The Global Energy Challenge

Environment, Energy, and Development

Anant Sudarshan

Institutional and Organizational Economics Academy Summer School

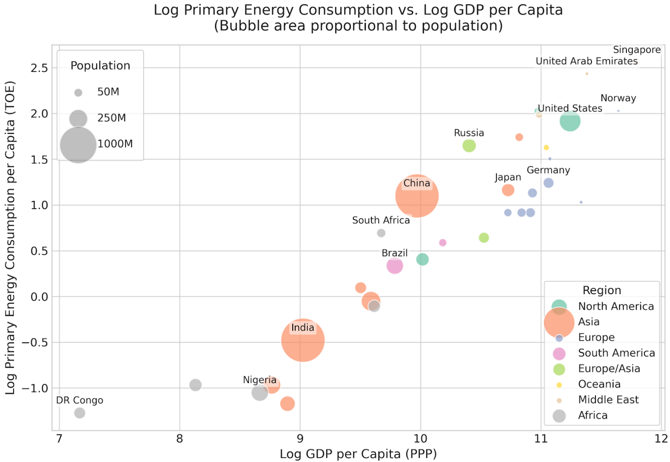
2026-04-06

1 / 82

Part I: What Is the Global Energy Challenge?

2 / 82

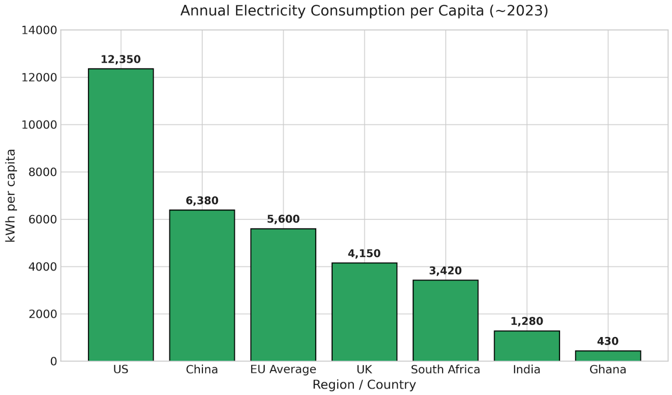
Energy consumption is critical for living standards



- Strong positive relationship between energy use and economic output
- No economic growth without energy
- Continued growth in energy demand is critical for improving quality of life

3 / 82

Energy consumption is extremely low in many highly populated regions

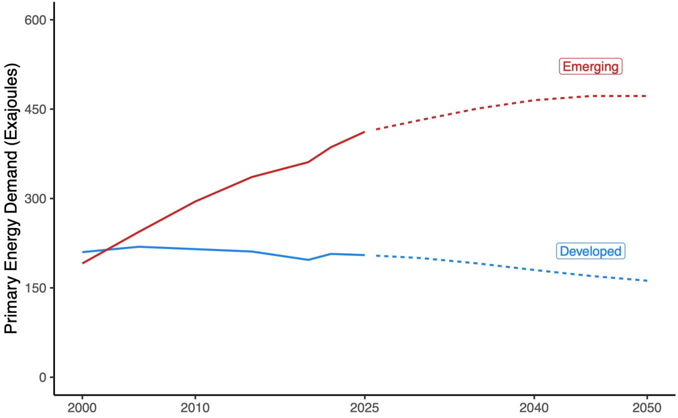


- 750 million people globally lack access to reliable electricity (IEA 2023)
- Bihar's 350 kWh/capita $\approx$ running a 60W bulb for 6 hours/day for 2.7 years
- Even connected households face severe rationing

Source: Ember Yearly Electricity Data

4 / 82

Energy demand in emerging economies is projected to grow

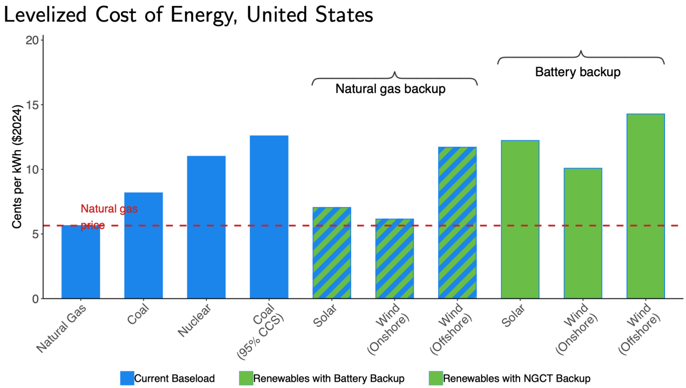


Source: BP Energy Outlook (2024), Current Trajectory Scenario

- Global energy demand set to grow 15% by 2050
- **100% of expected growth** occurs in emerging markets, especially Asia
- This growth is essential for development — not optional

5 / 82

Fossil fuels remain cheap — especially once storage costs are included

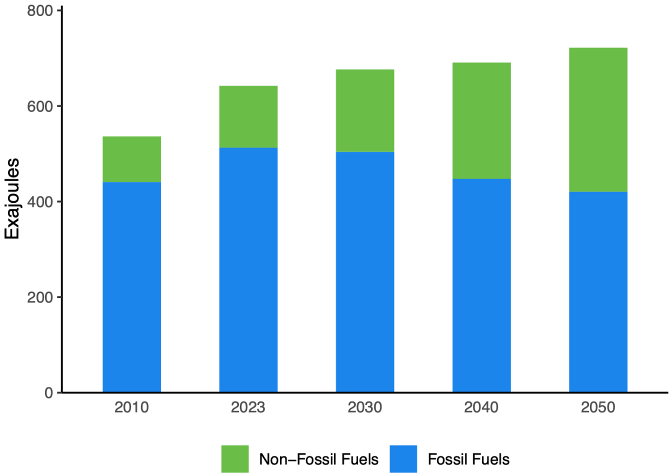


Source: EIA AEO (2025), EPIC via Greenstone (2025)

- Natural gas: cheapest source in the power sector
- Renewables + battery backup: >100% more expensive than gas
- Intermittency costs substantially change the calculus

6 / 82

Fossil fuels are expected to remain the dominant energy source

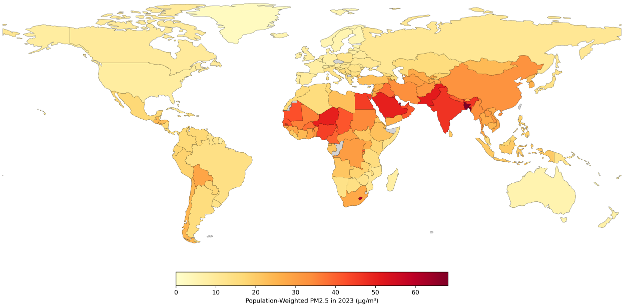


- 2023 fossil fuel share: 80%
- Projected 2050 share: 58% (IEA Stated Policies Scenario)
- Even under optimistic scenarios, fossil fuels remain central for decades

Source: IEA World Energy Outlook (2024)

7 / 82

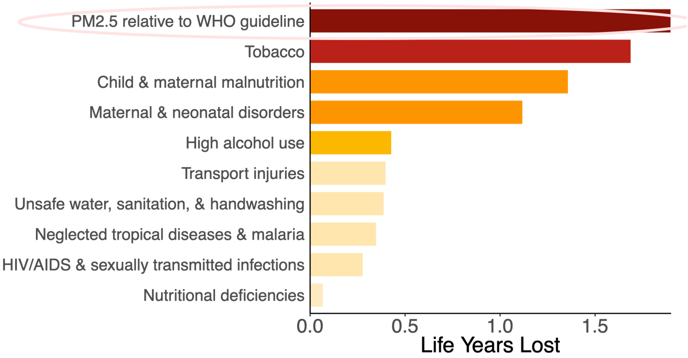
But fossil fuels cause severe air pollution



