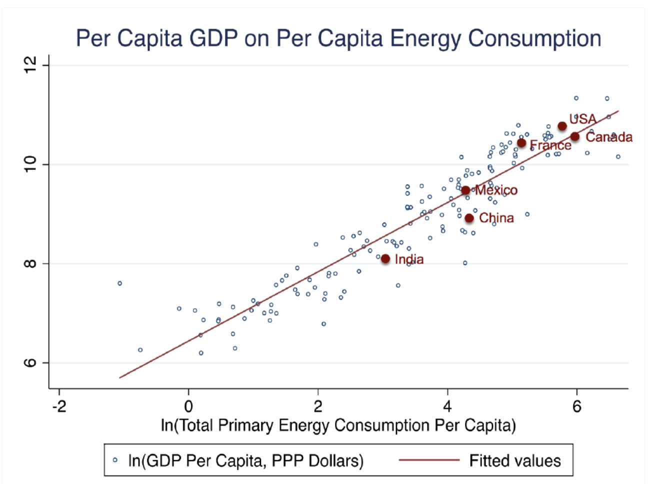
Energy and Development

Jonathan Colmer

University of Virginia

Fact 1: Energy is strongly correlated with economic development

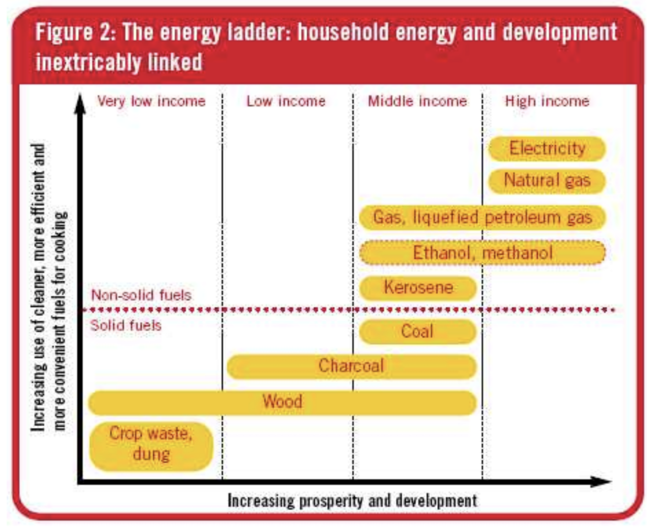


Fact 2: Electricity access varies by country

Country	Population (millions)	KWh/Capita	% Access
USA	314	12,954	100%
UK	63	5,452	100%
Russia	143	6,617	100%
China	1,350	3,475	100%
India	1,263	744	78%
Bihar	99	95	52%
Ghana	25	346	64%
Ethiopia	92	57	26%

It takes 131 KWh to use a 60 Watt bulb for 6 hours per day for a full year.

Fact 3: Energy sources vary in quality



Energy as a driver of development

- The general argument is that lack of access to reliable energy fundamentally constrains the set of productive activities that households can be engaged in.
- It is potentially a key contributor to the large productivity gap between developed and developing countries
  - Small fraction of aggregate employment
  - But provides key input
    - Low substitutability with other inputs (Hassler et al. 2016)
    - Potential "weak link" in development (Jones, 2011)
- Frequently ranked as a key barrier to growth by firm managers
- Demand tends to exceed supply $\Rightarrow$ frequent blackouts

The Problem

- There are several layers to the energy-development problem

  1. lack of access to grid electricity $\Rightarrow$ particularly in rural areas and in informal settlements in urban areas
  2. demand tends to exceed supply $\Rightarrow$ frequent blackouts
  3. electricity interuptions common $\Rightarrow$ electricity supply unreliable
  4. key reasons for shortage

     4.1 theft

     4.2 distribution companies cannot raise retail prices to clear the market

     4.3 underinvestment in generation capacity

- equilibrium where electricity prices low or zero but supply either limited or unreliable

In Short, Energy Is Not Priced Correctly

- Low repayment rates limit investment and supply
    - Potential for a virtuous cycle between repayment rates, energy supply and growth
- Energy subsidies are huge and fail to target the poor
    - Subsidies vs. direct redistribution
- Pricing distortions favor fossil fuels
    - Correct pricing of energy will improve health and reduce climate damages.

