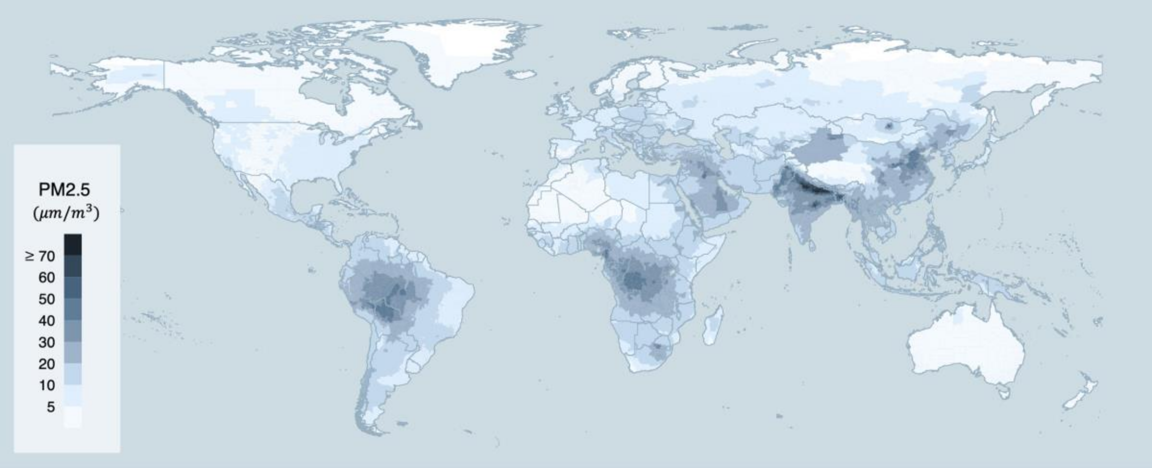

Air Quality Life Index (2024)

PM is Largest External Threat to Global Health

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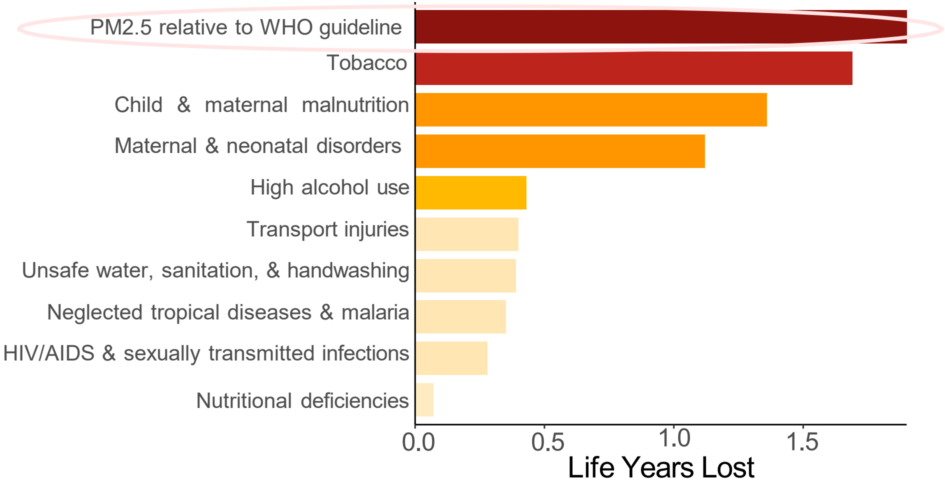

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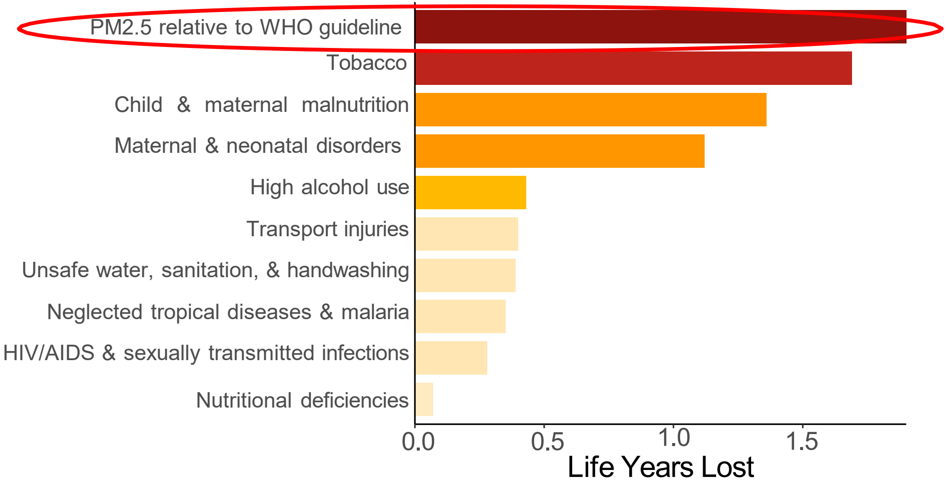

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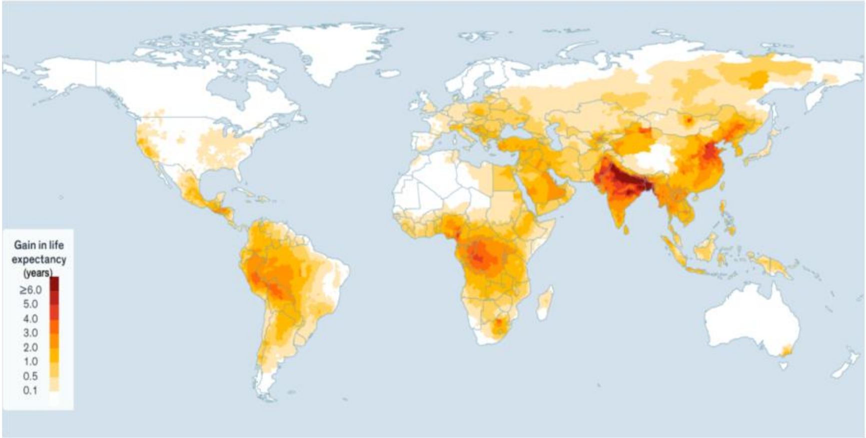

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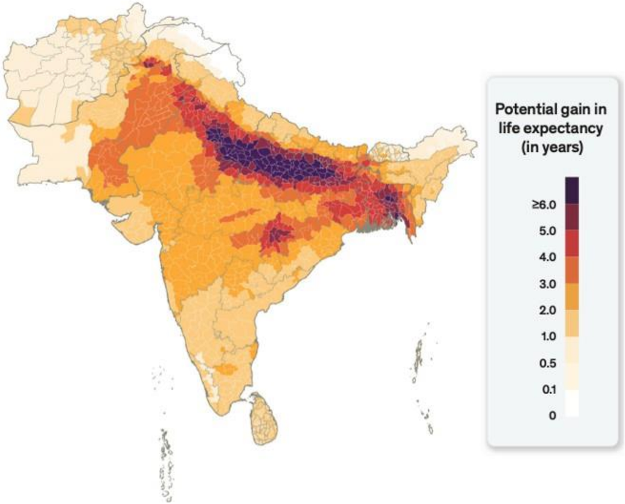

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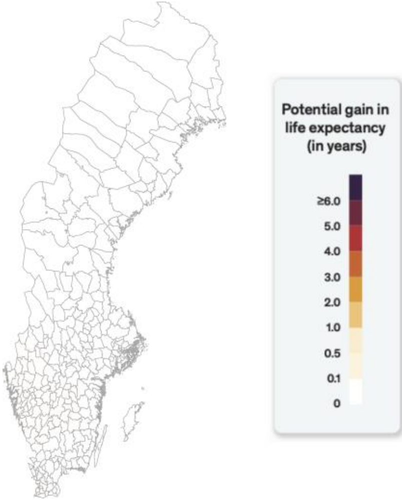

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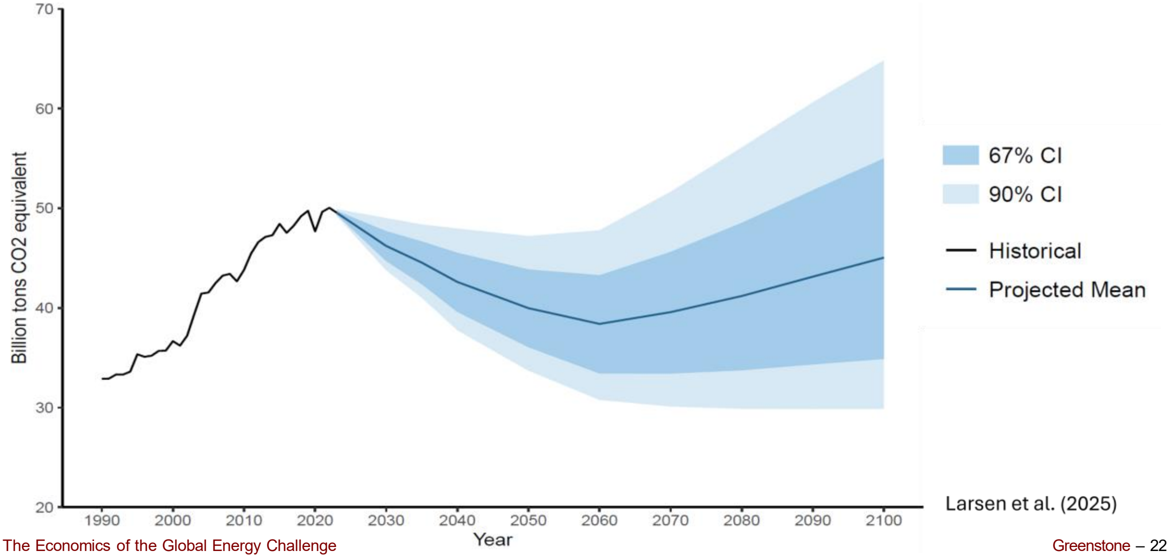
Global Emissions Path

Fact 6: Impacts of Climate Change are Large and Unequal



Global Warming Path

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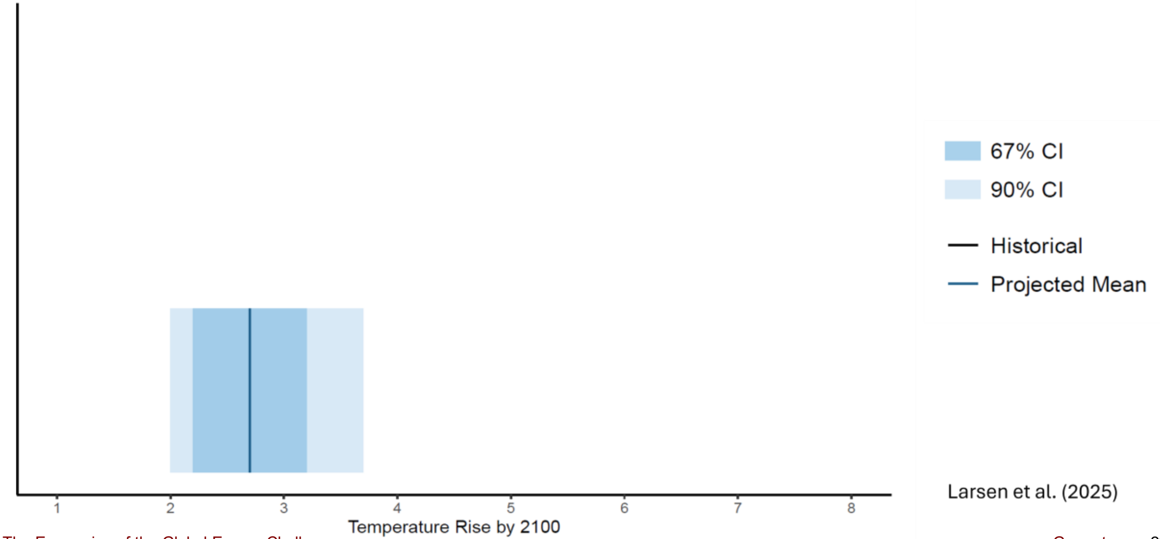

Larsen et al. (2025)

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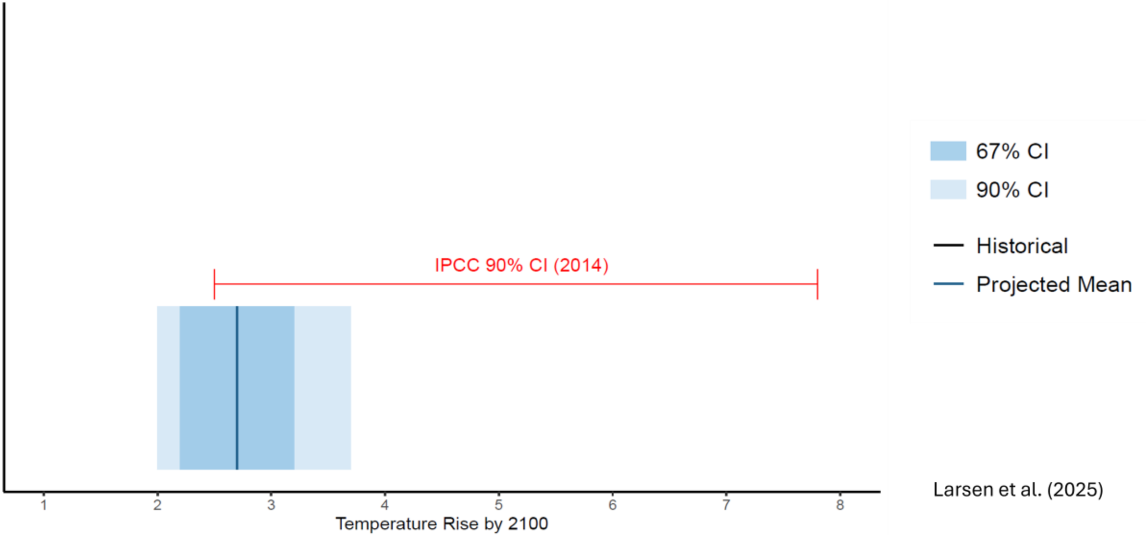

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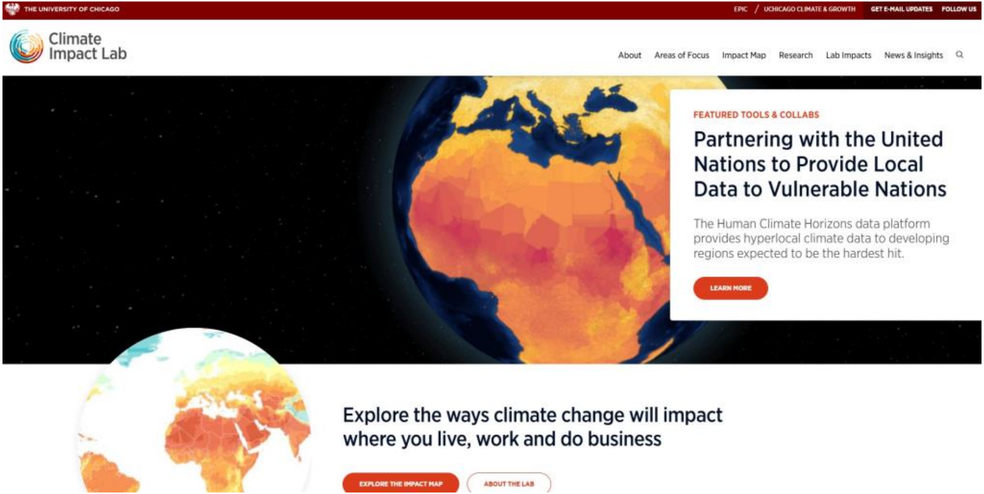
Estimating Climate Damages: Climate Impact Lab



https://impactlab.org/

Social Cost of Carbon

- The Social Cost of Carbon (SCC) measures the present value of total global future damages from releasing a single ton of CO_2 today.

- The location of the emission does not matter as CO_2 is well-mixed in the atmosphere.

→ The global SCC masks the underlying differences in local damages across locations and over time.