Satellite derived estimates of fine particulate air pollution in 2023 (Shen et al 2024)

- Developing countries face pollution levels 10× WHO guidelines
- Air pollution damages estimated at $4.5–6.1 trillion/year (World Bank 2016; Lancet Commission on Pollution and Health 2017)
- 4.7–6.5% of global GDP

Air pollution is the largest external threat to human life expectancy



Air Quality Life Index (2024)

Life-years lost: $PM_{2.5}$ vs. other risk factors (AQLI 2024).
Source: Air Quality Life Index Website (2024)

- $PM_{2.5}$: single largest external threat to global health
- Larger than alcohol, malnutrition, HIV/AIDS, malaria, or tobacco
- Burden falls overwhelmingly on developing countries

9 / 82

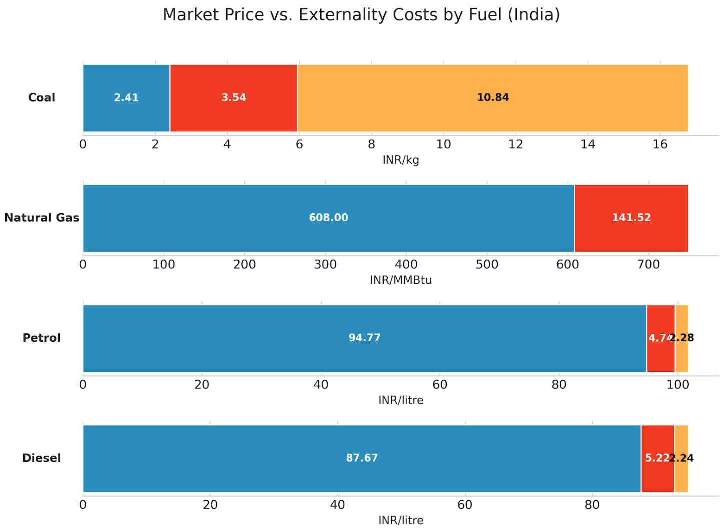
Pollution damages operate on multiple margins

Dose-response evidence across outcomes:

- **Life expectancy:** Each 10 μg/m^3 PM_{10} $\rightarrow$ ~0.6 years of life lost (Ebenstein et al. 2017)
- **Worker productivity:** Significant output losses from pollution exposure (He, Liu & Salvo 2019)
- **Cognitive performance:** Air pollution reduces test scores and decision quality (Zhang, Chen & Zhang 2018)
- **Crop yields:** Pollution reduces agricultural output (Burney & Ramanathan 2014)

10 / 82

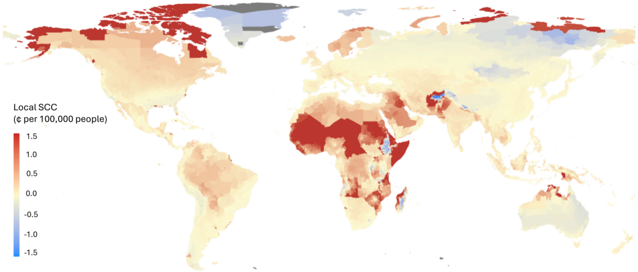
Local air pollution externalities dwarf the carbon tax on coal



The optimal pollution tax on coal due to mortality from local air pollutants alone (~0.145 USD/kg) is roughly 3× the carbon tax component (~0.047 USD/kg)

11 / 82

Climate change impacts are large and unequal



Social costs of carbon (Rennert et al. 2022 / EPA 2023, DSCIM framework, RCP4.5, $\eta = 1.34$)

- SCC: \$190/ton globally
- Non-OECD: \$184/ton; OECD: \$6/ton
- Annual damages (~57 Gt CO_2e): \$10,830 bn
- OECD causes \$2,429 bn more in damages to non-OECD than it bears

12 / 82

Related literature: Climate damages and adaptation

- **Carleton et al. (2022, *QJE*):** Global SCC from mortality alone ∼$37/tCO ; poor countries bear disproportionate burden due to limited adaptation capacity
- **Dell, Jones & Olken (2012, *AEJ: Macro*):** Temperature shocks reduce economic growth in developing (but not rich) countries
- **Barreca et al. (2016, *JPE*):** Dramatic 20th-century decline in US heat-mortality driven by AC diffusion — but adaptation requires energy access

See backup slides for additional references: Park et al. (2020), Davis & Gertler (2015)

13 / 82

The cruel arithmetic of the global energy challenge

Even if every OECD country goes **completely carbon neutral**, non-OECD countries must still cut their emissions by **88%** to reach the 2.0°C target

- Current annual emissions: ~57 Gt CO_2e (UNEP 2024)
- 2°C-consistent pathway (67% probability) implies a remaining budget of ~1,150 Gt CO_2 from 2020, or ~14 Gt/year on average (IPCC AR6)
- This requires massive cuts from countries that are poor, need energy for growth, and bear the least historical responsibility

Climate mitigation is not just an OECD problem — it requires transforming energy systems in precisely the countries that can least afford it

Source: Larsen et al. (2025)

14 / 82

The three prongs of the challenge

	Oslo	**Beijing**	**Lahore**
GDP per capita	High	Moderate	Low
$PM_{2.5}$ life-years lost	~0	2.9 years	5.3 years
kWh per capita	>20,000	~5,000	~590
Climate damage (% GDP, 2099)	−9%	2%	14%

Any energy-source choice simultaneously determines:

1. **Energy prices** → growth and poverty alleviation
2. **Air pollution** → health and human capital
3. **Climate change** → long-run damages, mostly borne by the poor

15 / 82

Summary: The policy challenge

The developing world faces three interlinked problems:

1. **Energy access:** Hundreds of millions lack reliable electricity; expanding access requires cheap power, which today means fossil fuels
2. **Air pollution:** Fossil fuel combustion causes enormous local health damages — but existing environmental regulation in developing countries largely fails
3. **Climate change:** Damages fall disproportionately on poor countries — adaptation requires cheaper energy and mitigation (likely) requires raising prices

The rest of this lecture: **research on two key policy frontiers**

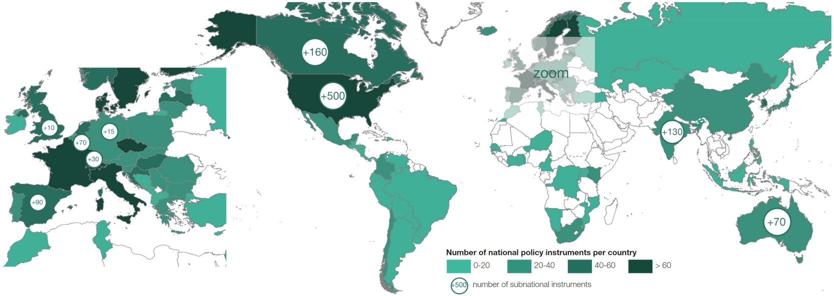
- Designing environmental regulation that actually works in low-capacity settings
- Reforming energy markets to enable access without fiscal collapse

16 / 82

Part II: Environmental Regulation Under Low State Capacity

17 / 82

The puzzle: stringent laws but dirty air



OECD PINE dataset of policy instruments

- Many developing countries have strict environmental standards and laws
- Yet pollution remains extreme
- *"I must emphasize that standards are not enough. They must also be enforced which is often difficult"* — Former Indian PM, Dr. Manmohan Singh

18 / 82

Why does command-and-control regulation fail?