Research Questions

- What are the constraints to electricity access?
    - What are the economic consequences of electrification?
- How can repayment rates be increased to encourage investment?
- What are the external costs of energy consumption and how can environmental regulation and policy internalise these costs?
    - How do firms respond to these policies?
    - How do external costs affect worker and firm performance? To what degree can firms manage these effects?
- There is very little evidence on any of this or the channels involved.

Identifying the Effect of Electrification on Development

- Identifying the effect of energy access on development indicators suffers from the classic reverse causality problem:
    - Does energy access (e.g. electrification) drive development?
    - Or, does future development in an area encourage governments and private entities to invest in the energy infrastructure in that area?
- Methodological approaches include:
    - Instrument for energy infrastructure (electrification)
    - Randomize infrastructure access

Rural Electrification

Rural electrification is a priority for policymakers

- 1.3 billion people live without electricity in their homes
- UN Sustainable Energy for All (SE4All):
  - "Nearly one person in five on the planet still lacks access to electricity... This is a major barrier to eradicating poverty and building shared prosperity."
- Power Africa: Connect 60 millions new homes
- Countries have Rural Electrification Authorities

Possible Effects

- The IADB identified these potential effects of a rural electrification program:
  - Within the household: **time use, education, health, mental health, security, communication, level of employment/income, time and expense of transport, energy expenses and consumption**.
  - Effects may vary by gender
  - Some of the effects are likely internalized by the household but not all.
  - At the community level: **health services and security, education, income, employment**

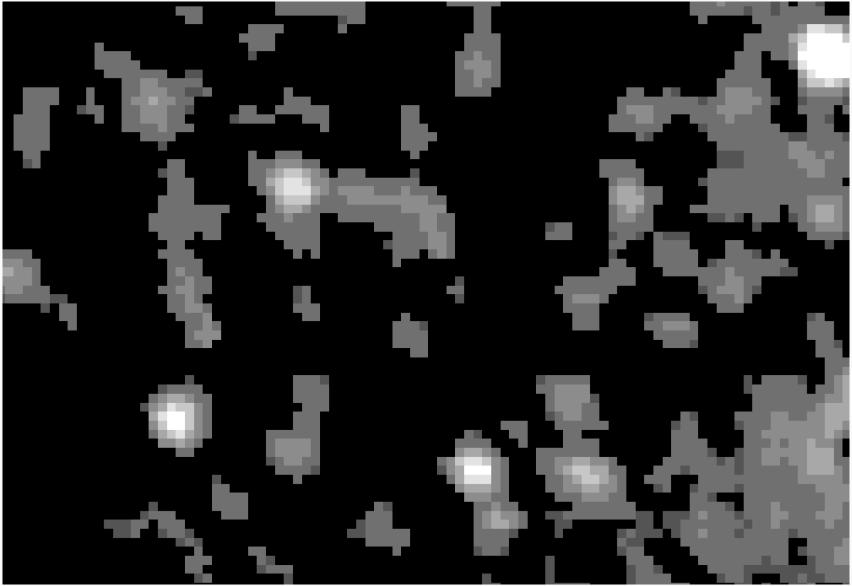
Burlig and Preonas (2022) – Context

- Context: Massive rural electrification program in India
  - World's largest un-electrified population
  - Program targeted $>$ 400,000 villages ($\approx$2/3)
- Research design: RDD based on population eligibility cutoff set in 2001
  - Estimate an ITT effect
  - Identifying assumptions:
    - Continuity across threshold
    - Population not manipulable
    - No spillovers
- Outcomes; administrative data on development indicators 3-5 years into the program.