Estimating Climate Damages Across Sectors

Climate Impact Lab

DAMAGE FUNCTIONS

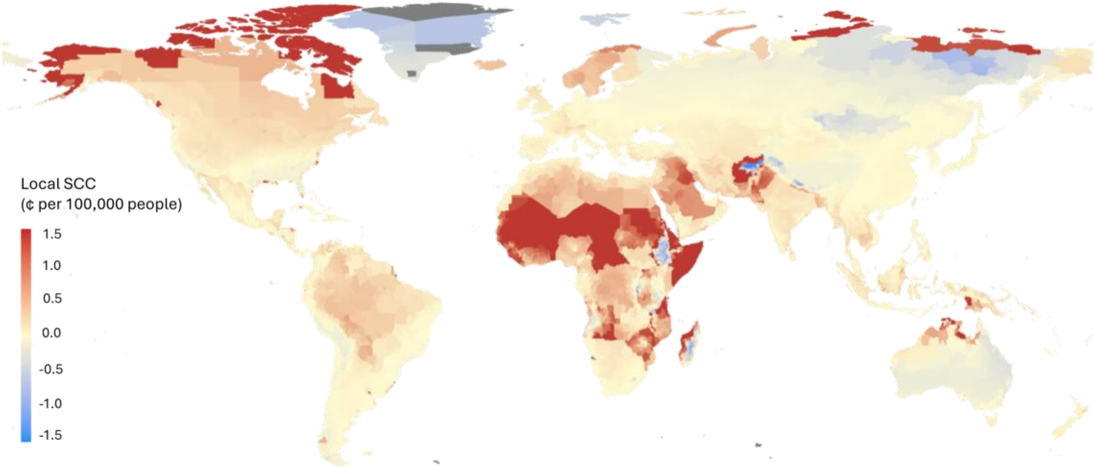
Climate Impact Lab current coverage

- ☑ **Mortality** — heat and cold deaths
  - All cause mortality (<5)
  - All cause mortality (>64)
  - All cause mortality (5-64)
- ☑ **Agriculture** — crop yields
  - Maize
  - Wheat
  - Rice
  - Soybean
  - Sorghum
  - Cassava
- ☑ **Energy** — energy and electricity demand
  - Electricity consumption
  - Other fuels consumption
- ☑ **Labor** — labor supply effects
  - High risk labor
  - Low risk labor
- ☑ **Coastal** — sea level rise and storm damages
  - Sea level rise inundation
  - [Tropical cyclone damage]

The Distribution of Damages is Highly Unequal

Fact 6: [Impacts of Climate Change are Large and Unequal]

Global and Local Social Cost of Carbon (SCC) across 25,000 regions



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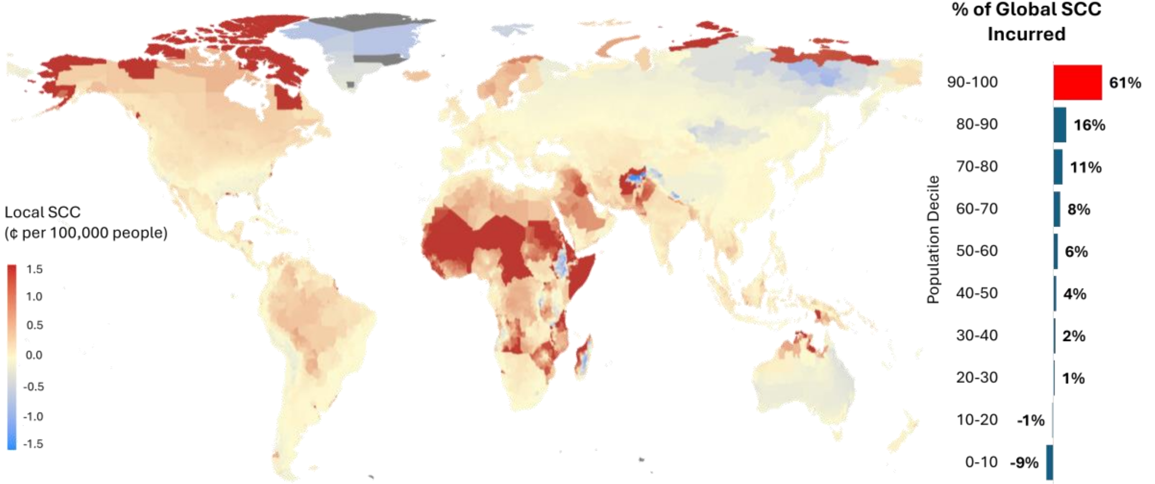

Climate Change Damages caused by Current Annual CO_2 Emissions

Fact 6: Impacts of Climate Change are Large and Unequal

Country	Social Cost of Carbon	Emissions in 2022	Total Damage to		Damages caused minus incurred
			World	Non-OECD	
	(1)	(2)	(3a)	(3b)	(4)
World	190				
Non-OECD (LMIC)	182				
Non-OECD (High Income)	2				
OECD	6				

Climate Change Damages caused by Current Annual CO_2 Emissions

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Country	Social Cost of Carbon (1)	Emissions in 2022 (2)	Total Damage to		Damages caused minus incurred (4)
			World (3a)	Non-OECD (3b)	
World	190	50.1	9,530	9,221	
Non-OECD (LMIC)	182				
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Climate Change Damages caused by Current Annual CO_2 Emissions

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World	190	50.1	9,530	9,221	
Non-OECD (LMIC)	182	33.8	6,429	6,221	
Non-OECD (High Income)	2	1.9	363	351	
OECD	6	14.4	2,737	2,649	

Climate Change Damages caused by Current Annual CO_2 Emissions

Fact 6: Impacts of Climate Change are Large and Unequal

Country	Social Cost of Carbon (1)	Emissions in 2022 (2)	Total Damage to World (3a)	Total Damage to Non-OECD (3b)	Damages caused minus incurred (4)
World	190	50.1	9,530	9,221	0
Non-OECD (LMIC)	182	33.8	6,429	6,221	-2,698
Non-OECD (High Income)	2	1.9	363	351	270
OECD	6	14.4	2,737	2,649	2,429

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Climate Change Damages caused by Current Annual CO_2 Emissions

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Estimated Climate Damages for Selected Countries

Country	Social Cost of Carbon	Emissions in 2022	Total Damage to		Damages caused minus incurred
			World	Non-OECD	
	(1)	(2)	(3a)	(3b)	(4)
Africa	100.57	4.50	855	827	-4,183
China	3.29	12.93	2,459	2,379	2,294
India	22.08	3.78	718	695	-388
U.S. + E.U. + U.K.	3.67	9.68	1,841	1,781	1,656
Sweden	0.47	0.04	7	7	-17

Cities with Largest Damages

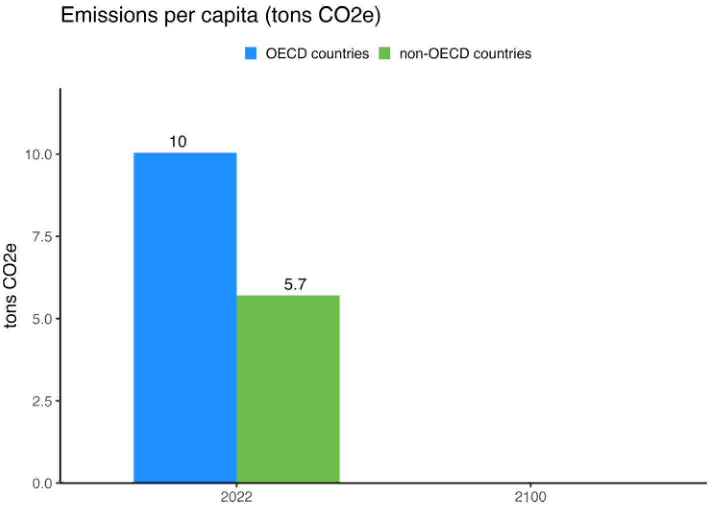
I. Seven Facts that Define the Global Energy Challenge
   1. Energy Consumption is Critical for Living Standards
   2. Energy Consumption is Low in Many Highly Populated Areas
   3. Energy Consumption in Emerging Countries is Projected to Grow
   4. Fossil Fuels Are Expected to Remain the Dominant Source of Energy
   5. Fossil Fuels Increase Air Pollution Which Shortens Lives
   6. Impacts of Climate Change are Large and Unequal
   7. The Cruel Arithmetic of the Global Energy Challenge

II. Actions to Address the Global Energy Challenge

III. Conclusion

The Politically Challenging GHG Accounting

Fact 7: The Cruel Arithmetic of the Global Energy Challenge



Larsen et al. (2025)

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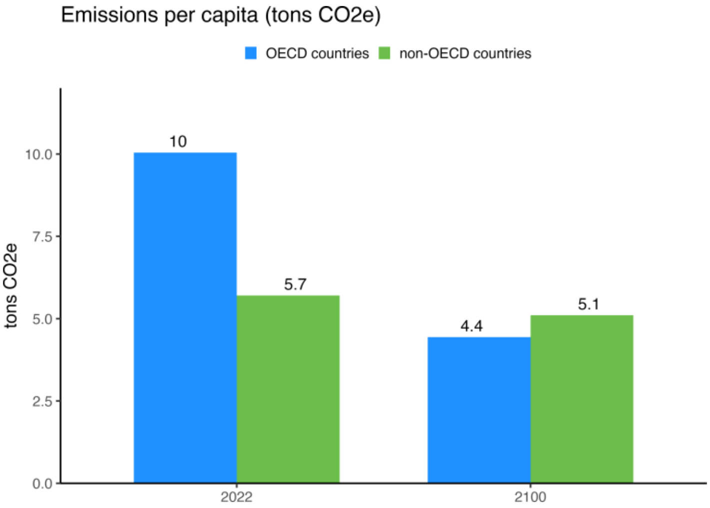

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The Cruel Climate Arithmetic

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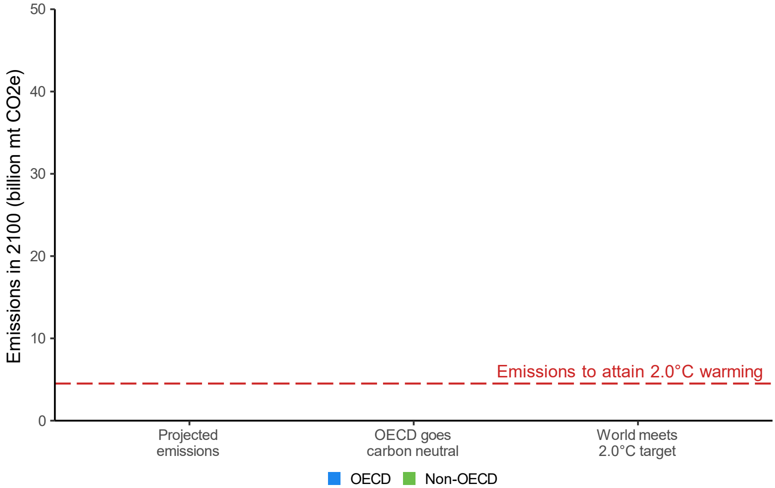

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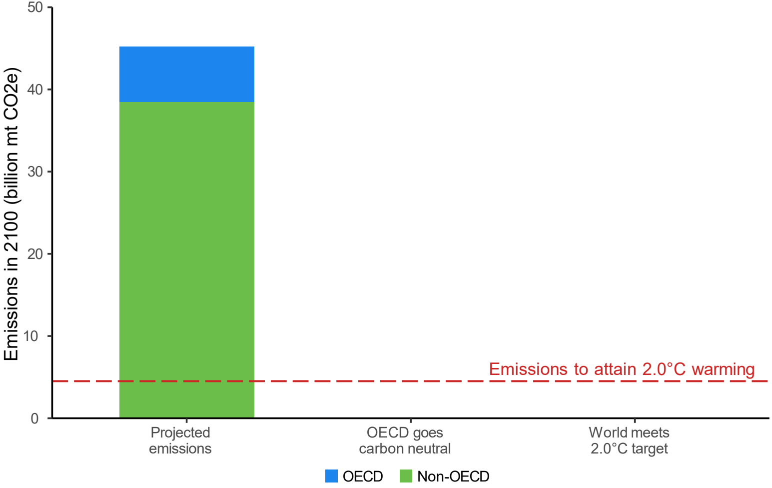

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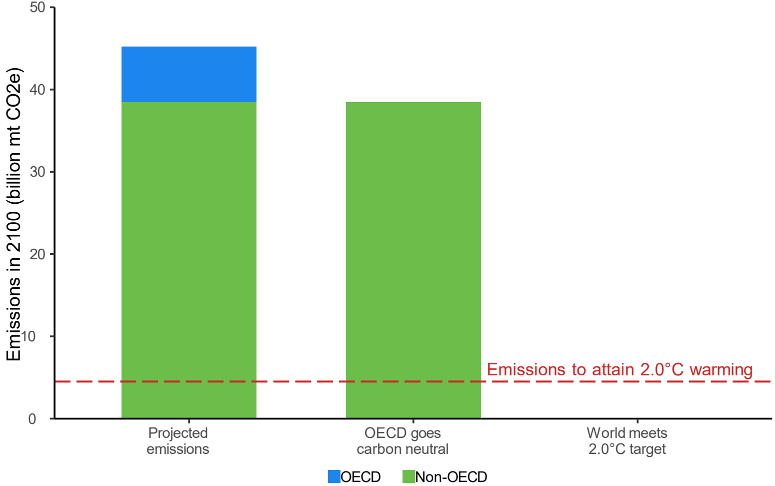

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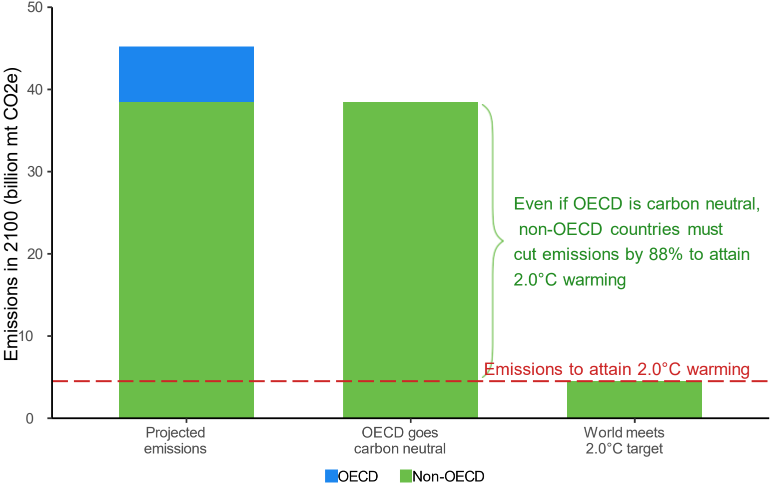

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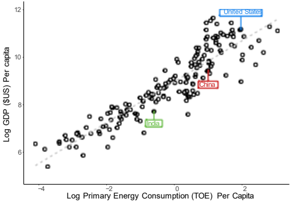
Summarizing the 3 Prongs of the Challenge

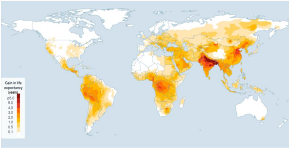
Global Energy Challenge

Energy Accesibility



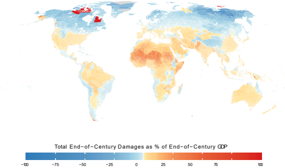
Needed for Growth
& Quality of Life

Air Pollution



Causes Loss of
Life Expectancy

Climate Change



Causes Global
Climate Damages

The Global Energy Challenge Across 3 Cities

	Oslo
Population (millions)	0.7
GDP pc (2022$)	117,200
Energy Use (kWh p.c.)	12,000
Potential Life Gain from PM ↓	0.1
2099 Damages from 3°C Warming (% 2099 GDP)	-9%

The Global Energy Challenge Across 3 Cities

	Oslo	Beijing
Population (millions)	0.7	21.5
GDP pc (2022$)	117,200	27,500
Energy Use (kWh p.c.)	12,000	5,720
Potential Life Gain from PM ↓	0.1	2.9
2099 Damages from 3°C Warming (% 2099 GDP)	-9%	2%

The Global Energy Challenge Across 3 Cities

	 Oslo	 Beijing	 Lahore
Population (millions)	0.7	21.5	12.5
GDP pc (2022$)	117,200	27,500	4,100
Energy Use (kWh p.c.)	12,000	5,720	590
Potential Life Gain from PM ↓	0.1	2.9	5.3
2099 Damages from 3°C Warming (% 2099 GDP)	-9%	2%	14%

I. Seven Facts that Define the Global Energy Challenge

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1. Energy Pricing
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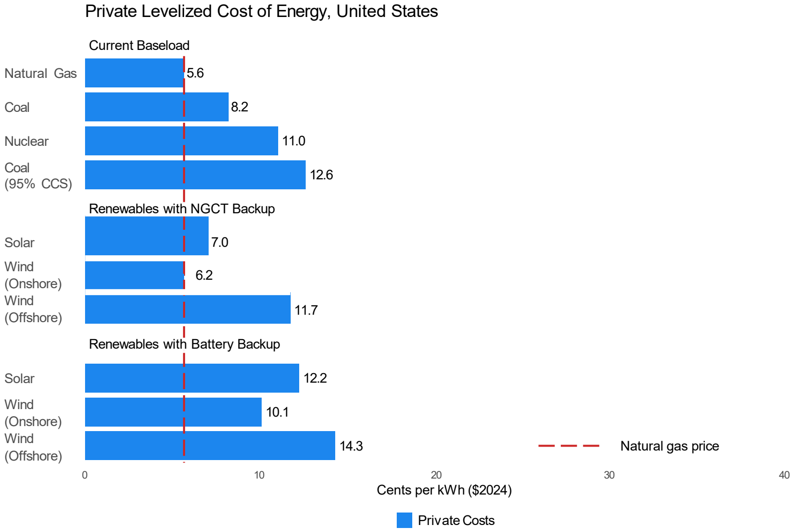
Price Energy to Reflect Social Costs



- Private costs heavily favor conventional fossil generation.
- Pricing carbon at $234 per ton would upend the electricity market.