The standard regulatory approach in India:

- **Command:** Mandate pollution control equipment installation
- **Control:** Uniform concentration standards (e.g. 150 mg/Nm^3 for PM)
- **Enforcement:** State Pollution Control Boards inspect plants

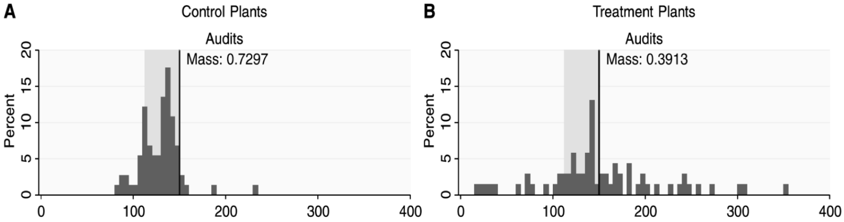
In practice:

- Incomplete compliance, limited capacity, discretionary enforcement
- Gujarat: $\sim$300 regulatory staff monitoring 20,000+ industrial plants
- $<$5% of plants inspected regularly
- Inspections: 1–2 times/year, each taking hours/days

19 / 82

Regulators operate with systematically false information

Evidence from :



Source: Duflo, Greenstone, Pande and Ryan (2013)

- Under the status quo: **73% of audit reports** cluster exactly at the regulatory standard
- Third-party auditors randomly assigned to plants produce accurate distributions
- Massive systematic misreporting ⇒ regulators cannot even identify violators

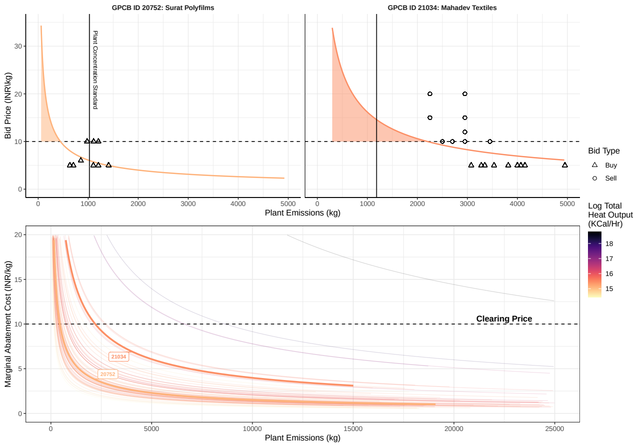
Related literature: Environmental regulation and monitoring

- **Greenstone & Hanna (2014, *AER*):** India's air and water regulations had limited impact on pollution and infant mortality despite stringent standards on paper
- **He, Wang & Zhang (2020, *QJE*):** Environmental regulation in China strategically weakened away from monitoring stations; automated monitoring improves accuracy
- **Zou (2021, *AER*):** US pollution is systematically higher on unmonitored days — strategic behaviour even in high-capacity regulatory settings

See backup slides for additional references: Greenstone et al. (2022), Ryan (2012)

21 / 82

Efficient regulation also requires knowing costs — C&C ignores heterogene



- C&C imposes a uniform standard regardless of abatement costs
- Textbook result: inefficient when firms have heterogeneous costs
- Markets equalize MACs across firms ⇒ same reduction at lower total cost

22 / 82

Three regulatory innovations tested via field experiments

A series of large-scale RCTs in India to test alternatives to C&C:

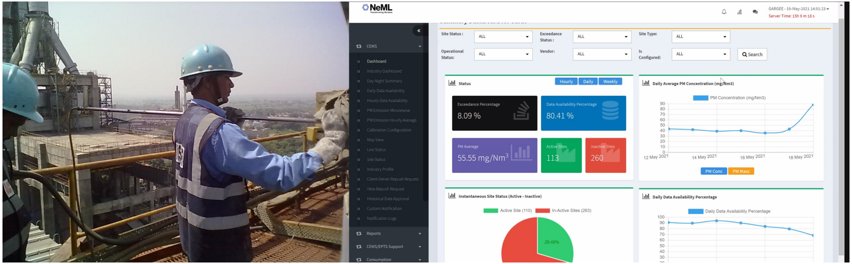
1. **Continuous Emissions Monitoring (CEMS)** — solve the information problem with technology
2. **Transparency and public disclosure** — leverage social pressure via star ratings
3. **Emissions trading** — create a market that aligns incentives

All three require **CEMS as infrastructure** — real-time automated pollution data from every plant's smokestack

Joint work with Michael Greenstone (UChicago), Rohini Pande (Yale), Nicholas Ryan (Yale)

23 / 82

Innovation 1: Continuous Emissions Monitoring Systems (CEMS)



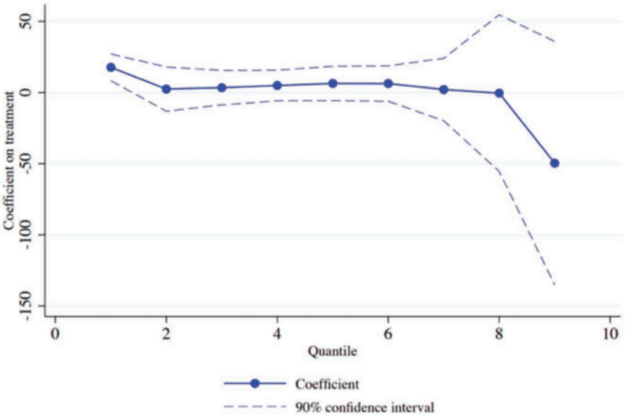
- Automated sensors on every smokestack, reporting data every 15 minutes
- Tamper-resistant, directly transmitted to regulator
- Replaces manual inspections: no need for inspectors to climb stacks and collect samples

Potential: Eliminates information asymmetry at low marginal cost

24 / 82

CEMS alone had limited impact on emissions

Experiment: ∼300 plants in Gujarat randomly assigned to CEMS vs. continued manual monitoring (3-year study)



25 / 82

CEMS alone had limited impact on emissions

Experiment: ~300 plants in Gujarat randomly assigned to CEMS vs. continued manual monitoring (3-year study)

Results:

- Pollution fell among the dirtiest plants
- **No strong evidence of significant overall emissions reductions**
- Better data did not automatically translate into better enforcement

Key lesson: Technology alone doesn't solve regulatory challenges — regulators still face capacity constraints and weak incentive structures. Better information is *necessary* but not *sufficient*.

26 / 82

Innovation 2: Public disclosure via star ratings (Maharashtra)

- Nearly 500 large industries across Maharashtra rated 1–5 stars based on emissions
- Ratings published online, updated regularly
- 7 workshops across 6 cities, social media outreach, local press coverage

Hypothesis: Public pressure + reputation concerns → lower emissions

27 / 82

Transparency increased regulatory action but not emissions reductions

Results:

- Star ratings **increased** the probability of receiving a show-cause notice (regulators responded to the information)
- But **no significant reduction in emissions**

Why?