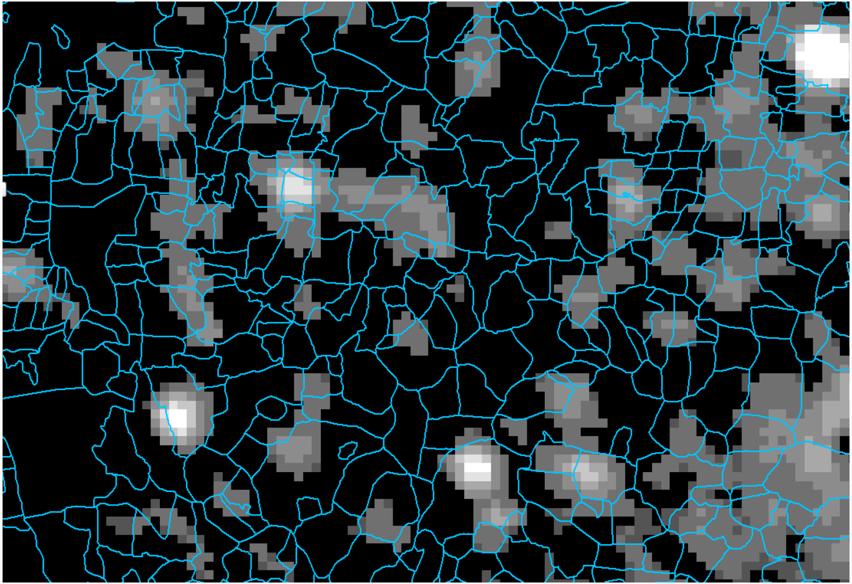
Nighttime Lights (2001)

Nighttime Lights (2011)