Based on EIA AEO (2025), Hernandez-Cortes et al. (2023), NREL (2021)

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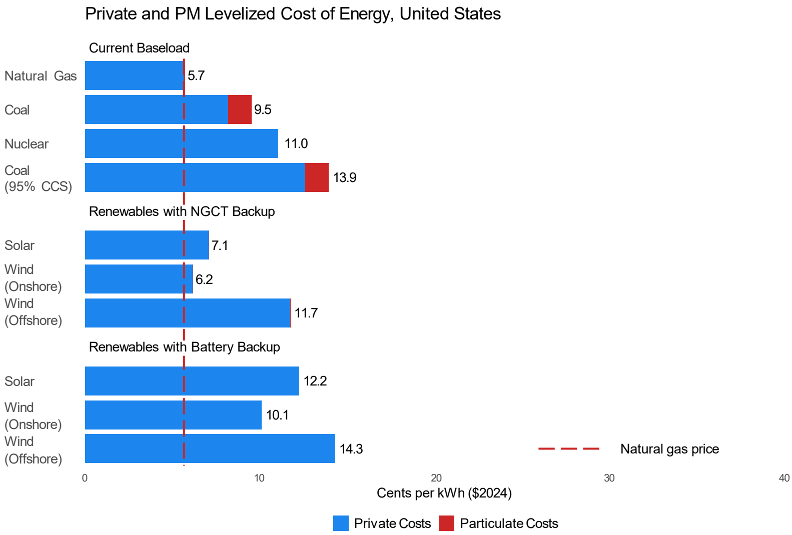

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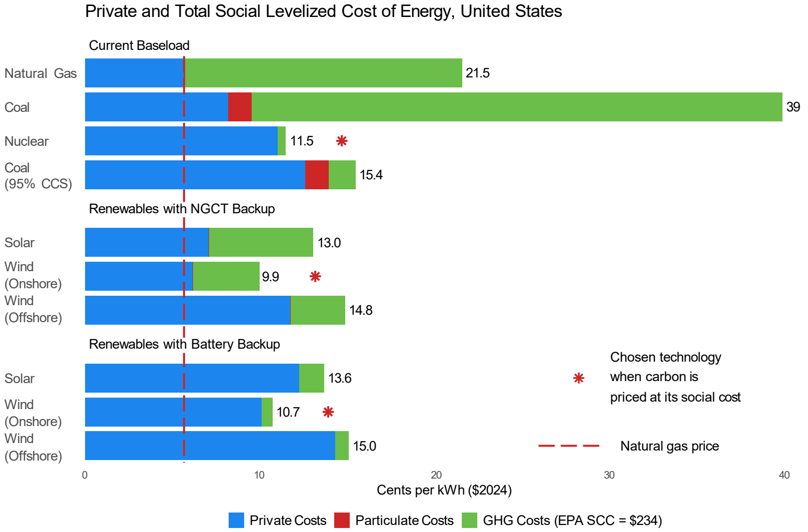

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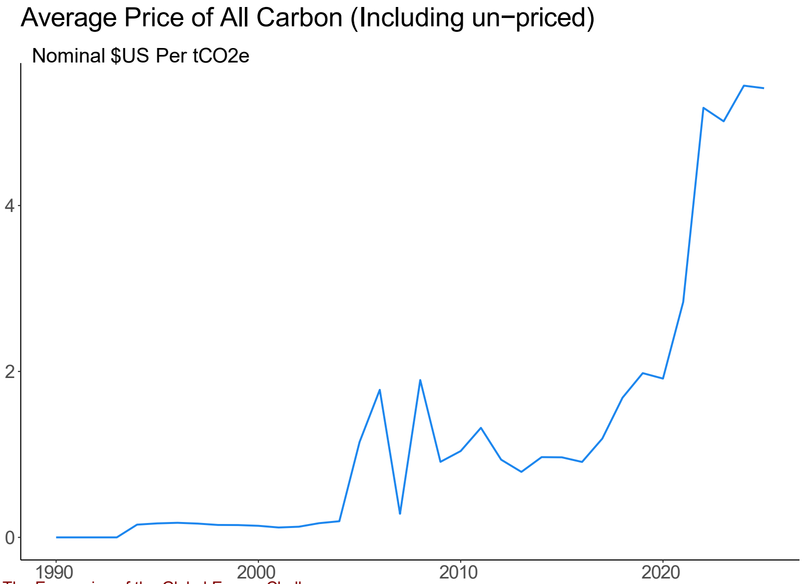
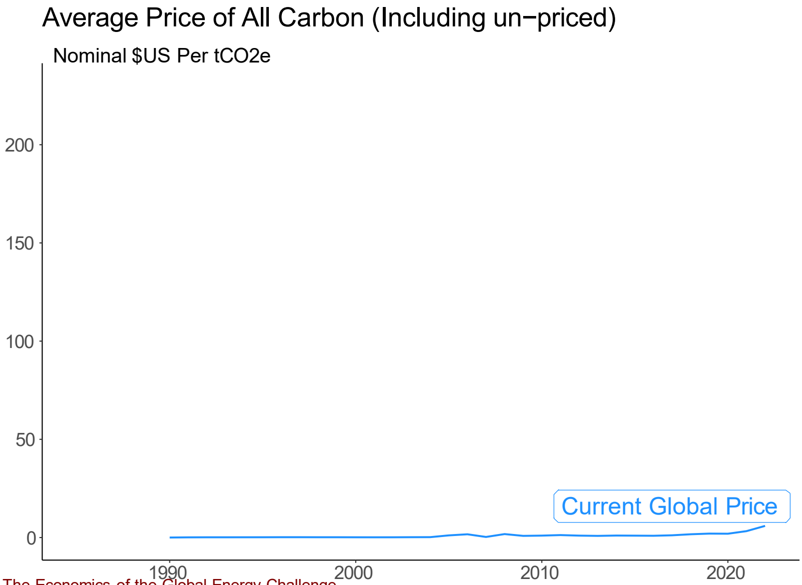
Global Carbon Prices are Low



- The average price of carbon (including un-priced carbon) is $5.41.
- The 2024 EPA Social Cost of Carbon is $234 per ton.
- The 2025 Sweden carbon tax is SEK 1,510 ($163) per ton.
- Pricing critiques can be addressed by design.

Details

Global Carbon Prices are Low



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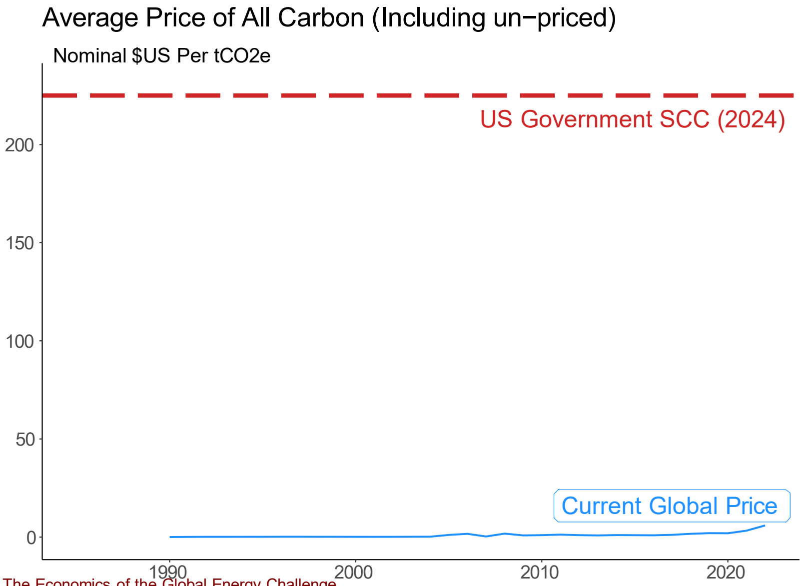

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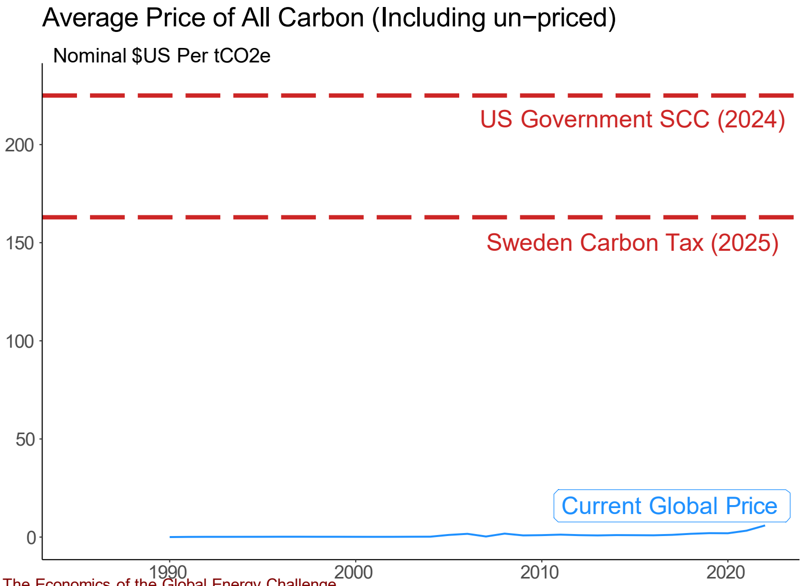

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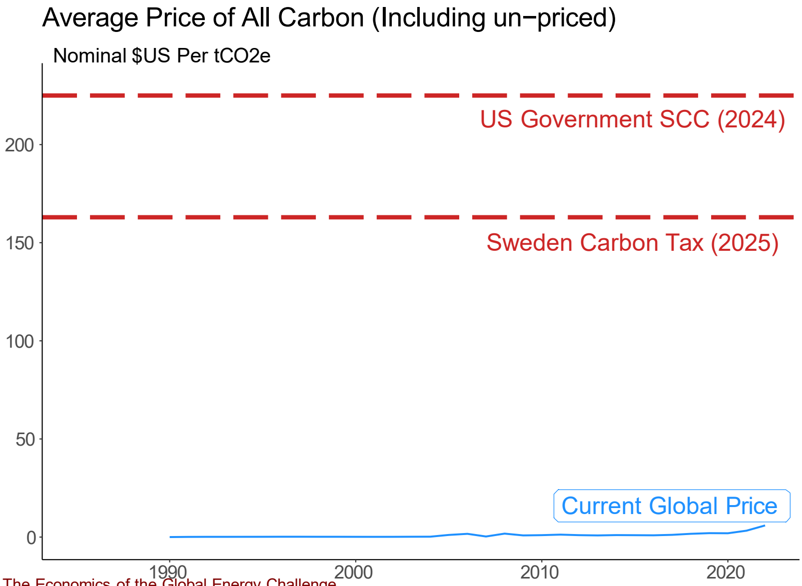

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Imperfect Information

- For markets to deliver efficient outcomes, individuals must have reliable information
- But markets often have an incentive to supply sub-optimally low levels of information, causing individuals to:
  - Fail to protect themselves from environmental risks
  - Fail to take advantage of adaptation opportunities
  - Fail to politically organize
- There is a growing literature on the effects of information Literature

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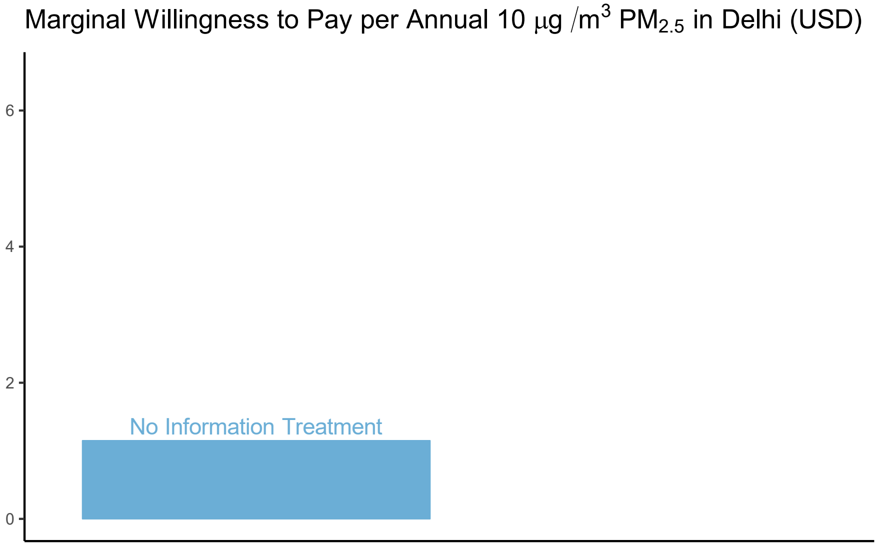
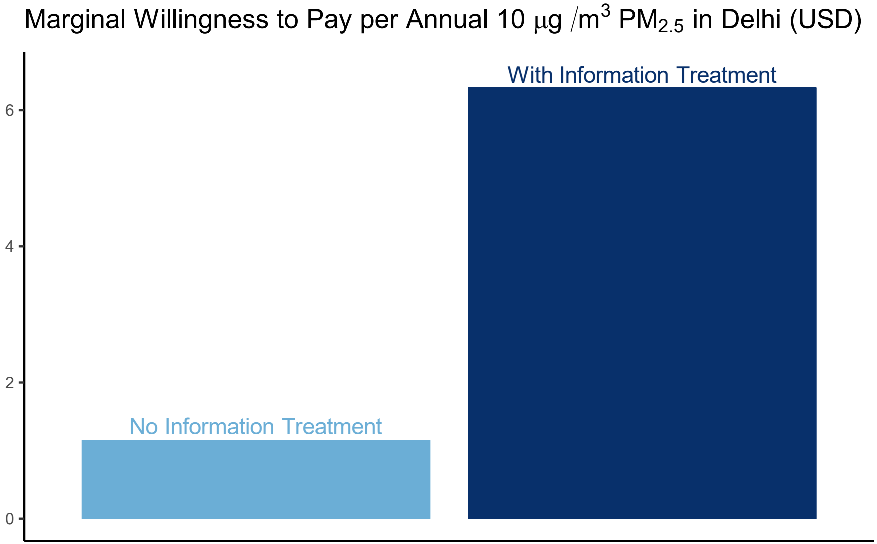


Baylis et al. 2024

Effects of Information



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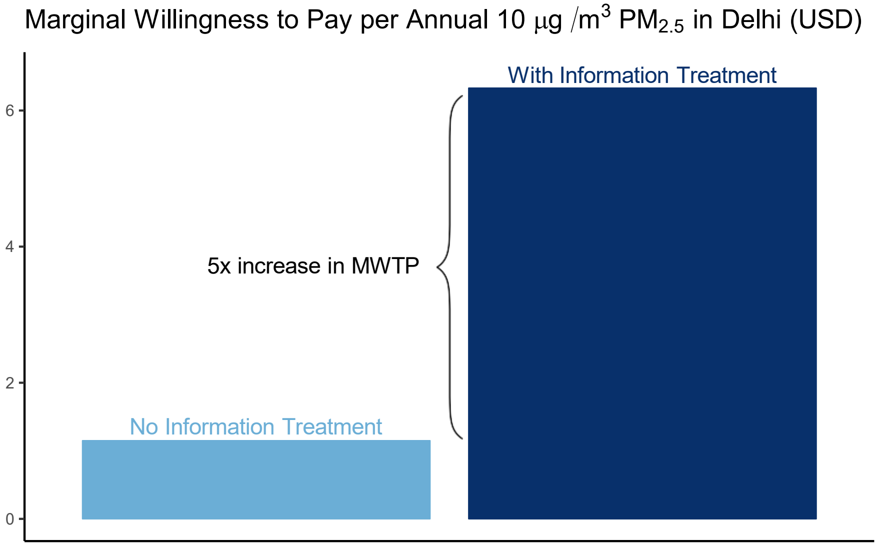

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   - Technical Innovation
   - Policy Innovation

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Innovation is a Public Good

Technical Innovation: Firms cannot capture all benefits of R&D, so they underinvest compared to social optimum.