1. **Limited public awareness** — low website traffic despite outreach
2. **Weak transmission mechanisms** — communities had limited leverage; industrial customers didn't respond to ratings
3. **Context dependence** — requires strong civil society, active media, responsive governance

Information and transparency are not enough without channels for action

28 / 82

Innovation 3: The Surat Emissions Trading System

The world's first particulate-matter emissions trading system in a developing country

Setting: Surat, Gujarat — 342 industrial plants (85% textiles)

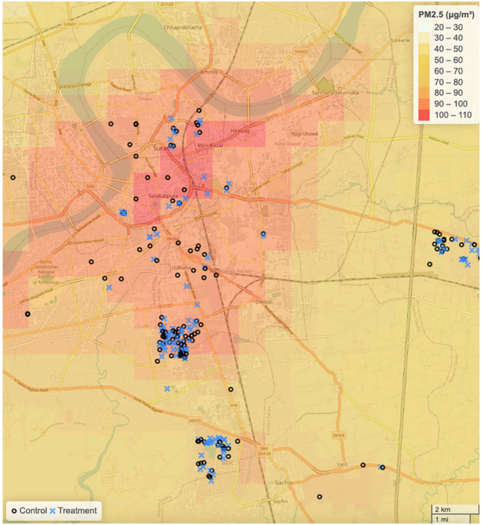
Design:

- **Cap:** Initially 280 tons SPM/month, revised down to 170 tons
- **Allocation:** 80% free (pro rata to boiler capacity); 20% auctioned
- **Trading:** Weekly double-sided auctions with uniform clearing prices
- **Price collar:** Floor 5/kg, ceiling 100/kg
- **Compliance:** Upfront deposit; fines at 2× ceiling for excess emissions
- **CEMS on all plants** — both treatment and control

Greenstone, Pande, Ryan & Sudarshan (2025, *QJE*), 140(2), 1003–1060

29 / 82

ETS experimental design

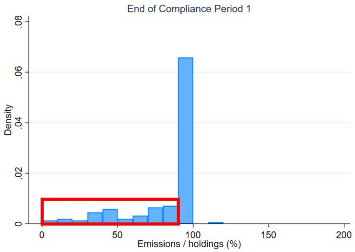


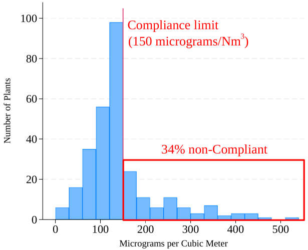
- **RCT:** Plants randomly assigned to market vs. C&C status quo
- CEMS on **all** plants
- 10 compliance periods, ∼1.5 years (from July 2019); each 4–6 weeks

Distribution of ambient pollution and plant

30 / 82

Result 1: The market dramatically improved compliance

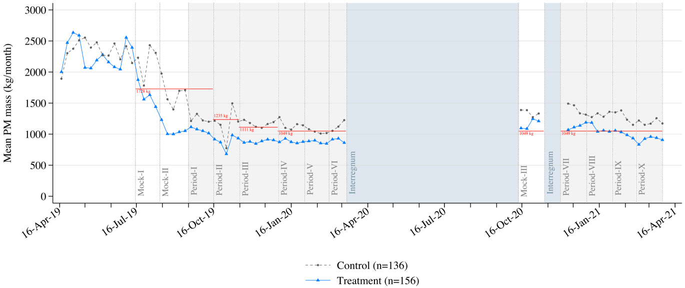




- C&C: **34% non-compliant**; ETS: **only 1%**
- Plants actively traded permits and aligned emissions with holdings
- "Money left on the table" fell from 12.5% to 2.8%
- Plants learned to use the market efficiently

31 / 82

Result 2: Emissions declined ~20%



$$\log(\mathrm{PM}_{it}) = \alpha + \beta \cdot \mathrm{ETS}_i \times \mathrm{Post}_t + \gamma_i + \delta_t + \varepsilon_{it}$$

- Effect: ~**19–32% reduction**
- Gap opens during first trading period and persists
- Cap was set loosely — efficiency gains freed up abatement capacity

32 / 82

Result 3: Abatement costs fell ∼12%

Approach: Recover plant-specific Marginal Abatement Cost (MAC) functions from auction bidding data (revealed preference)

$$\log \text{MAC}_i = \beta_1 \log E_i + \beta_2 \log H_i + \xi_i$$

- Identified from equilibrium condition: firms bid up to their MAC
- Structural estimation allows counterfactual comparison with C&C costs

Result: The market reduced total variable abatement costs by **10–16%** relative to a uniform-standard C&C regime, holding total emissions constant

Cost heterogeneity across firms is substantial; the market exploits it

33 / 82

Cost-benefit analysis: benefits vastly exceed costs

Component	Estimate
Treatment effect on emissions	-19.4%
Reduction in ambient $PM_{2.5}$	5.5–8.5 $\mu g/m^3$
Life-years gained (annual, city-wide)	53,000–89,000
Annual health benefit	INR 34 billion ($847 million)
Annual monitoring costs (city-wide)	INR 310 million ($3.9 million)
Benefit-cost ratio	$\sim$**100:1 to 215:1**

Health benefits valued using: Ebenstein et al. (2017) dose-response $\times$ Nair et al. (2021) VSL for India

34 / 82

Why did markets succeed where the other approaches failed?

	CEMS Only	**Transparency**	**ETS**
Emissions reduction	Low	None	**High**
Compliance	Moderate	Low	**Near-perfect**
Cost-effectiveness	Low	Moderate	**High**
Scalability	High	High	Moderate
Political feasibility	High	High	Moderate

Markets work because they **align incentives** (pollution reduction = profit), **solve the information problem** (CEMS + price discovery), **reduce discretion** (financial penalties self-execute), and **accommodate heterogeneity** (multiple compliance pathways).

35 / 82

Related literature: Market-based environmental policy

- **Schmalensee & Stavins (2013, *JEP*):** US SO allowance trading demonstrated feasibility and large cost savings of cap-and-trade at scale
- **Fowlie, Holland & Mansur (2012, *AER*):** NOx cap-and-trade in southern California reduced emissions but had distributional consequences across communities
- **Fowlie (2009, *AEJ: Economic Policy*):** Under incomplete regulation (some firms regulated, others not), cap-and-trade can cause emissions leakage — design details matter

See backup slides for additional references: Shapiro & Walker (2018), Hernandez-Cortes & Meng (2023)

36 / 82

Scaling: from Surat to national policy

- **2019:** Surat pilot — 155 plants
- **2022:** Control plants added to market — 350+ plants
- **2023:** New PM market launched in Ahmedabad
- **2024–25:** Maharashtra developing SO_2 market; other states exploring
- Gujarat announced plans for CO_2 and water markets

Emissions Market Accelerator (EMA): Working across 8 Indian states to help design and implement environmental markets

Developing countries can leapfrog to modern regulatory approaches — much as they did with mobile phones and digital payments

37 / 82

Part III: Energy Access, Markets, and Subsidy Reform

38 / 82

The electricity access problem: connections do not mean supply

- ~750 million people unconnected to the grid
- Hundreds of millions more connected but with unreliable service
- Grid coverage has expanded dramatically — but connection $\neq$ 24-hour supply

39 / 82

Per-capita electricity consumption in developing countries is strikingly low

Country	kWh/capita	% of US consumption
United States	~13,000	100%
China	~5,000	38%
India	~1,200	9%
Bihar (India)	~350	3%
Sub-Saharan Africa (avg.)	~500	4%

- The strong cross-country correlation between electricity consumption and GDP suggests this is a binding constraint on development
- And retail electricity prices are **no cheaper** in developing countries despite much lower incomes

40 / 82

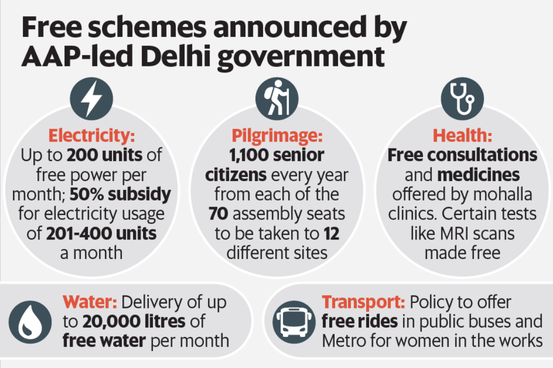
Related literature: Energy access and development

- **Dinkelman (2011, *AER*):** Rural electrification in South Africa increased female employment — electricity frees time from fuel collection and enables home production
- **Allcott, Collard-Wexler & O'Connell (2016, *AER*):** Electricity shortfalls reduce Indian manufacturing output by 5–10%; generators are a costly but common substitute
- **Lee, Miguel & Wolfram (2020, *JPE*):** Subsidised grid connections in rural Kenya have high take-up but very low usage — raising cost-effectiveness concerns about grid expansion

See backup slides for additional references: Lipscomb, Mobarak & Barham (2013), Wolfram, Shelef & Gertler (2012)

41 / 82

Is electricity a right?