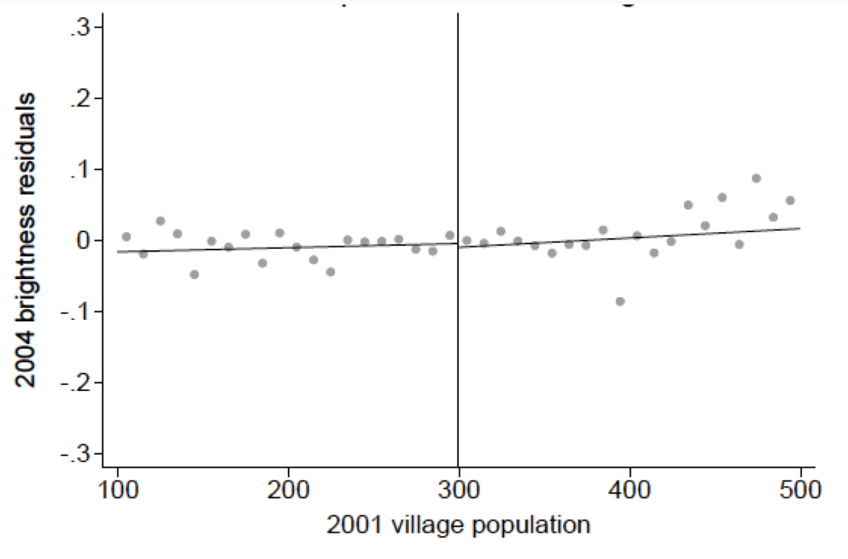
Zoomed In



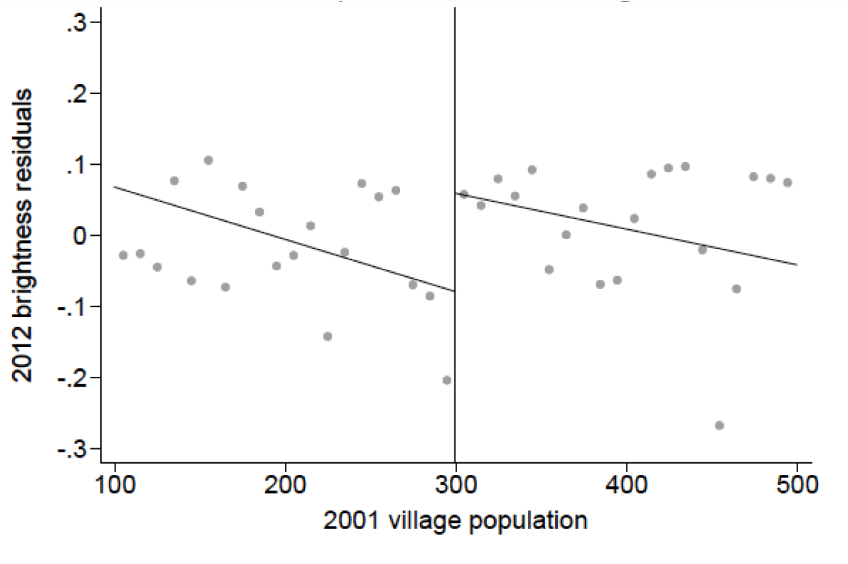
Village-level Brightness



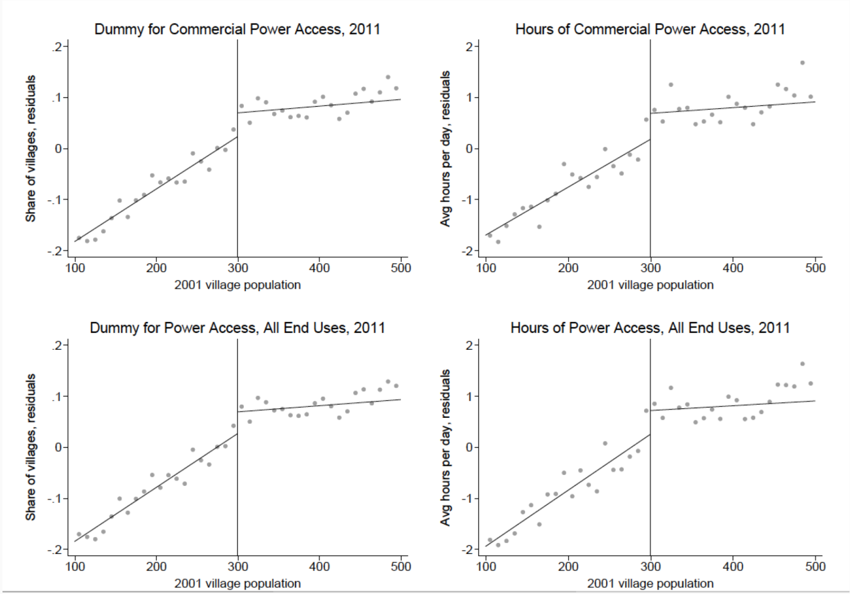
No Difference between Villages prior to RGGVY



Differences between Villages emerge post-RGGVY



Eligible villages get more energy



Burlig and Preonas (2022) – Results

- Electrification led to meaningful increases in electricity consumption, shrinking India's electricity access gap.
- However, precisely-estimated null results for,
  - employment
  - assets
  - housing stock characteristics
  - education
  - poverty
  - village-wide outcomes
- Rural electrification may be less beneficial for households than previously thought?
- Sizeable welfare gains for larger villages – suggests targeting can help improve efficiency of last-mile electrification.

Other Quasi-Experimental Estimates

- Lipscomb, Mobarak, and Barham (2013) use IV approach in Brazil
    - Analyze several development indicators (housing values, HDI, etc.)
    - Large positive effects
- Chakravorty et al. (2016) use IV approach in India.
    - Similar IV to LMB
    - Large positive effects

Wolfram et al. (2018)

- We have discussed results from non-experimental impact evaluations.
- There has been some limited experimental work on off-grid solar.
  - Kudo et al. (2015) find that solar lights increased study time and initial school attendance. No effect on test scores
  - Grimm et al. (2015) find kids study the same number of hours, but more at night and less during the day.
  - Small samples.
- Little on demand and nothing (known) on estimating costs, outside of engineering simulations.