- Among US firms, gross social returns to R&D are 55%. Private returns are 21% (Bloom et al. 2013).

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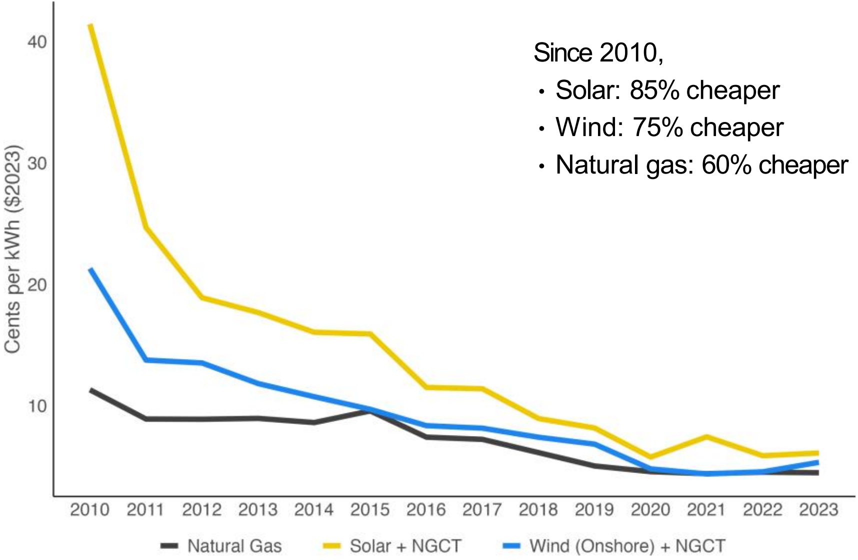
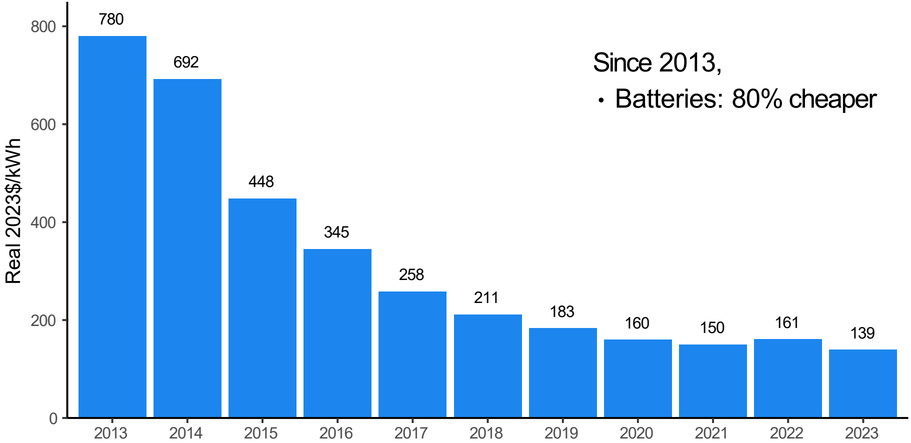
Renewable Costs are Decreasing



Since 2010,

- Solar: 85% cheaper
- Wind: 75% cheaper
- Natural gas: 60% cheaper

Battery Costs are Decreasing as Well

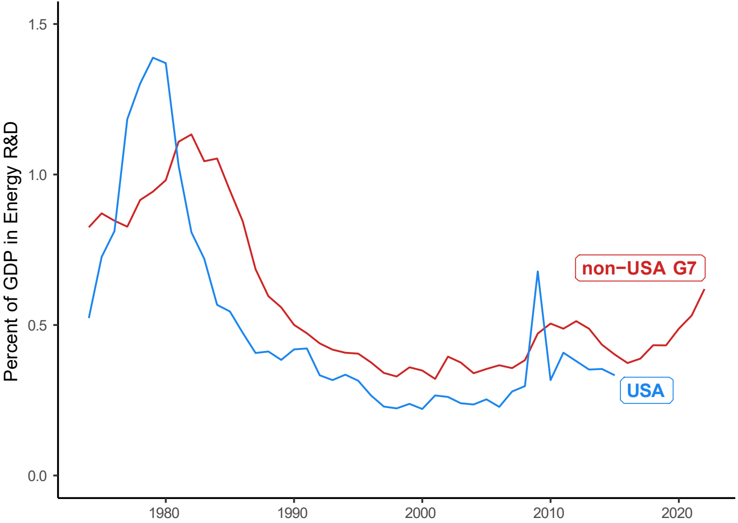


Since 2013,

- Batteries: 80% cheaper

Weighted average of battery uses from BNEF (2023)

...But R&D Investment Remains Low Relative to the 1970s



IEA (2024), World Bank (2024)

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Policy Innovation is Also a Public Good

Policy Innovation: Governments incur all costs but benefits spill over, so they underinvest in policy compared to social optimum.

- Benefits of US Government's Development Innovation Ventures were 17 times larger than costs (Kremer et al. 2021). Literature

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Case Study: World's First Particulates Pollution Market

JOURNAL ARTICLE

Can Pollution Markets Work in Developing Countries? Experimental Evidence from India

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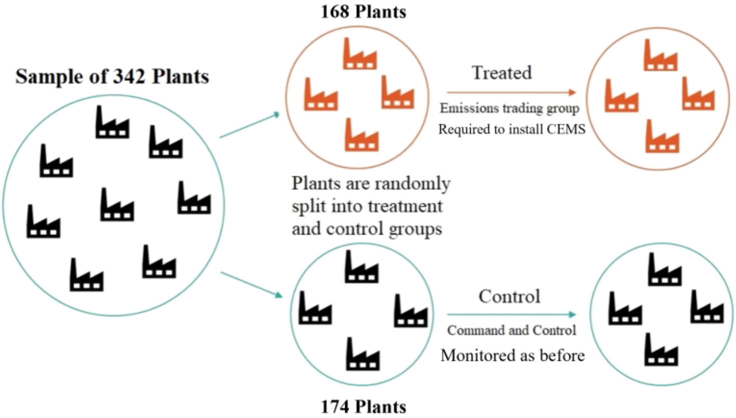
Michael Greenstone , Rohini Pande , Nicholas Ryan , Anant Sudarshan

The Quarterly Journal of Economics, Volume 140, Issue 2, May 2025, Pages 1003–1060, https://doi.org/10.1093/qje/qjaf009

Published: 05 February 2025 **Article history ▾**

The ETS pilot designs and evaluates a particulate emissions market in Surat, India.

Experimentally Testing an Emissions Market



- Two groups continue to be identical, except for treatment (market)
- Any differences in pollution between the groups can be attributed to treatment

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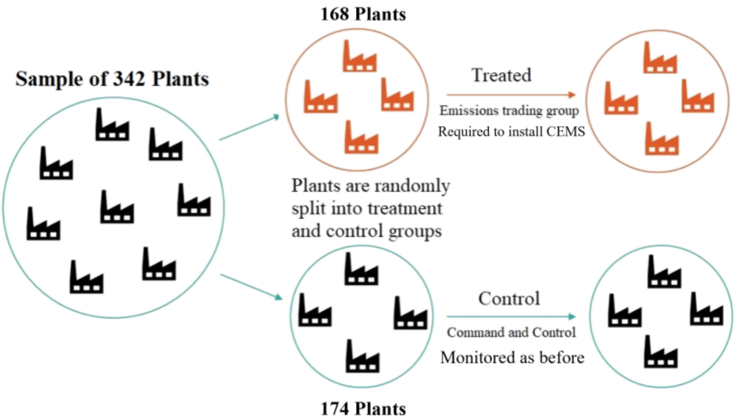

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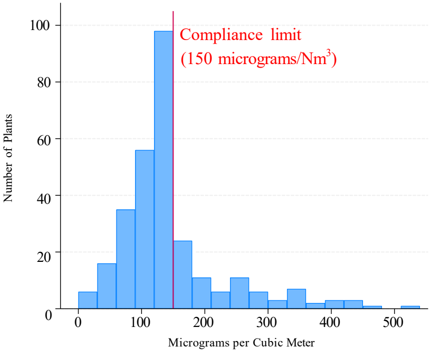
Result 1: Market Drastically Reduced Noncompliance and Functioned Well

Dramatic Compliance Improvements

Command-Control Compliance



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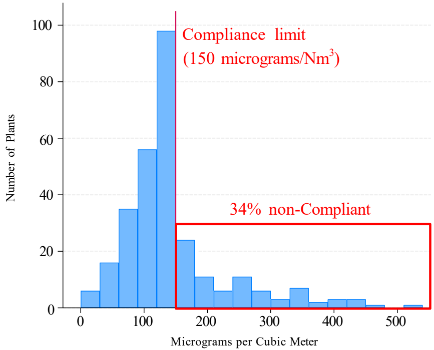

- **34%** of plants out of compliance in status-quo command-control.

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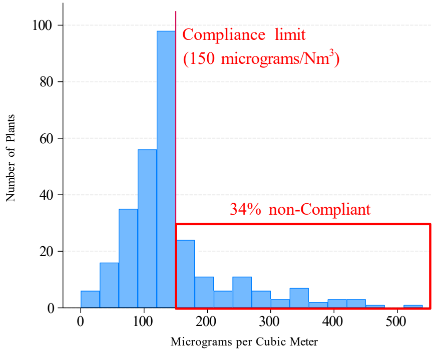
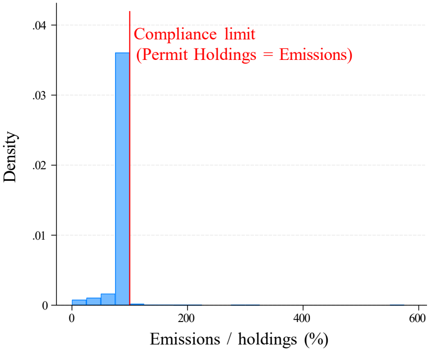
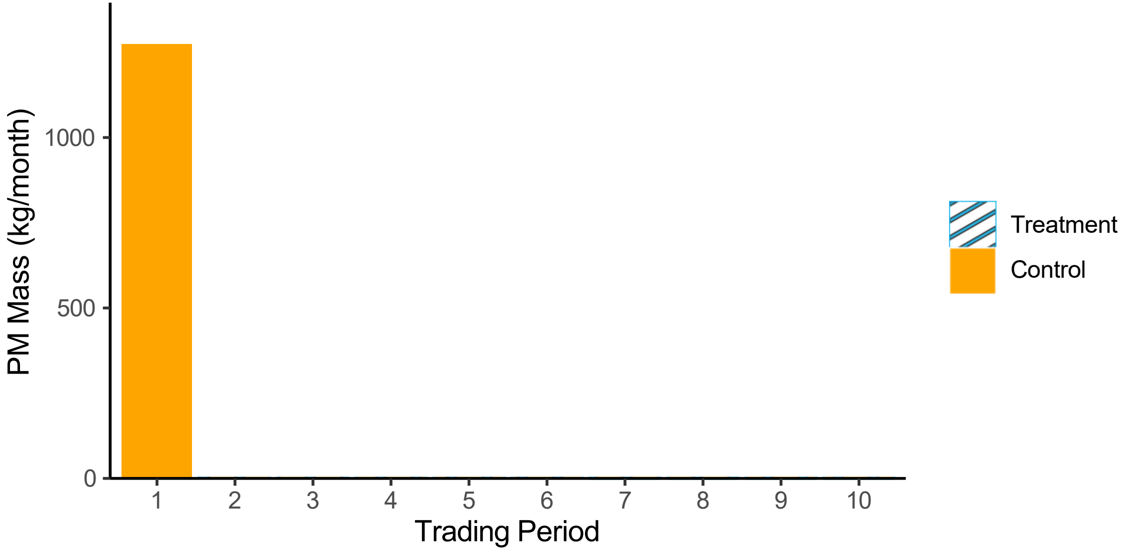


Aggregate Market Compliance



- **34%** of plants out of compliance in status-quo command-control.
- **1%** of plant-periods out of compliance over course of market.

Result 2: Market (Surprisingly) Reduced Pollution



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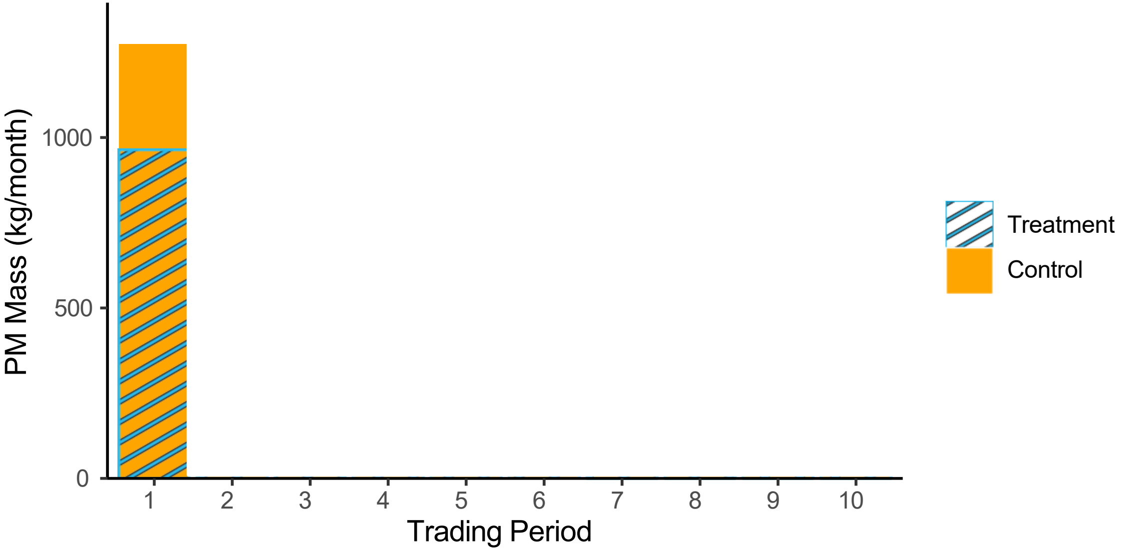

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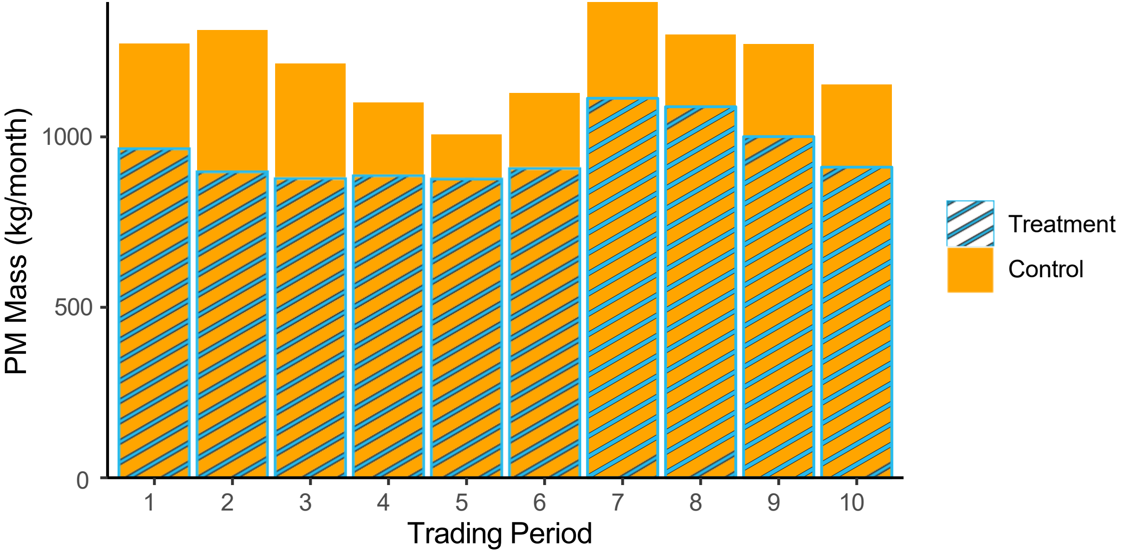