A powerful **social norm** in many developing countries:

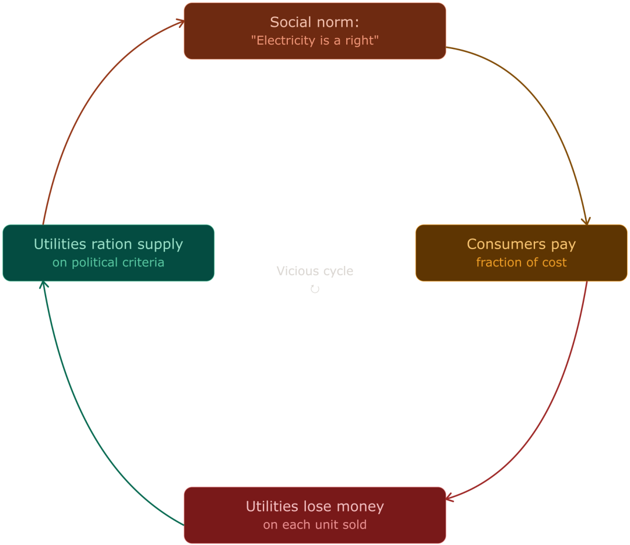
- Electricity treated as a basic right, not a market commodity
- Politicians promise cheap or free power
- Non-payment and theft are tolerated
- Enforcement is politically costly

What are the consequences?

Burgess, Greenstone, Ryan & Sudarshan (2020), *JEP*

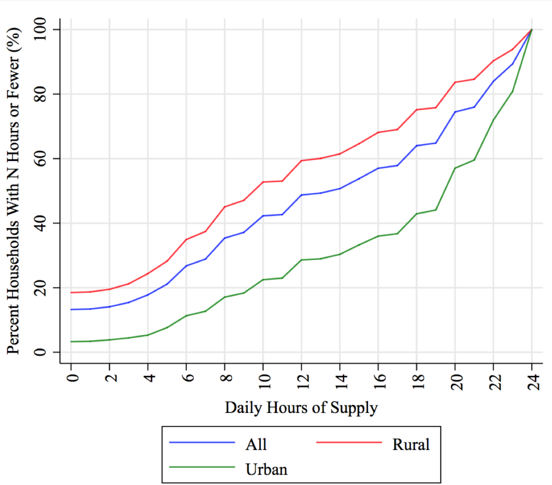
42 / 82

The vicious circle of electricity as a right



43 / 82

Evidence: Massive rationing even among connected households

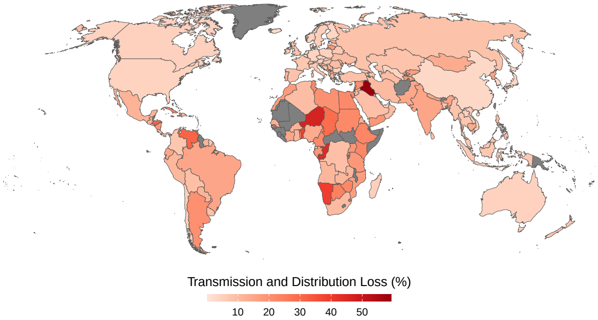


CDF of daily hours of electricity (IHDS 2012)

- Even connected households face heavy rationing
- Rural areas: many receive <12 hours/day
- Urban areas: better but far from 24-hour supply
- Quality varies enormously across regions and time

44 / 82

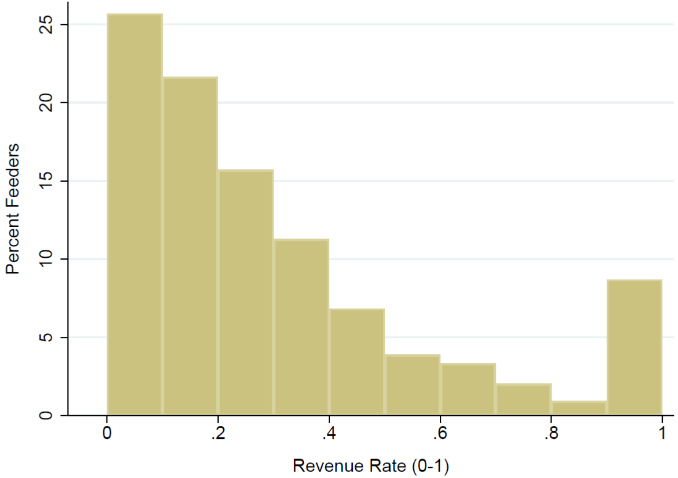
T&D losses reveal the scale of the problem



- OECD technical losses: ~5–6%
- Indian states: 20–50%+
- Excess = theft + non-payment + billing failures
- A business receiving only $80 per $100 of product would want to sell much less

45 / 82

Revenue recovery at the feeder level is catastrophically low

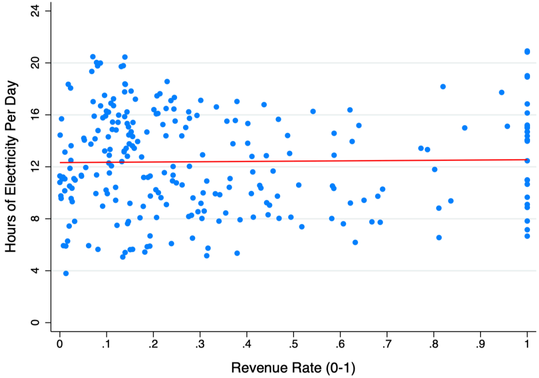


- ~50% of feeders recover <20% of tariff value of electricity injected
- Payment bears **no relationship to supply quality** — markets do not clear
- 122 different tariff schedules — a tangled web of subsidies

Distribution of feeder-level revenue rates in Bihar

46 / 82

The market is broken: payment supply



- Consumers who pay more do **not** receive better service
- Consumers who pay less do **not** get cut off
- The feedback loop between WTP and service provision is severed
- This is the core market failure

47 / 82

Customers expect no enforcement

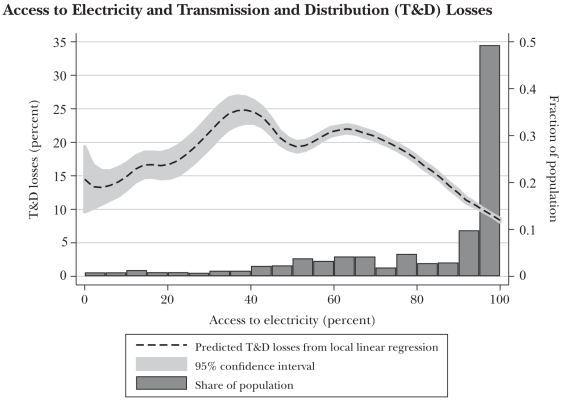
Violation	% who think penalty unlikely
Late payment	78%
Meter tampering	75%
Illegal hooking	76%
Bribing utility officials	77%

- Survey evidence: the overwhelming majority of consumers believe violations will go unpunished
- This is rational — enforcement is indeed rare
- The equilibrium is self-sustaining

Source: Burgess, Greenstone, Ryan & Sudarshan (2020)

48 / 82

A "New Kuznets Curve" in electricity losses



Source: World Bank.