Wolfram et al. (2018)

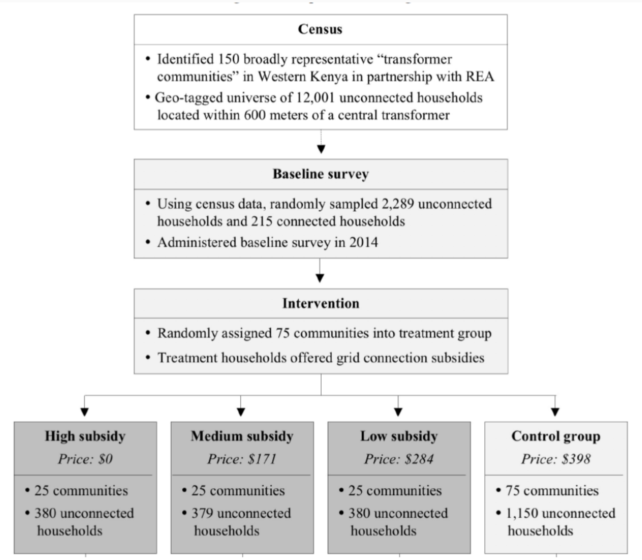
- Wolfram et al. (2018) provided households in randomly selected transformer communities with an opportunity to connect to the national grid at a subsidized price.

- The experiment generated random variation in:

  1) Effective connection price (at the community-level)

  2) Number of households connecting to the grid at the same time from each community

Wolfram et al. (2018) – Experimental Design



Results

1) Are there economies of scale in grid connections?

    - Using actual electrical utility cost data, strong evidence for declining average costs in the range of connections from $5,000-$6,000 per connection to ¡ $1,000 per connection as community coverage increases.

2) What is the demand for grid connections in rural Kenya?

    - Demand declines rapidly with price; is lower than expected by policymakers (or the authors)

3) What are the welfare implications of a mass electrification program in rural Kenya?

    - Consumer surplus is far smaller than total costs, suggesting this is an unattractive policy.

Understanding costs and demand

- How much should these results guide public policy?

  1) Are actual costs “too high?”

     - Some evidence of leakage, over-invoicing among contractors.
     - In a setting with less corruption, costs might be lower.
     - However, this is a dense area with existing infrastructure.

  2) Is demand “too low?” Are there additional social benefits? Is electricity an “experience good”?

     - Bureaucratic red-tape leads to long delays in connections and metering (212 days on average!), likely dampening demand.
     - Grid reliability is low: 18% of transformers failed in a year, median repair time of 3 months; plus regular black-outs.
     - Credit constraints: little financing available for connections, and stated WTP is far higher
     - Spillovers to neighbors might justify subsidies.

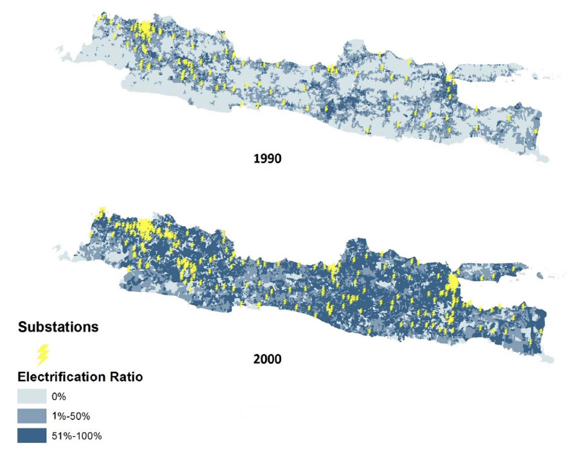
What do we learn?

- Wolfram et al. (2018) provide experimental evidence that:
  1) there are meaningful economies of scale in electrical grid expansion in rural Kenya
  2) consumer demand for a connection falls sharply with price
  3) consumer surplus (as they measure it) from a mass connection program is far smaller than the cost
- Cost and demand estimates likely depend strongly on local institutional quality, credit access, and income levels.
- There remains plausible rationales for public subsidies

Industrial Electrification

Electrification and Industrial Development

- Kassem (2018) examines the effect of a rapid, government-led grid expansion in Indonesia between 1990 and 2000 to explore the effects of electrification on manufacturing activity.