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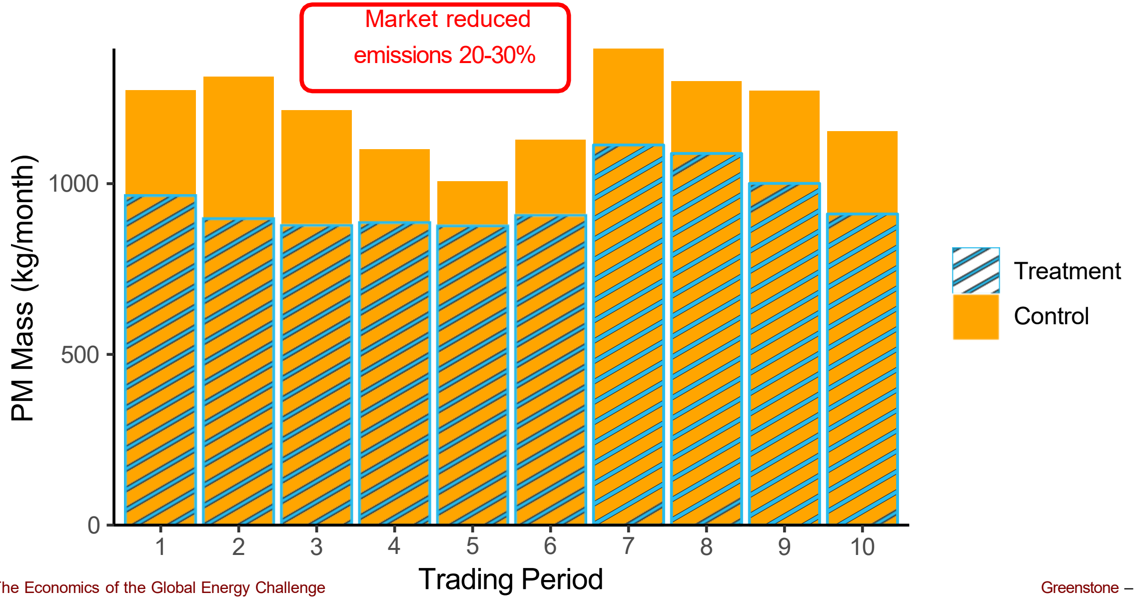
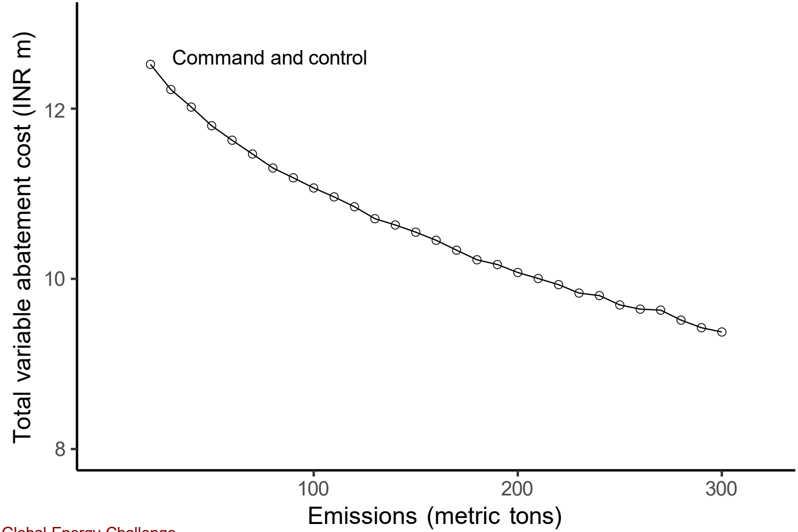


Result 3: Market Reduced Abatement Costs

Total Abatement Costs: Comparing Regimes



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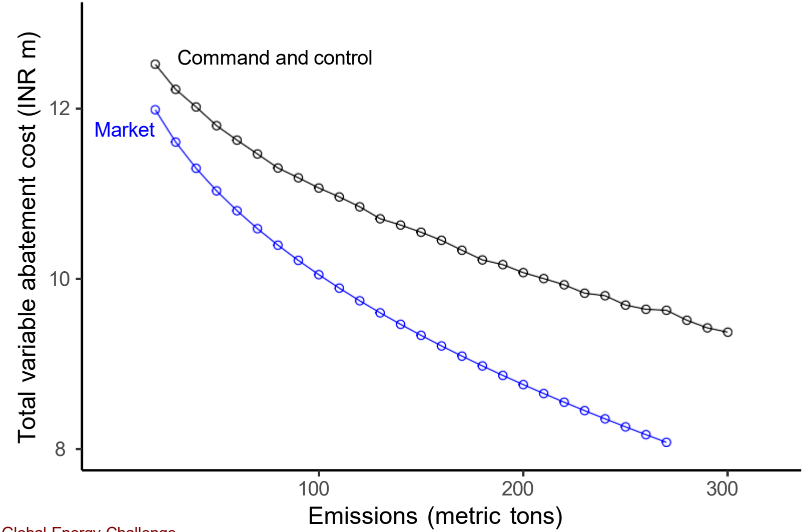

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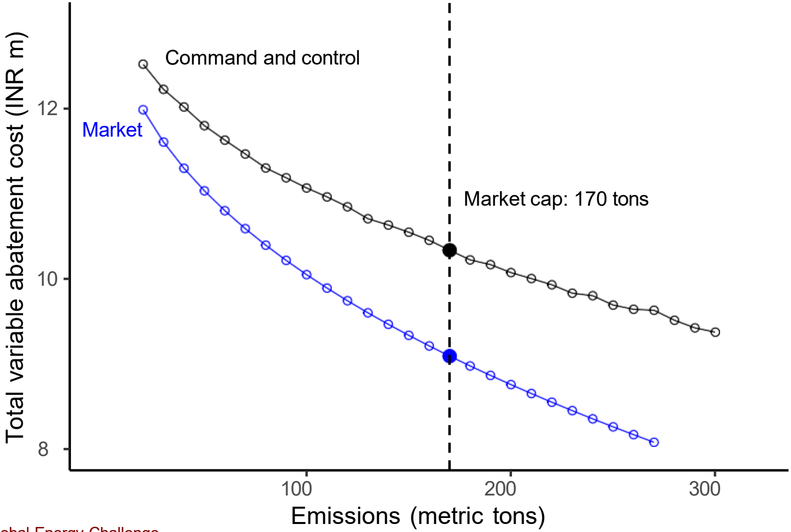

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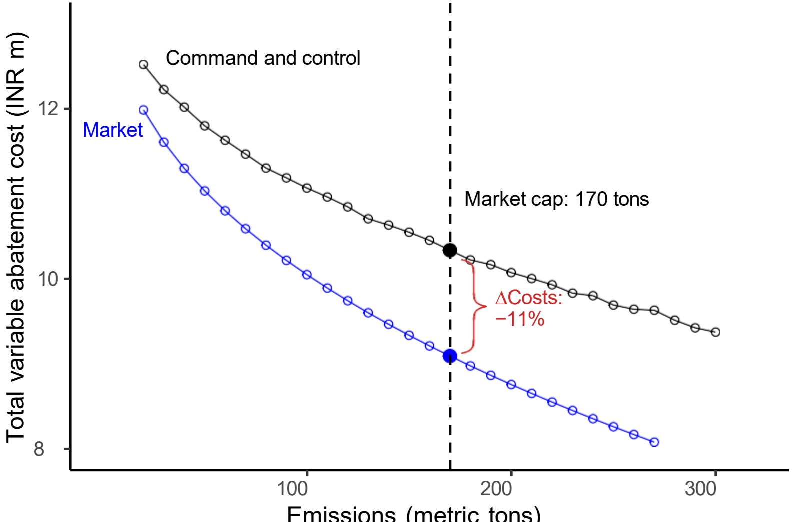

Result 4: Market Benefits Vastly Outweighed Costs

Benefit Cost Analysis of the Market

Expanding the ETS for one year to all industrial plants in Surat

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Costs Monitoring costs + Δ(abatement costs) = **$3.9m**

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Benefits Reduction in ambient $PM_{2.5}$ = 8.5 $\mu g/m^3$

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$\rightarrow$ Health gains per 1 year of ETS = 89, 208 life-yrs

Result 4: Market Benefits Vastly Outweighed Costs

Benefit Cost Analysis of the Market

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Costs Monitoring costs + Δ(abatement costs) = **\$3.9m**

Benefits

Reduction in ambient $PM_{2.5}$ = 8.5 $\mu g/m^3$

Health gains per 1 year of ETS = 89, 208 life-yrs

→ Value of gain in life-yrs = **\$847m**

Result 4: Market Benefits Vastly Outweighed Costs

Benefit Cost Analysis of the Market

Expanding the ETS for one year to all industrial plants in Surat

Costs Monitoring costs + Δ(abatement costs) = **$3.9m**

Benefits

$$\text{Reduction in ambient PM}_{2.5} = 8.5\ \mu g/m^3$$

$$\text{Health gains per 1 year of ETS} = 89,208 \text{ life-yrs}$$

$$\rightarrow \text{Value of gain in life-yrs} = \mathbf{\$847m}$$

Benefit-cost ratio: 215:1

Surat Experiment is Having Broad Impact

1. **New cities:** Trading starts in Ahmedabad's new PM market. 4 new emissions markets planned for Gujarat.


Trading begins in Ahmedabad's pollution market

Live trading of the Emission Trading Scheme (ETS) in Ahmedabad was launched by Shri Mulubhai Bera, Honorable Minister of Forest & Environment, Government of Gujarat. Ahmedabad has become India's second city to implement an ETS for particulate pollution.

Source: EPIC India

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2. **New pollutants:** Government of Gujarat has announced plans to start a market for CO_2 emissions and to add a new water market.


Gujarat inks MoU to develop India's first carbon market

The MoU was signed in the presence of Chief Minister Bhupendra Patel and officials from climate change and mines and industries department.

By: Express News Service | Ahmedabad |
May 24, 2022 5:42:04 am

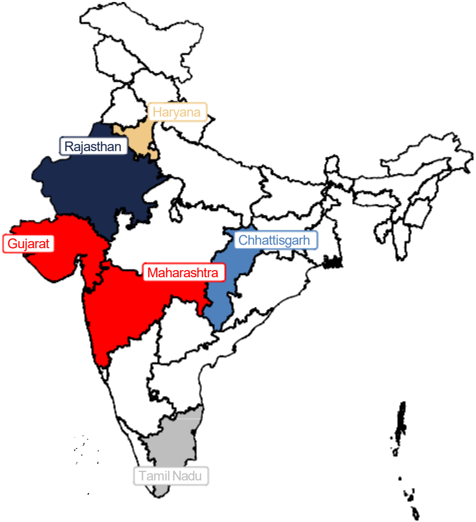
Source: Indian Express

Surat Experiment is Having Broad Impact

Expanding role of markets: Maharashtra is developing an SO_X trading program

Source: The Times of India

Coming Soon: Launch of Emissions Market Accelerator



Surat's success prompts a wave of interests from other states in India...

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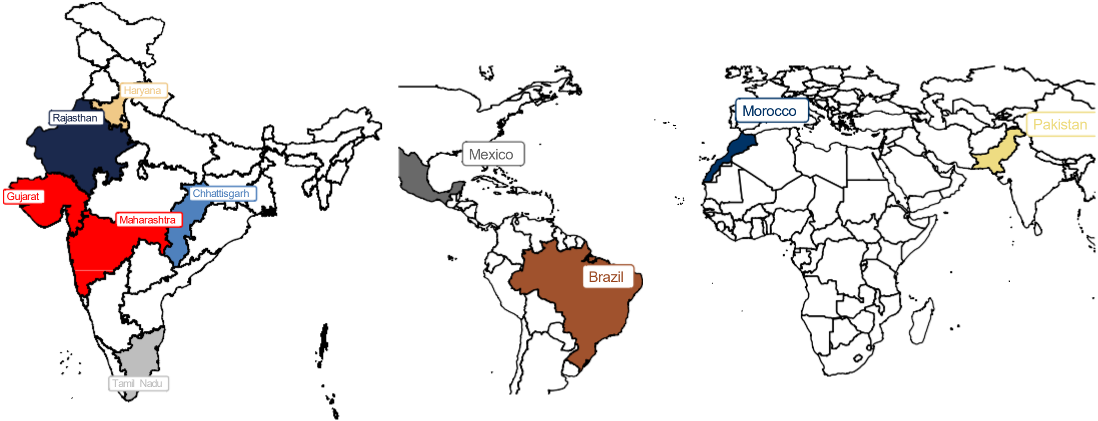


Surat's success prompts a wave of interests from other states in India...

...and other countries

I. Seven Facts that Define the Global Energy Challenge

II. Actions to Address the Global Energy Challenge

III. Conclusion

The Global Energy Challenge

Annex

Penalization Scheme

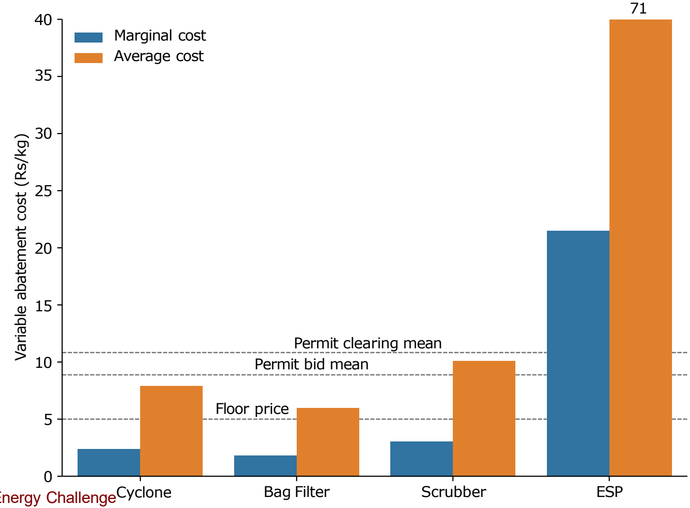
To incentivize data reporting, missing emissions were progressively penalized to incentivize reporting them for missing data.