- Losses first **rise** with development (grids expand but institutions lag)
- Then **fall** as institutions strengthen and enforcement capacity grows
- Many developing countries are stuck on the rising portion
- Breaking through the peak requires institutional reform, not just infrastructure

49 / 82

The fiscal scale of the problem

- India's full subsidy/theft/non-payment costs: ~**$40 billion/year**
  - 31% of direct tax collections
  - 1.5% of GDP
  - 3.5× the central education budget
- Lowest-income countries recover <50% of electricity costs from consumers

Two research questions:

1. Can existing enforcement tools break the cycle?
2. Can infrastructure investment (smart meters) break the cycle?

50 / 82

Can enforcement tools work? Setting: Madhya Pradesh

Context:

- Population: 85 million; GDP per capita: $1,500
- Utilities recovered only 70% of power purchase costs (2020)
- Accrued $1.43 billion in losses in 2018–19
- Average rural outages: ∼4 hours/day

Key stylised facts:

- Non-payment is **not** primarily about income — payment fractions are low across the income distribution
- "Carrots" (debt waivers) have limited effects on payment behaviour
- "Sticks" are practically never used — vanishingly small share of defaulters receive notices or disconnections

51 / 82

Literature context

This work sits at the intersection of:

Energy economics:

- Non-payment as a central constraint (Burgess et al. 2020; Jack & Smith 2020; McRae 2015)

Public finance / tax compliance:

- Allingham & Sandmo (1972), Becker (1968): deterrence theory
- Recent experimental evidence: Bergeron et al. (2024, *AER*), De Neve et al. (2021), Brockmeyer et al. (2019, *AEJ: EP*), Holz et al. (2023, *JEBO*), Pomeranz (2015, *AER*)

Contribution: Brings tax-compliance experimental tools to a fiscally important development setting where the enforcement margin is arguably more binding

52 / 82

RCT design: 30,000 households in Madhya Pradesh

Sample: All households with INR 1,200 in arrears; metered, non-BPL domestic customers

Light-touch treatments (SMS):

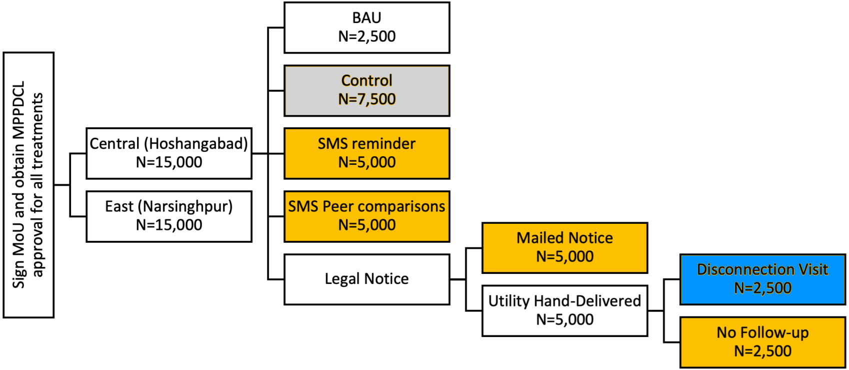
- SMS reminder: standard "pay or be disconnected" warning
- SMS peer-comparison nudge: "You paid X%, similar customers paid Y%"

Heavy-touch treatments (formal legal notices under Electricity Act 2003, §56):

- Mailed legal notice
- In-person delivery by utility staff (no follow-up disconnection)
- In-person delivery with actual disconnection for non-payers

53 / 82

RCT design: 30,000 households in Madhya Pradesh



54 / 82

SMS nudges and peer comparisons: no effect

- Neither SMS reminders nor peer-comparison nudges reduce debt
- Point estimates near zero, confidence intervals include zero
- Behavioural nudges that work in rich-country tax settings have **no effect** in this context
- The baseline expectation of non-enforcement is too strong for light-touch interventions to overcome

Mailed notices work — but in-person delivery by staff does not

Treatment	**ITT on arrears (INR)**	**SE**
Mailed legal notice	−186.5***	(42.04)
In-person delivery (utility staff)	−6.20	(54.93)

A striking result:

- Formal mailed notices (impersonal, from the institution) produce significant arrears reduction
- The **same notice delivered in person** by utility staff has **zero effect**
- Interpretation: staff presence undermines credibility — consumers may infer that the "stick" is negotiable

56 / 82

Ongoing work: norms, honesty, and social pressure

If standard deterrence tools are insufficient, perhaps the problem is fundamentally about **norms**

New study: Lab-in-the-field + real-world interventions with 80,000 consumers in MP

1. **Honesty game** (adapted from Abeler, Nosenzo & Raymond 2019, *Econometrica*): consumers privately report arrears with monetary incentive to lie — measures intrinsic honesty norms
2. **Fairness/dictator game:** Enumerators offer to pay bills; consumers choose how much to "return" — measures norms of reciprocity
3. **Naming & shaming:** Public disclosure of defaulter lists — leverages social pressure

Experimental measures are linked to actual administrative payment data

57 / 82

Can infrastructure solve the problem? The case for smart meters

If the social norm of non-payment cannot be easily broken with enforcement, perhaps the solution is **technological:**

Smart meters:

- Prepaid or remotely disconnectable meters
- Eliminate the billing–collection gap
- Make electricity **excludable** — a prerequisite for treating it as a private good
- India's RDSS program: $40 billion to install 250 million smart meters

Key question: What happens when you make it harder to steal electricity?

Burgess, Greenstone, Ryan & Sudarshan (ongoing)

58 / 82

Theoretical framework: theft as an effective price reduction

Consumer demand: $D(\cdot)$. Only fraction $\delta \in [0,1]$ of consumption is billed.

Effective price $= \delta\tau$ (where $\tau =$ official tariff)

$$q = D(\delta\tau), \qquad \text{Billed quantity} = \delta \cdot D(\delta\tau)$$

Smart metering $=$ increase in δ

Two effects of raising δ:

- Quantity demanded falls: $\frac{\partial q}{\partial \delta} \propto \varepsilon_D$ (always negative)
- Billed quantity: $\frac{\partial(\delta q)}{\partial \delta} \propto 1 + \varepsilon_D$ (rises unless $|\varepsilon_D| > 1$)

Smart meters simultaneously **reduce consumption** and **increase billing** — provided demand is not too elastic

59 / 82

The deadweight loss from under-pricing via theft

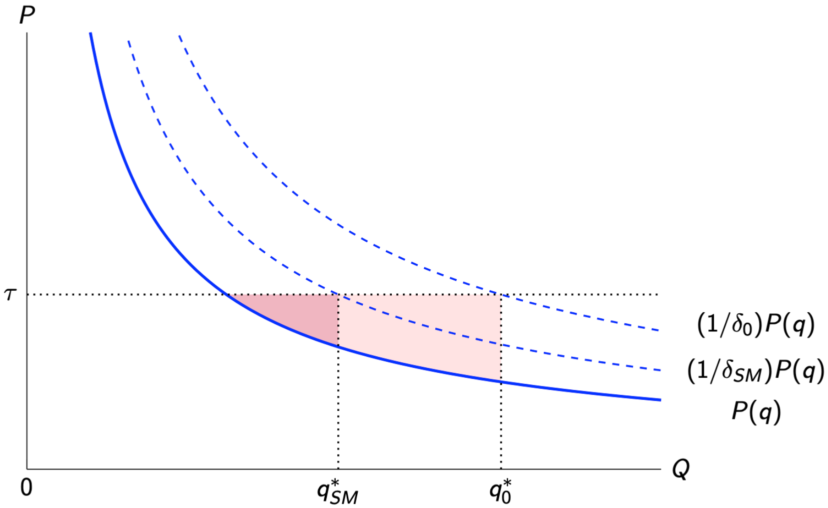
- Demand curve $D(p)$ slopes downward; tariff τ; effective price $\delta\tau < \tau$
- Lower effective price quantity consumed rises from $q(\tau)$ to $q(\delta\tau)$
- The triangle between the demand curve, tariff, and effective price is **deadweight loss**