The Effects of Electrification are Ex-ante Ambiguous

- Electrification might cause industrialization by attracting firms (extensive margin)
- Electrification could be a *white elephant*: a costly investment that delivers nothing
  - Lee, Miguel, and Wolfram (2016)
  - Burlig and Preonas (2022)
- Electrification might just reduce the price of electricity (intensive margin)

Indonesia during the 1990s

- Economy:
  - Average GDP per capita: 700 USD, similar to Ethiopia or Uganda today
  - Sector shares of employment: Agriculture 56%, Industry 14%, Services 30%
- Electricity Supply:
  - State provided (generation, transmission, and distribution)
  - Uniform pricing across the country
  - 40% of generating capacity was owned by the manufacturing sector (self-generation)
  - Objective of the government: replace 80% of captive generation by the industrial sector.

Data

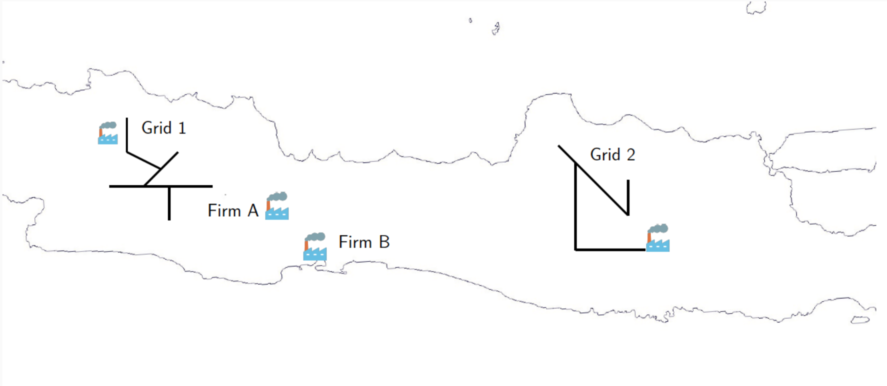
- Kassem digitized the location, capacity, and operation year of electric transmission substations and electric power-plants from 1990 to 2000.

- $Access = 1$ if a Desa is with 15km of the closest substation.

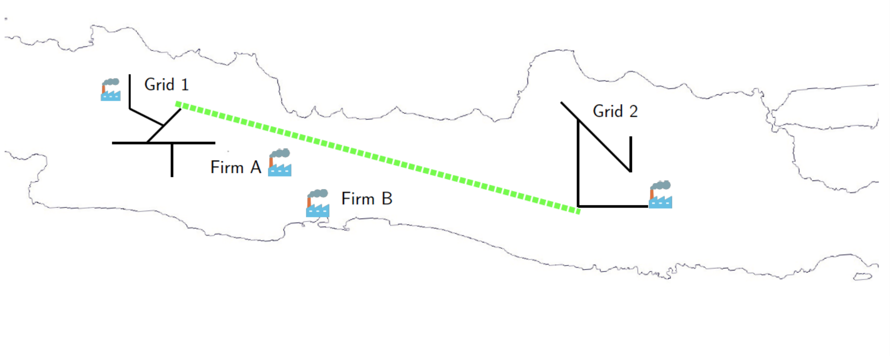
- Data on number of firms, manufacturing outcomes at the desa level, plus firm-level data on outputs, inputs, industry, entry and exit.

  Unbalanced panel of all manufacturing firms with 20 or more employees.