% Data Available During Week	Imputation for Missing Data Values (kg/hr)
> 95%	Plant mean emissions load during the period
80-95%	Plant 75^{th} percentile emissions load during the period
50-80%	Plant 90^{th} percentile emissions load during the period
1-50%	Plant 90^{th} percentile emissions load during the period and prior three months of valid CEMS data, up to the start of the compliance period
< 1%	Flat rate of population emissions load (8.08 kg/hr)

Back

Engineering Estimates and Price Collar

Figure: Engineering estimates of abatement costs



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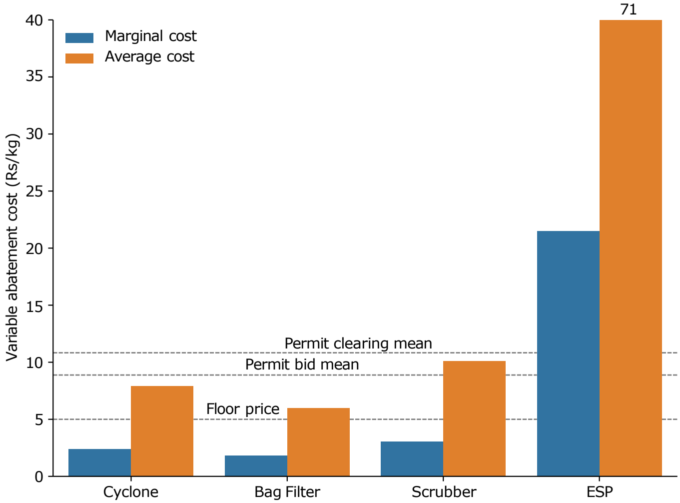
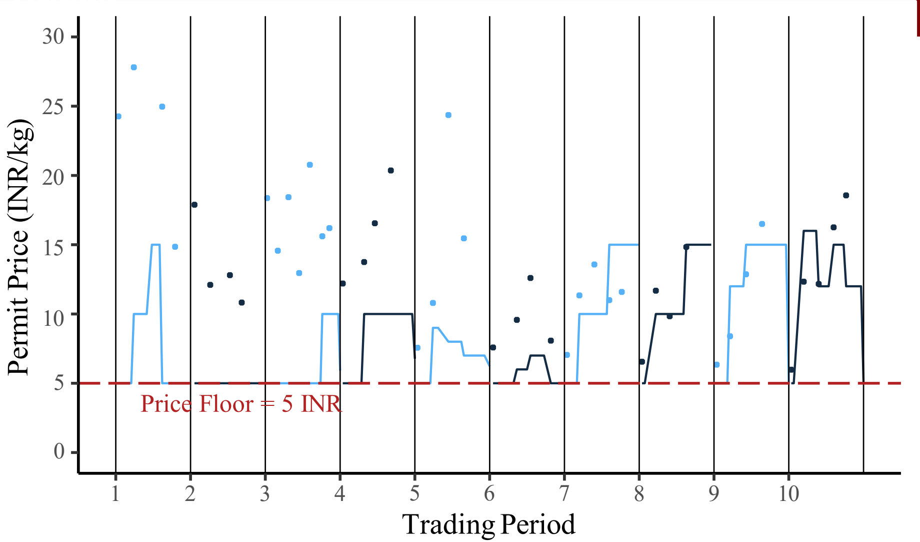


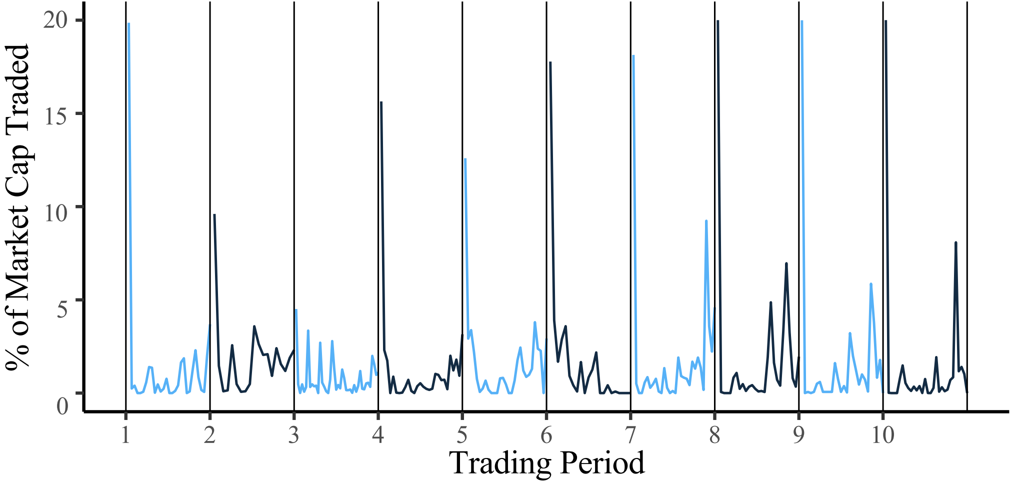
Market Prices



Dots = average auction bid prices. **Lines** = market prices.

- Market design emphasized early liquidity

Market Design Emphasized Early Liquidity



- Regulator sold off 20% of the cap in permits at floor price (INR 5 per kg) in the first auction of each period
- This gives firms an incentive to anticipate emissions and purchase early. Later auctions

Market Cap Progression

Table: Market Cap Gradually Lowered

Compliance Periods	Dates	Cap (kg/30 days)
Mock 1 - Compliance 1	2019/07 - 2019/09	280,000
Compliance 2	2019/10	200,000
Compliance 3	2019/11 - 2019/12	180,000
Compliance 4 - 10	2020/01 - 2021/3	170,000

Back

Imputation Rules Description

The first step is imputing daily average PM mass rate with the stack's weekly average PM mass rate. If the weekly average is not available, we use different averages to impute as summarized below:

Consideration	No Imputation	Imputation Rule A: **Stack-Experiment**	Imputation Rule B: **Treatment-Month**
Impute for missing values	Stack weekly mean PM mass rate	Stack weekly mean PM mass rate	Stack weekly mean PM mass rate
Impute for the rest of missing values	Stack monthly mean PM mass rate	Stack mean PM mass rate across ETS experiment	Treatment group monthly mean PM mass rate

Back

Regression Specification

$$log(PM_{it}) = \beta_1 Treatment_i + \alpha_t + \epsilon_{it}$$

PM_{it}	SPM emissions in kg per month
$Treatment_i$	dummy for plant being assigned to treatment
α_t	Year-month fixed effects.

- Standard errors clustered at the plant level.

Back

Treatment Reduces Pollution

Table: Treatment effects on PM emissions (log(PM mass/month))

	No Imputation		With Imputation	
	(1)	(2)	(3)	(4)
ETS Treatment=1	-0.193**	-0.194**	-0.282***	-0.316***
	(0.0763)	(0.0751)	(0.0745)	(0.0568)
Month FE	Yes	Yes	Yes	Yes
Imputation rule			Rule A	Rule B
Reweighted		Yes		
Plants	292	292	292	292
Observations	3235	3235	3796	3796

Survey Cost Results

Table: Treatment effects on plant costs (1000's of USD)

	Total Costs	All APCDs	Components			
			Cyclone	Bag	Scrubber	ESP
	(1)	(2)	(3)	(4)	(5)	(6)
ETS Treatment=1	11.26	-3.467				
	(26.31)	(3.089)				
R^2	0.93	0.90				
Control mean	578.8	44.04				
Plants	185	276				

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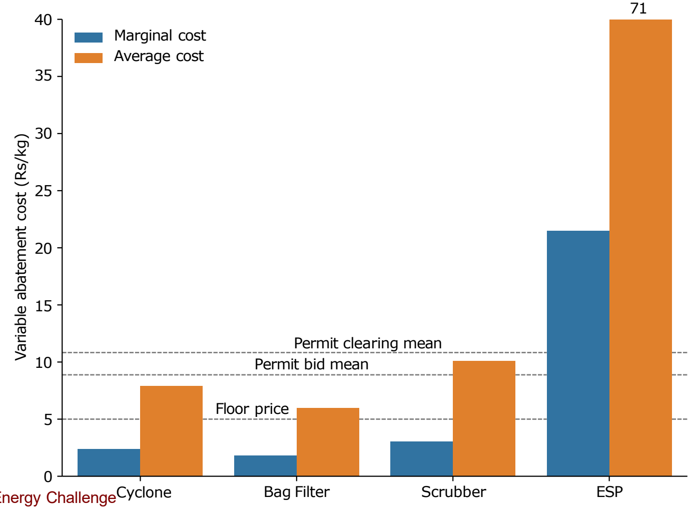
			Cyclone	Bag	Scrubber	ESP
	(1)	(2)	(3)	(4)	(5)	(6)
ETS Treatment=1	11.26	-3.467	0.602**	0.530*	-0.222	-4.281
	(26.31)	(3.089)	(0.266)	(0.318)	(0.407)	(3.344)
R^2	0.93	0.90	0.85	0.83	0.84	0.89
Control mean	578.8	44.04	7.80	9.85	9.69	16.70
Plants	185	276	276	276	276	276

Back

Engineering Estimates of MAC are Similar to Bids

Figure: Engineering estimates of abatement costs



Functional Form Assumptions

- Assume abatement cost function:

$$Z_{it}(E_{it}) = e^{\xi_{it}} H_i^{\beta_2} \frac{1}{\beta_1 + 1} \left(\bar{E}_i^{\beta_1+1} - E_{it}^{\beta_1+1} \right), \quad \beta_1 \in (-1, 0)$$

  - H_i: Max total heat output of plant i
  - $\underline{E}_{it}$: emissions of plant i in period t
  - $\bar{E}_i$: emissions of plant i with no abatement investment (calculated from measured flow-rates and assumed concentrations)
  - ξ_{it} consists of a full set of plant-period fixed-effects
- Simple estimation of marginal variable abatement costs:

$$MAC(E_{it}) = -\frac{\partial Z_{it}(E_{it})}{\partial E_{it}} \Longrightarrow \log MAC(E_{it}) = \beta_1 \log E_{it} + \beta_2 \log H_i + \xi_{it}$$

Functional Form Assumptions

- Assume abatement cost function:

$$Z_{it}(E_{it}) = e^{\xi_{it}} H_i^{\beta_2} \frac{1}{\beta_1 + 1} \left(\overline{E}_i^{\beta_1+1} - E_{it}^{\beta_1+1} \right), \quad \beta_1 \in (-1, 0)$$

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Estimating MAC Function

- Revealed preference approach: Plants bid their MAC plus an additively separable in logs error term (forecast error)

$$\log MAC(E_{it}) = \beta_1 \log E_{it} + \beta_2 \log H_i + \xi_{it}$$

$$\downarrow \quad \text{(estimated by)}$$

$$\log b_{itk} = \beta_1 \log E_{itk} + \beta_2 \log H_i + \xi_{it} + \epsilon_{itk},$$

  where b_{itk} is the price of the bid k by plant i at period t, and E_{itk} are emissions (permit holdings) if this bid were executed.

- **Identification Assumption:** $E[\epsilon_{itk} | E_{itk}, \xi_{it}] = 0$.
  - Economically justified if plants form rational, unbiased expectations of their emissions but have uncertainty about the exact emissions level.
  - Plausible in our setting because plants could know their emissions but validated emissions for the market were releasesed at a lag.

Back

Command-and-control regulation

- A command-and-control regime is any rule that dictates emissions $\{E_{it}\}$ for each plant.

→ Represent the intensity standard as a plant-specific emissions rate

$$\overline{R}_{it} = E_{it}/H_i .$$

- Assume plants' observed emissions rate in control group are the *de facto* intensity standard they face, and use this to estimate distribution of assigned emissions rate $\overline{R}_{it}$ across plants

→ With $\overline{R}_{it}$ and a plant's MAC function it is straightforward to estimate a plant's abatement costs

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Predict Counterfactual Emissions in Command-and-control

- **Capacity-based rate (CBR):** Intensity standard depends on plant heat capacity H_i → In the control group, fit

$$\log R_{it} = \gamma_{0t} + \gamma_{1t} \log H_i + \epsilon_{it}.$$

- Predict the counterfactual emissions of treatment plants if they were subject to the regulation in the control group (recall $R_{it} = E_{it}/H_i$):

$$\hat{E}_{it} = \hat{R}_{it} H_i, \quad \hat{R}_{it} = \exp(\widehat{\log R}_{it} + \epsilon^s_{it}).$$

  - ϵ^s_{it} is i.i.d. Normal or Normal with $\rho(\epsilon^s_{it}, \hat{\xi}_{it}) = -0.1$.
    - Correlation introduced to capture that the regulator targets more polluting plants more aggressively (Duflo et al., 2018).

Back

Emissions market reduces costs 10-16%, holding constant emissions

Table: Variable abatement costs under alternative regulatory regimes

	Emissions = 170 tons			Emissions = 240 tons		
	Price (INR/kg) (1)	Cost (INR m) (2)	%ΔCost (%) (3)	Price (INR/kg) (4)	Cost (INR m) (5)	%ΔCost (%) (6)
ETS	12.23	10.08				
CBR, i.i.d. error		11.27	11.8%			
CBR, corr. error		11.39	13.0%			

Average across all periods. CBR = Capacity-based rate.

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Average across all periods. CBR = Capacity-based rate.

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Pricing Critiques Can Be Addressed by Design

Distributional Concerns

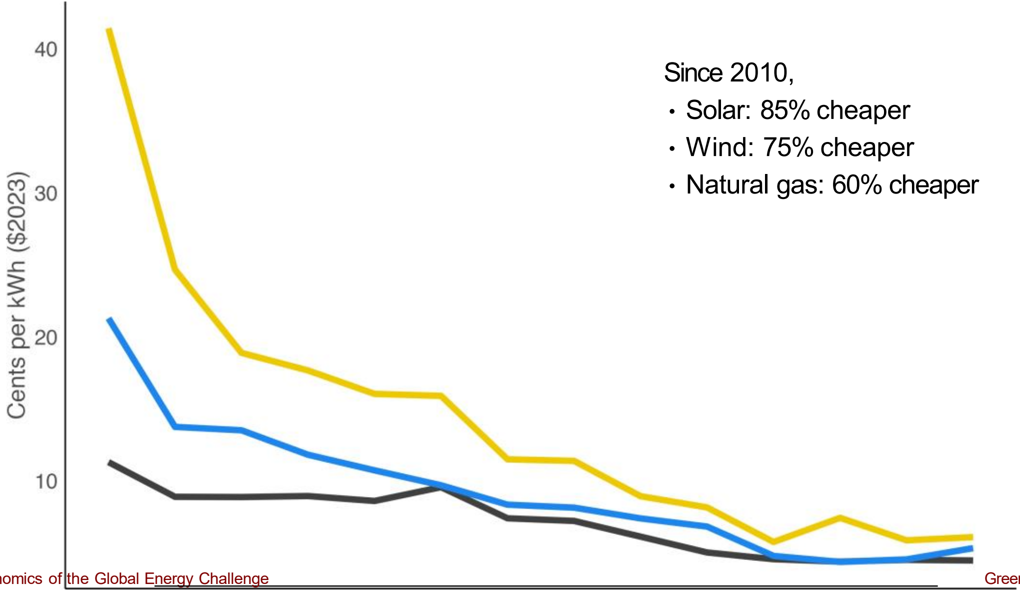
- Revenue rebating can offset higher energy costs (Rosenberg et al. 2018)

Impacting American Industry

- Border Tariff Adjustments.

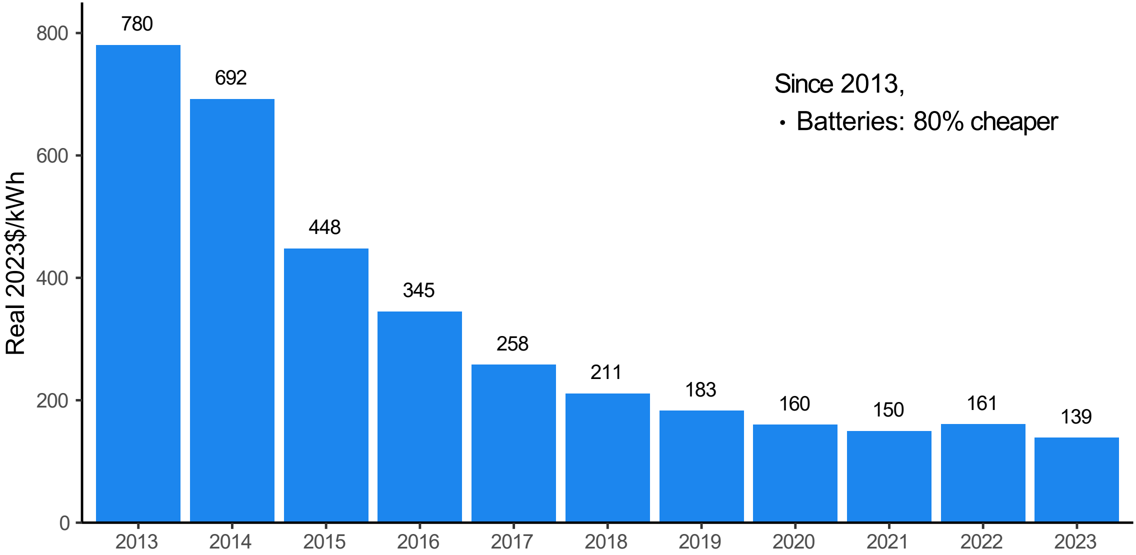
Back

Renewable Costs are Decreasing



Since 2010,
- Solar: 85% cheaper
- Wind: 75% cheaper
- Natural gas: 60% cheaper

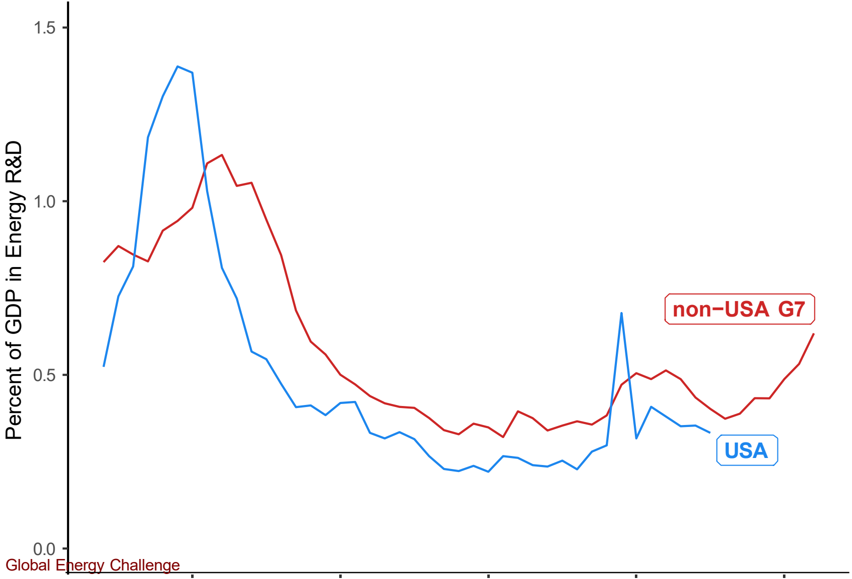
Battery Costs are Decreasing as Well



Since 2013,

- Batteries: 80% cheaper

...But R&D Investment Remains Low Relative to the 1970s



Research on Policy Has Been Insightful

- Residential energy efficiency improvements (Fowlie et al. 2018)
- Performance pay for tax collectors (Khan et al. 2016)
- Technology-based solutions to delivering benefits (Banerjee et al. 2023, Muralidharan et al. 2016)
- Returns to health insurance (J-PAL 2023)
- Efficacy of emissions markets in developing countries (Greenstone et al. 2024)
- Machine learning targeting of inspections (Buchsbaum et al. 2023)

→ **In several cases, the results of these experiments have altered policy in the jurisdiction they were tested and beyond**.