When $\delta < 1$, consumers face $\delta\tau < \tau$ overconsumption relative to the social optimum

- DWL $=$ resources used to generate power that consumers value at less than cost
- This is the efficiency cost of the implicit theft "subsidy"

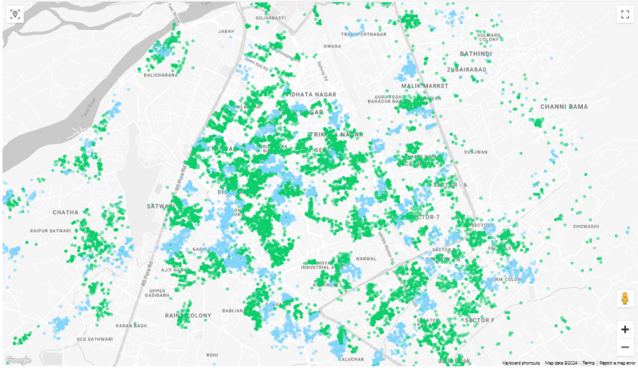
60 / 82

Smart meters push demand curve inward



61 / 82

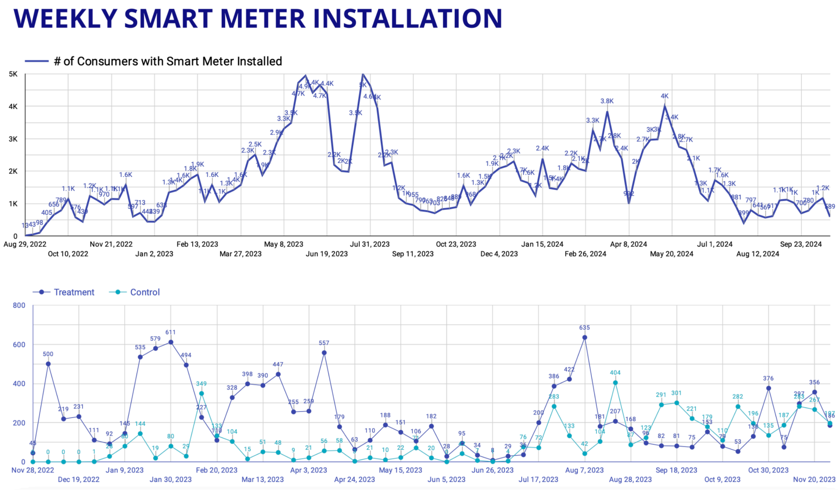
Experimental design: RCT at the transformer level in Jammu



- **Setting:** Jammu Power Distribution Corp. — high T&D losses
- **Randomization:** Distribution transformers (within feeders within subdivisions)
- **Treatment:** Smart meter installation
- **Data:** Consumer-level billing/payment + feeder-level energy injection

62 / 82

Smart meter installation: treatment vs. control over time



Treatment gap opens and closes over a one year period

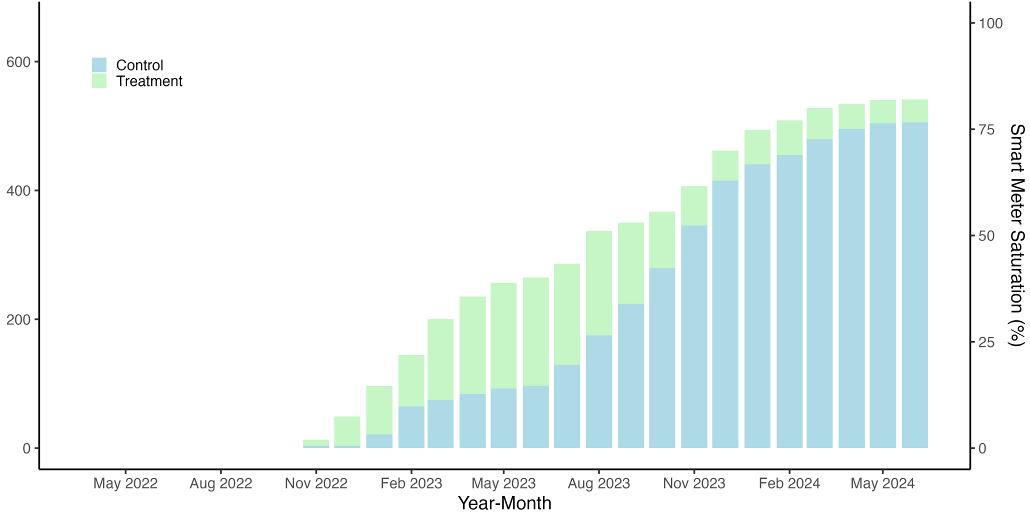
First stage: Treatment caused a roughly one-year boost in smart-meter installation rates

$$\text{SmartMeterShare}_{it} = \beta \cdot \text{Treatment}_i \times \text{Post}_t + \delta_c + \varepsilon_{it}$$

Clustered at transformer level. Experiment has power over a one-year horizon.

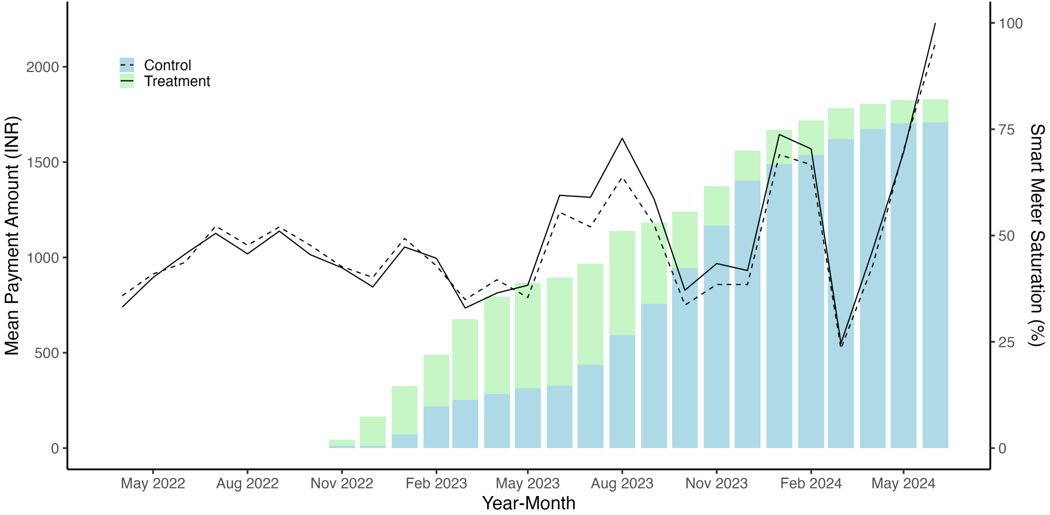
64 / 82

Smart meters increase the probability of a non-zero bill



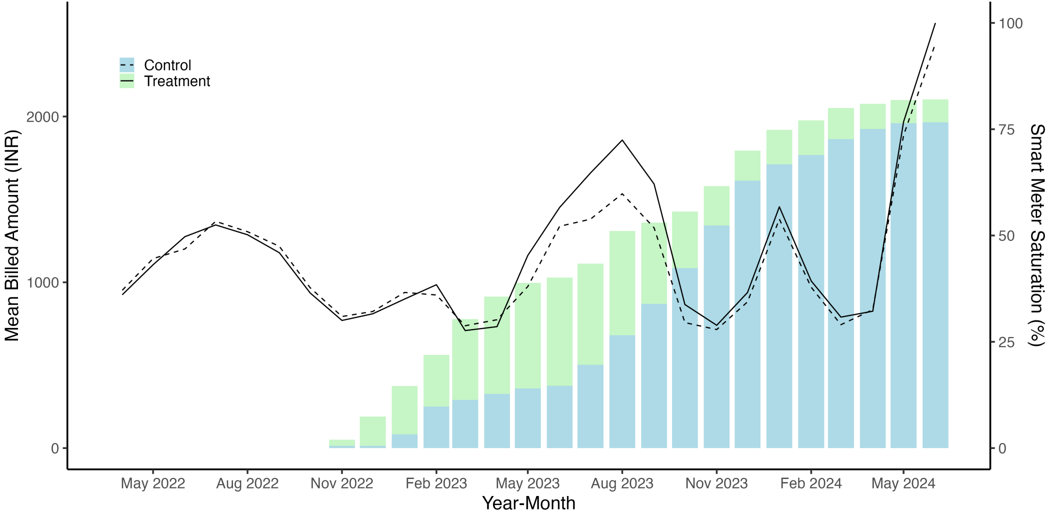
65 / 82

Smart meters increase billed amounts



66 / 82

Smart meters increase billed consumption (kWh)