Back

Recent Literature on Improving Information Quality

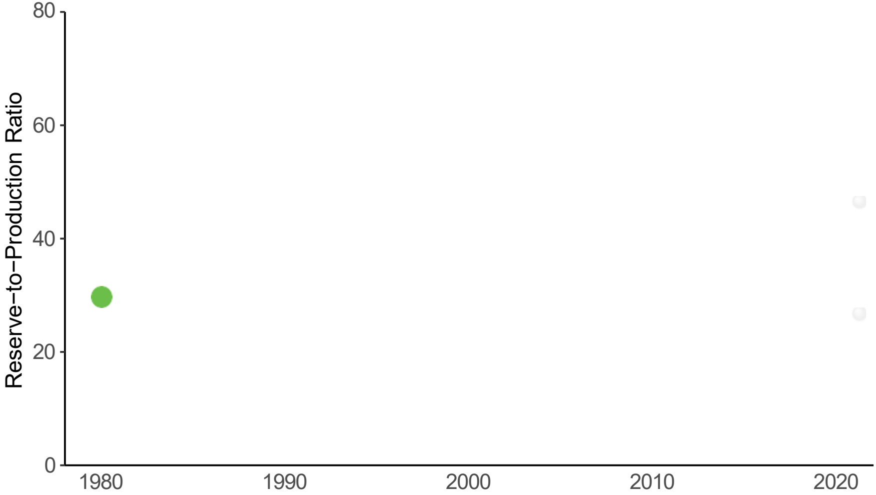
- Baylis et al. (2024)
  - Experimentally provide information to residents of Delhi on the health consequences of exposure to air pollution
  - Find that it increases their willingness to pay for reductions in air pollution by more than 5x
- Greenstone et al. (2022)
  - More accurate ambient pollution monitoring in China revealed that air pollution concentrations were 35% higher than previously reported.
  - Subsequent increase in online searches for face masks and air filters
- Other papers on adaptation in response to information:
  - Burlig et al. (2023): Monsoon-onset information changed farmer behavior
  - Shrader et al. (2023): Accurate weather forecasts on extremely hot or cold days decreased mortality

Back

Fossil Fuels Remain Abundant

Fact 0:

Fossil Fuel Reserves-to-Production Ratio



- Oil reserves have grown significantly over the past 30 years.
- Natural gas reserves have roughly equaled production.

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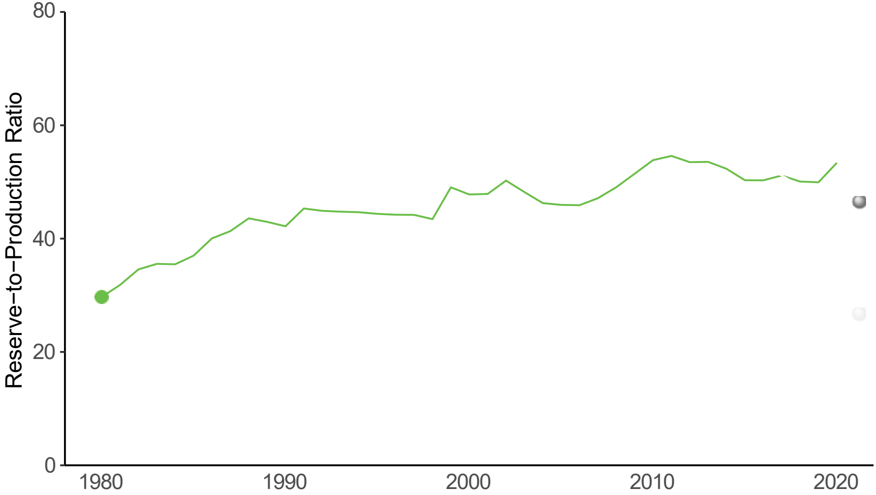

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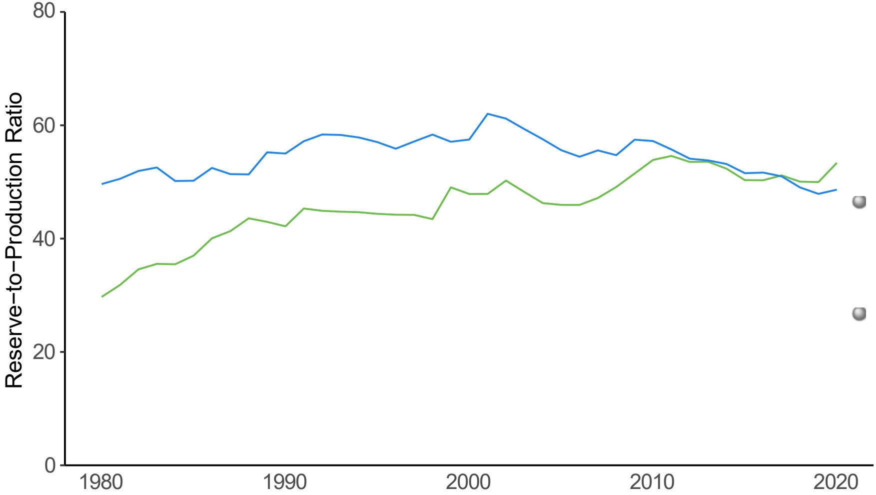

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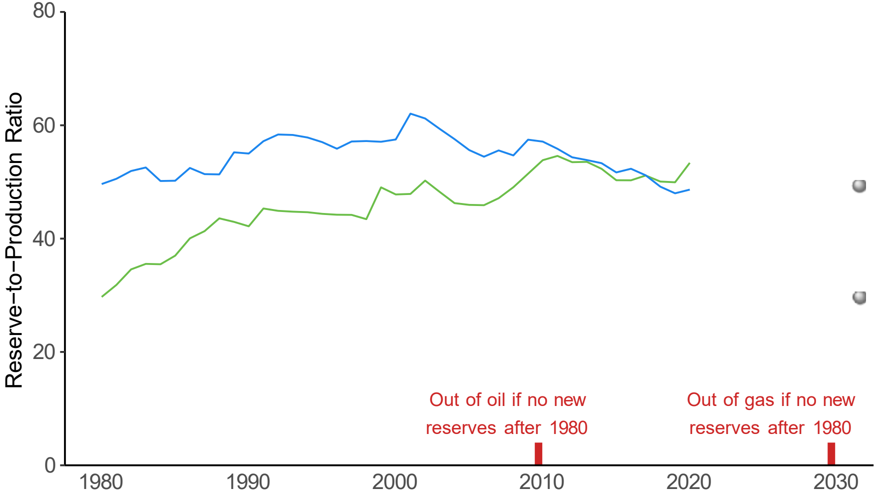

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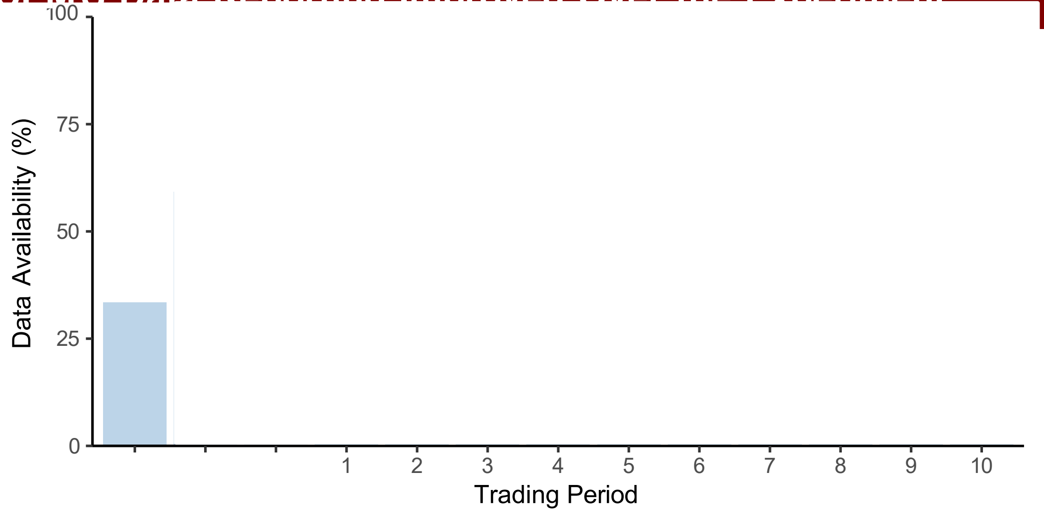
CEMS Data Reporting Improved Over the Experiment



- Treatment firms incentivized to report by penalties for poor data availability
  - Penalization Scheme

Back

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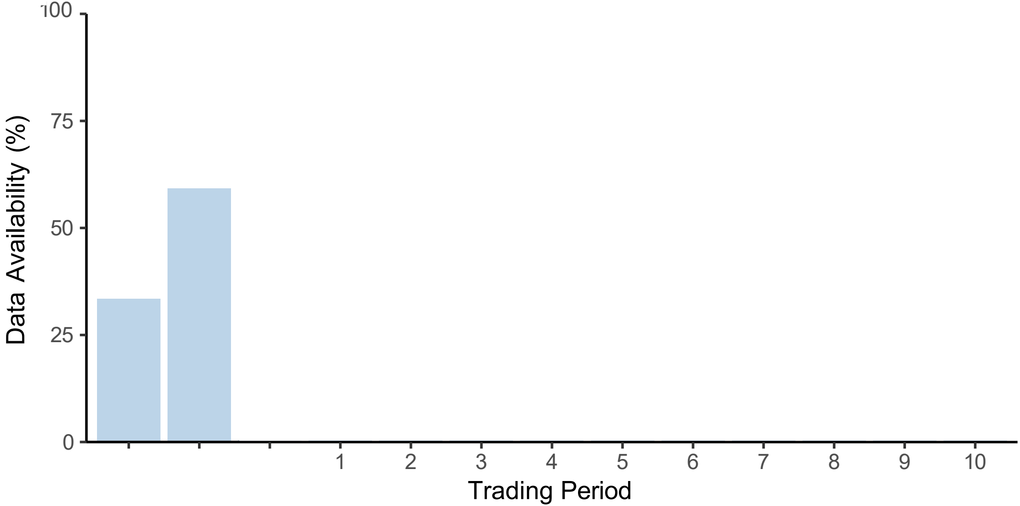

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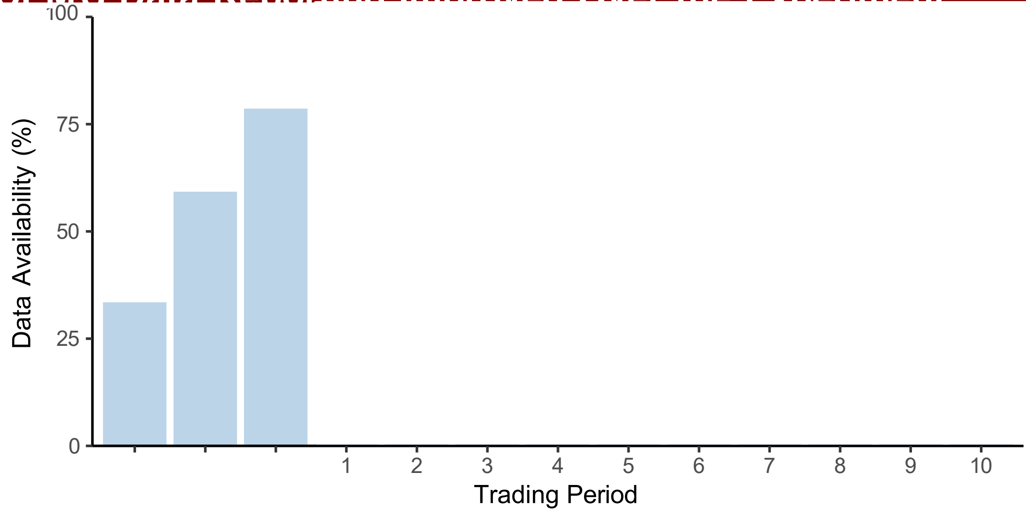

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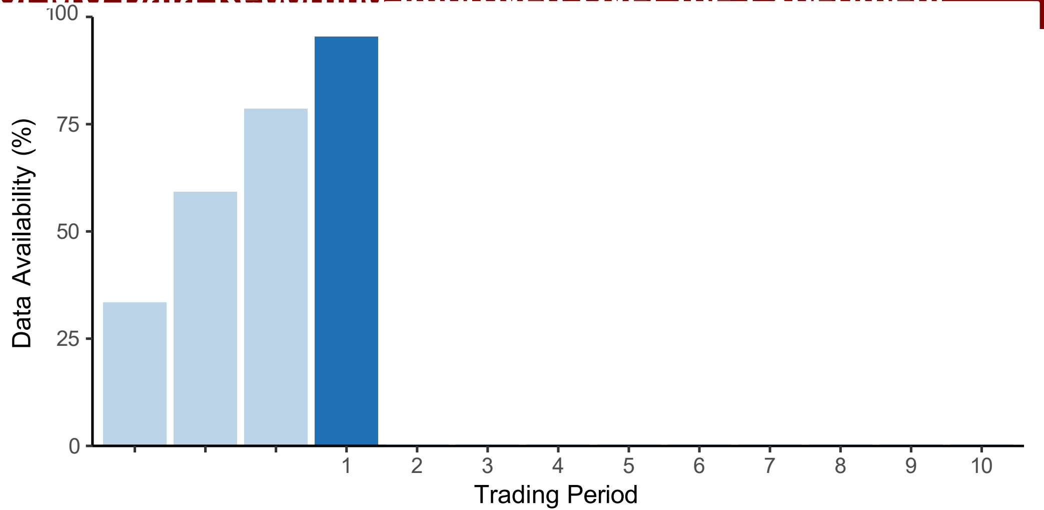

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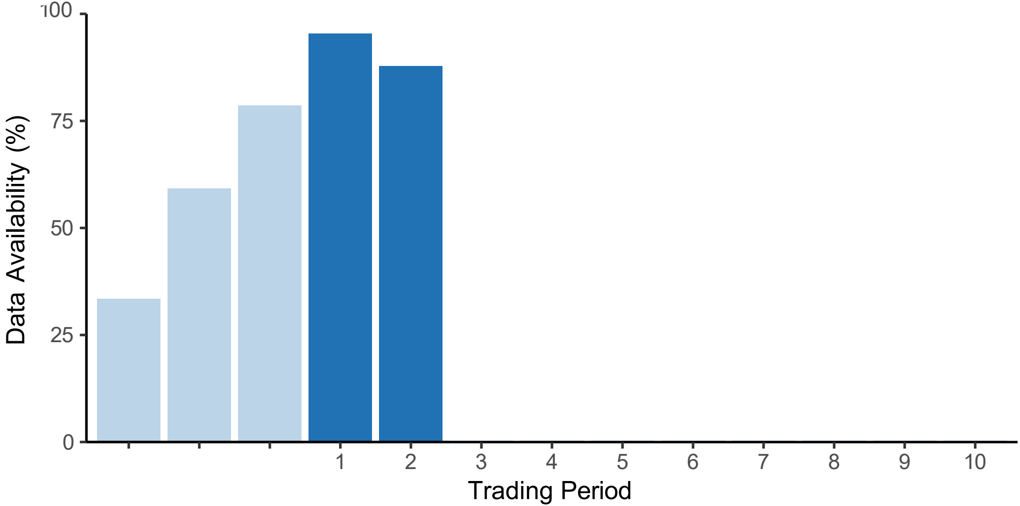