67 / 82

IV estimates: effect of smart metering on key outcomes

	Billed Consumption (kWh) (1)	Bills (INR) (2)	Payments (INR) (3)
Smart Meter Share	176.82***	765.67***	647.42***
	(17.96)	(72.74)	(55.69)
Year-Month FE	Yes	Yes	Yes
Transformer FE	Yes	Yes	Yes
Consumer Obs.	28906	28906	28906
Month-Year Obs.	30	30	30
Baseline Mean	304.86	1021.71	972.23

But is consumption actually rising, or just billing?

The consumer-level results could reflect:

1. **More accurate billing** (consumption was always there, just not measured), or
2. **Actual increase in consumption** (unlikely — prices rose)

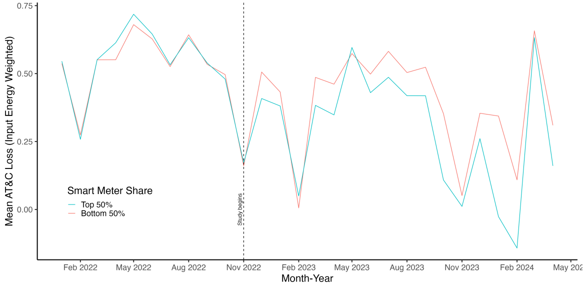
Critical test: Turn to **feeder-level energy injection data** — the only reliable measure of *true* total consumption

- Feeder meters measure total electricity entering the distribution network
- This quantity is measured at the utility's own infrastructure — not affected by consumer-level theft

See Ahmad et al. (2025) for similar approach in Pakistan

69 / 82

Aggregate result: actual consumption falls sharply



Smart metering **reduces quantity demanded** at the aggregate level

- Billed consumption up   charged for what they used to steal
- Actual consumption down   higher effective prices reduce demand
- **Losses down**   gap between injected and billed shrinks

70 / 82

Welfare calibration: recovering the efficiency loss

Two key parameters from the experiment:

1. **Billing efficiency:** $\delta_0 = 0.63 \rightarrow \delta_{SM} = 0.89$
   - Before smart meters: only 63% of consumption is billed
   - After: 89% is billed
2. **Demand elasticity:** $\varepsilon = -0.58$ (from aggregate feeder-level regressions)

Calibrate iso-elastic demand: $q_0 = A(\delta_0 \tau)^{\varepsilon}$

- Baseline consumption: $q_0^* = 466$ kWh
- Post-smart-meter: $q_{SM}^* = 381$ kWh
- ΔConsumer Surplus $= -221$ INR (consumers lose)
- ΔTotal Surplus $=$ **+75 INR** (DWL eliminated)

71 / 82

The efficiency cost of the theft "subsidy"

Metric	Estimate
Consumer surplus decline	37% of baseline bill payment
DWL per rupee transferred	0.20

For every 1 transferred to consumers via the status-quo (theft-enabled) metering system, society incurs a **deadweight loss of 0.20**

- This is a very leaky bucket (Okun 1975): the implicit subsidy through theft is highly inefficient
- By comparison, well-designed cash transfers have negligible administrative DWL
- Smart meters eliminate this DWL while direct transfers could compensate vulnerable consumers

72 / 82

Smart meters improve efficiency

In developed countries, smart meters have benefits via: - Cost reductions in meter reading - Enabling sophisticated tariffs (if only they were adopted!)

In a high-loss environment, smart meters also increase the effective price of power

- First-order implications for efficiency
- Externally relevant to India as a whole under massive RDSS metering campaign
- Literature suggests larger feedback to efficiency: stronger incentives for supply side to maintain reliable power supply

73 / 82

Policy relevance: India's $40 billion metering program

India's **Revamped Distribution Sector Scheme (RDSS):**

- Target: 250 million smart meters
- Budget: $40 billion
- Goal: Bring T&D losses to 12–15%

Our results suggest:

- Smart meters can substantially improve cost recovery
- The efficiency gains (DWL eliminated) are large
- But consumer welfare declines — the distributional question is central
- Complementary policies (targeted transfers, lifeline tariffs) are essential

Literature suggests a further feedback: stronger cost recovery → stronger supply-side incentives → more reliable power (Burlig & Preonas 2024; Fried & Lagakos 2023)

74 / 82

Related literature: Metering, pricing, and off-grid alternatives

- **Jack & Smith (2020, *AEJ: Applied*):** Prepaid metering in South Africa reduces consumption ∼13% (mostly among non-payers) and substantially improves utility revenue
- **McRae (2015, *AER*):** Below-cost electricity pricing in Colombia creates a subsidy trap — utilities can't invest, service deteriorates, making reform harder
- **Mahadevan (2024, *AER*):** Political corruption in Indian electricity increases theft and lowers revenue; alignment between local politicians and the utility worsens outcomes

See backup slides for additional references: Berkouwer & Dean (2022), Grimm et al. (2020)

75 / 82

Thank you!

76 / 82

Backup: Additional Literature References

77 / 82

Additional references: Climate damages and adaptation

- **Park et al. (2020, *AEJ: Economic Policy*):** Cumulative heat exposure during the school year reduces student achievement; school air conditioning substantially mitigates
- **Davis & Gertler (2015, *PNAS*):** Rising incomes and temperatures will drive massive AC adoption in developing countries, creating mitigation–adaptation tradeoffs

78 / 82

Additional references: Environmental regulation and monitoring

- **Greenstone et al. (2022, *AER: Insights*):** Automated monitoring in China combined with accountability policies $\rightarrow$ significant pollution reductions
- **Ryan (2012, *Econometrica*):** Structural estimation of environmental regulation costs in Indian cement — heterogeneous and substantial

79 / 82

Additional references: Market-based environmental policy

- **Shapiro & Walker (2018, *AER*):** US manufacturing pollution declined primarily due to environmental regulation, not offshoring or productivity changes
- **Hernandez-Cortes & Meng (2023, *J. Public Econ.*):** California's carbon market did not exacerbate pollution disparities across disadvantaged communities

80 / 82

Additional references: Energy access and development

- **Lipscomb, Mobarak & Barham (2013, *AEJ: Applied*):** Hydropower-driven electrification in Brazil raised incomes, housing quality, and HDI
- **Wolfram, Shelef & Gertler (2012, *JEP*):** Income growth in developing countries will drive massive energy demand increases — a first-order global challenge

81 / 82

Additional references: Metering, pricing, and off-grid alternatives

- **Berkouwer & Dean (2022, *AER*):** Credit constraints (not inattention) are the binding barrier to clean technology adoption by low-income households in Nairobi
- **Grimm et al. (2020, *JAERE*):** Off-grid solar in Rwanda — substantial demand for basic lighting but willingness-to-pay is well below cost of provision

82 / 82