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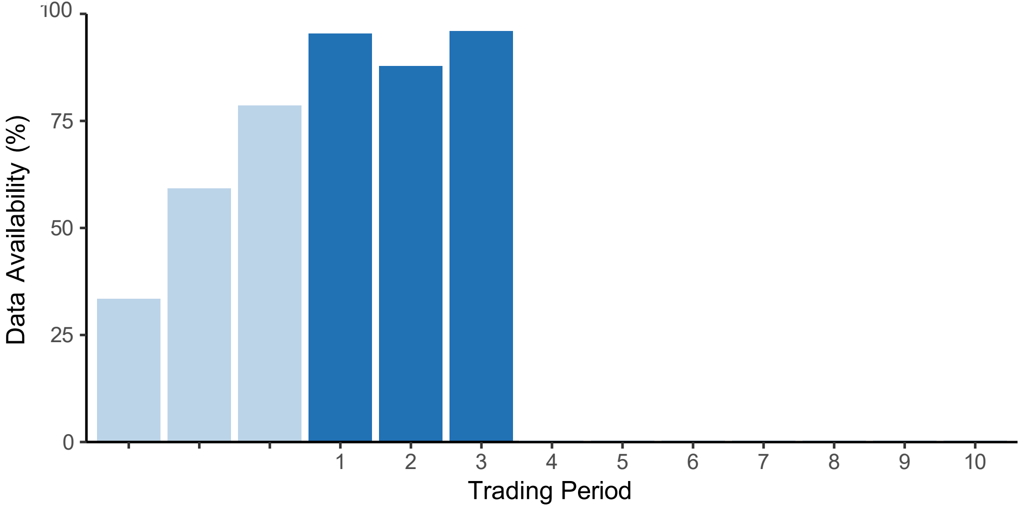

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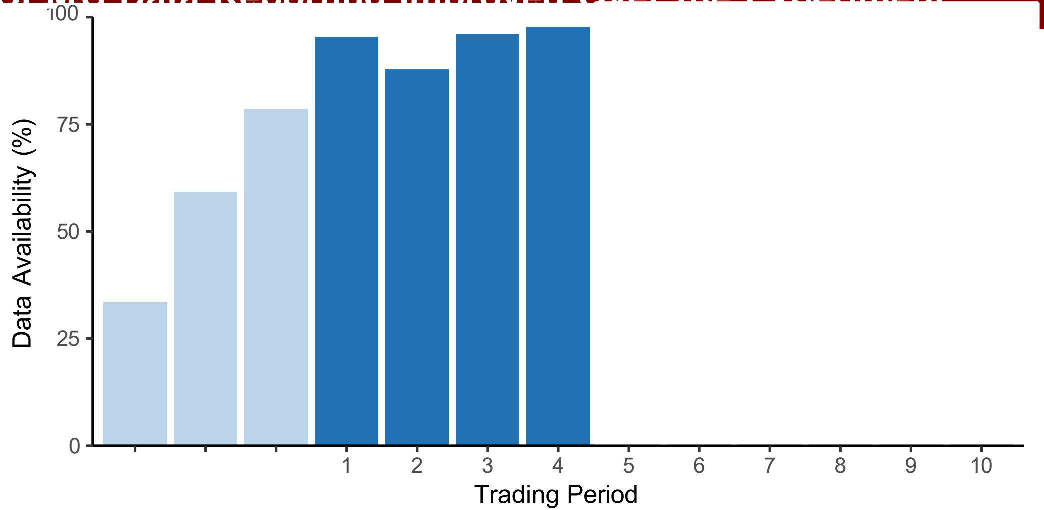

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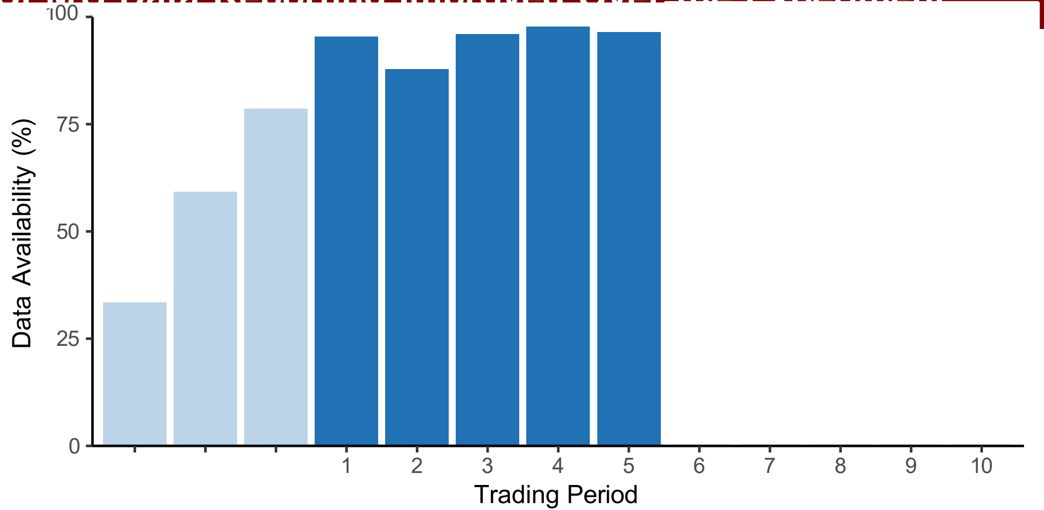

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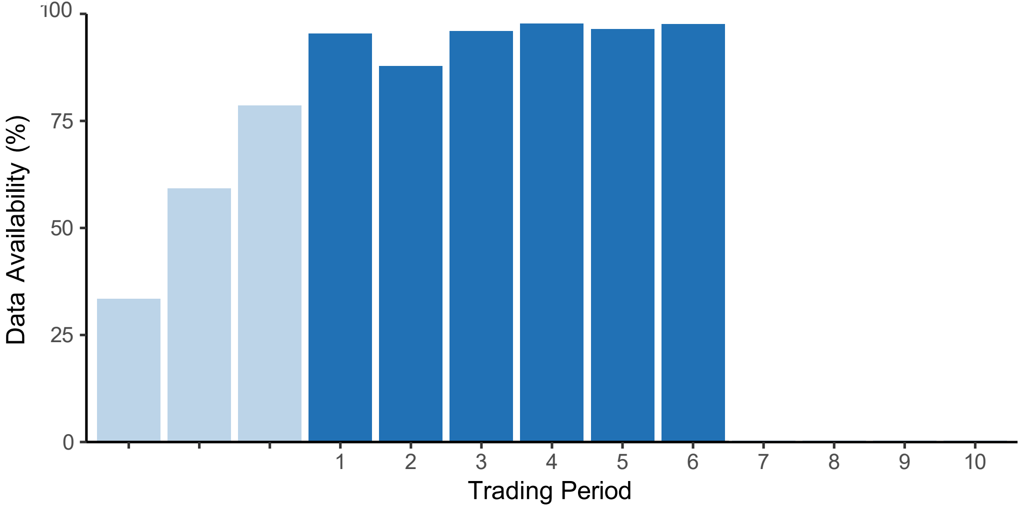

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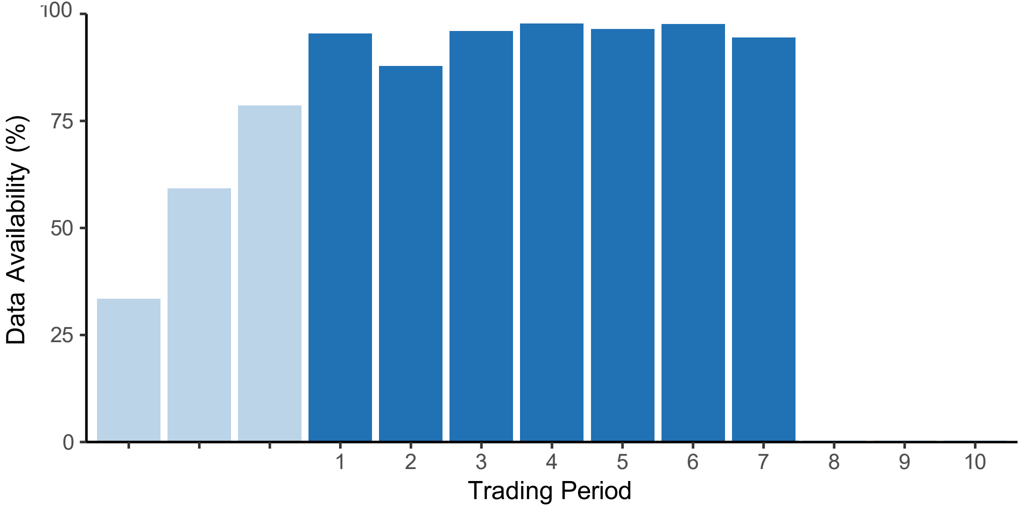

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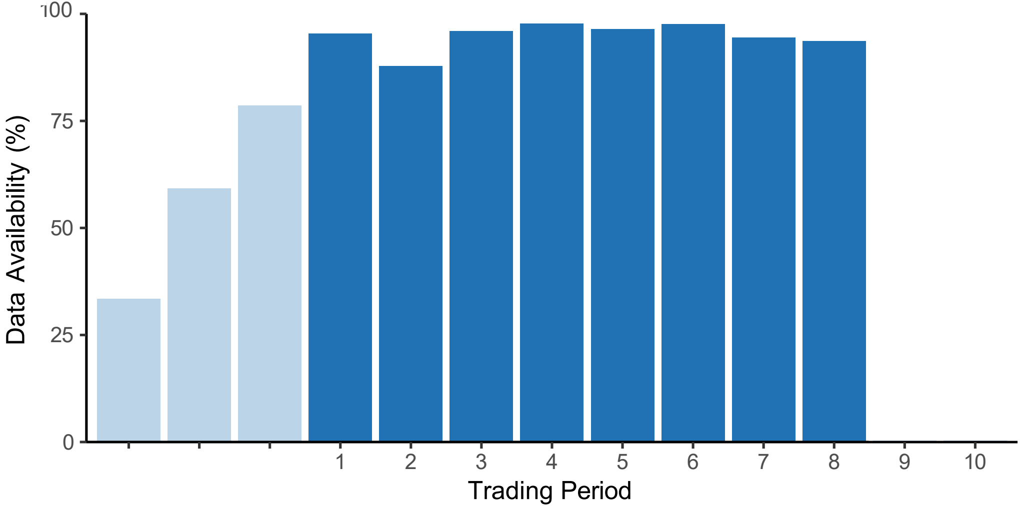

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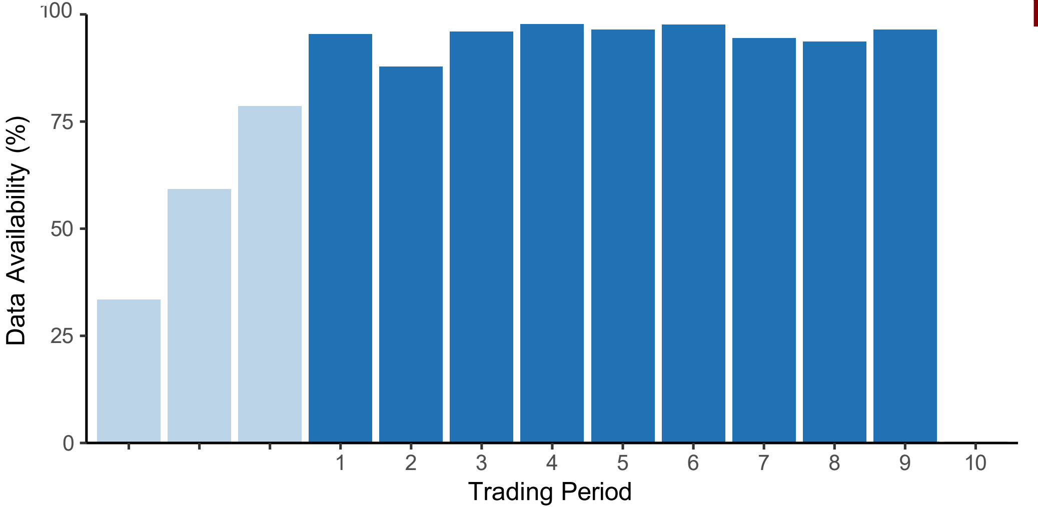

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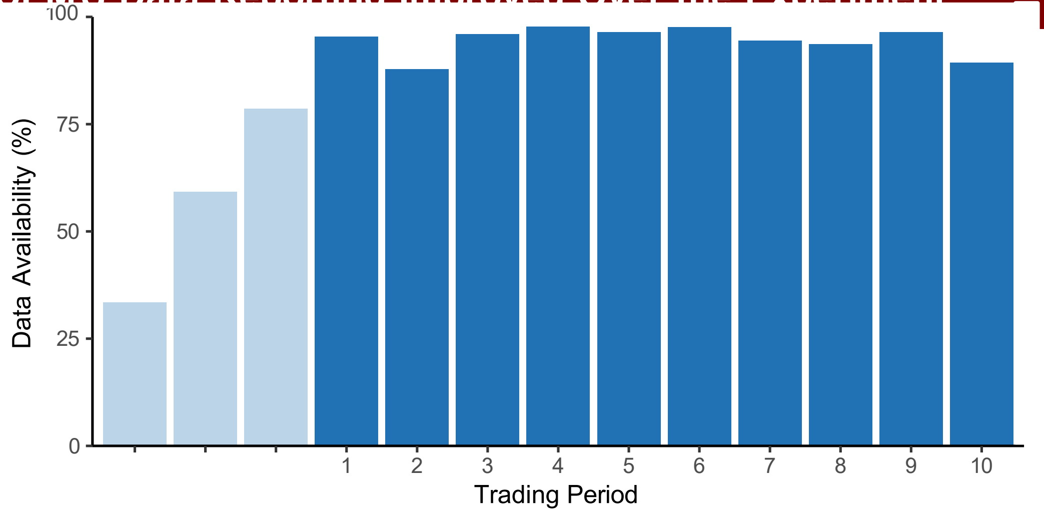

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Result 3: Market Reduced Abatement Costs

Revealed preference approach: Relate bids to costs

Firm *i* abatement costs in a compliance period:

$$Z_i(E_i) + P(E_i - A_i)$$

- $Z_i(E_i)$ is abatement costs as a function of emissions
- P is equilibrium permit price
- A_i is free allocation of permits to firm

Assume firms minimize pollution costs and they are price takers $\Longrightarrow$

$$\frac{\partial Z_i(E_i)}{\partial E_i} = MAC(E_i) = P$$

Plants bid their marginal abatement cost

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Places with Largest Combined Sector Damages

Fact 0:

	2030 (1)	2050 (2)	2099 (3)
1. Doha, Qatar	958	2831	12387
2. Dallas, United States	741	1144	6893
3. Phoenix, United States	686	1266	8316
4. Kuwait City, Kuwait	654	2283	13693
5. Manama, Bahrain	617	2125	9203
6. Las Vegas, United States	604	1115	7754
7. St. Louis, United States	533	694	5848
8. Baghdad, Iraq	505	1447	6544
9. Kansas City, United States	487	686	5293
10. Abu Dhabi, United Arab Emirates	468	1246	5685

Impacts are expressed as per-capita damages (2019 USD, PPP) for 2030, 2050, and 2099 under SSP3 and RCP8.5 scenario. The ten cities with the highest climate damages in 2030 are shown.

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	2030 (1)	2050 (2)	2099 (3)
1. Doha, Qatar	958	2831	12387
2. Dallas, United States	741	1144	6893
3. Phoenix, United States	686	1266	8316
4. Kuwait City, Kuwait	654	2283	13693
5. Manama, Bahrain	617	2125	9203
6. Las Vegas, United States	604	1115	7754
7. St. Louis, United States	533	694	5848
8. Baghdad, Iraq	505	1447	6544
9. Kansas City, United States	487	686	5293
10. Abu Dhabi, United Arab Emirates	468	1246	5685

Impacts are expressed as per-capita damages (2019 USD, PPP) for 2030, 2050, and 2099 under SSP3 and RCP8.5 scenario. The ten cities with the highest climate damages in 2030 are shown.

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