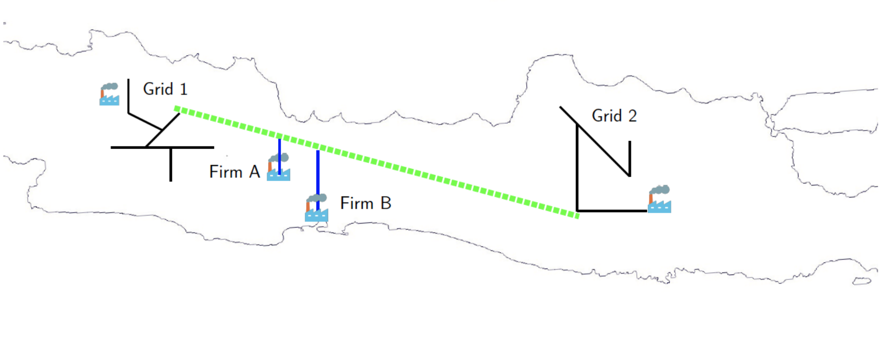
Empirical Strategy



Empirical Strategy



Empirical Strategy



Hypothetical Least Cost Grid

- Transmission lines could be targeted towards areas for non-random reasons
- Least cost grid: connects main power plants in the separate grids
- Algorithm:
  - cost = f(slope, waterway) (Faber (2014))
  - least cost path for each pair
  - Kruskal's algorithm finds the least cost grid connecting all power plants on a single grid. This is the combination of least cost paths that has the lowest cost.
- Instrumental variable: distance to the hypothetical grid.

Overview of Results

- Electrification increases industrial activity on the extensive margin.
- Extensive margin of electrification is a causal driver of manufacturing productivity
- Firm turnover is an important mechanism: more entry forces unproductive firms to exit and increase in allocative efficiency.
- Mechanism similar to the effect of trade liberalization on productivity

Infrastructure Quality

Infrastructure Quality and the Subsidy Trap – McRae (2015)

- 40% of urban residents in developing countries live in informal settlements.
- In Latin America generation capacity is not the key constraint
- Middle and upper income households enjoy electricity service that is close to that enjoyed in developed countries
- Situation for low income households locations in informal settlements very different
- Get subsidised but very low quality service supplying users who often do not pay for that service
- No real technological barrier to upgrading service which might benefit both users (through higher quality service) and distribution firms (through lower costs and higher payment rates).

Infrastructure Quality and the Subsidy Trap – McRae (2015)

- Puzzle $\Rightarrow$ why does this not happen?
- Elements of explanation

  1. households with informal connections receive low-quality service for which they do not pay
  2. utility firms tolerate nonpayment because they receive financial support from the government covering the cost of the service
  3. the government provides these payments to retain the political support of poor households and to avoid civil unrest should utility firms disconnect areas with many nonpaying users (see Hindi film *Katiyabaaz* (Powerless)
  4. financial transfers disincentivize utility firms from upgrading connections because fiscal transfers from the government may exceed the cost of providing service
  5. incremental profit from improving service is lower than the capital cost
  6. a subsidy program for short-term consumption displaces long-term investment

Infrastructure Quality and the Subsidy Trap – McRae (2015)

- Upgrading electricity service has two effects on electricity consumption
  1. an increase in the marginal price due to metering reduces the quantity demanded
  2. an increase in reliability increases household demand for electricity
- McRae uses large sample of metered households in Colombia (with similar characteristics to households in informal settlements) to estimate a model of household electricity demand.
- Uses the model to predict the consumption of unmetered households in 100 counties in Colombia with the least reliable electricity supply
- Allows him to look at consumption before and after a (hypothetical) upgrade
- Then combines this with cost and regulatory data to estimate the change in the utility firms profit before and after upgrade.

Infrastructure Quality and the Subsidy Trap – McRae (2015)

- Key result $\Rightarrow$ government program to maintain service for nonpaying, unmetered households may perpetuate the existence of low-quality connections by creating a disincentive for firms to invest.
- For all but one county in the sample it would be more profitable for the utility firm not to upgrade the network
- True even if payments move from 0 to 100 percent
- Household consumption is slightly lower after the upgrade improvement in quality is more than offset by the reduction in consumption from the higher marginal price
- Upgrade leads firms to lose subsidy payment from the government
- The capital cost of the upgrade (which the firms would cover) and the reduction in subsidies more than offset the increase in revenue from user payments

The Aggregate Effects of Electricity

A More Macro-Perspective

- It's important to understand which sectors make poor countries so unproductive.

> *"We argue that the answer to this question is not only interesting in its own right, but that it also helps us to distinguish between different possible causes of aggregate TFP differences"*
>
> – Herrendorf and Valentinyi (JEEA, 2012)

Is the Electricity Sector a Weak Link in Development?

- Two definitions of a **Weak link** sector:
  - sector whose productivity is relatively low relative to world frontier (Caselli, 2005; Hsieh-Klenow, 2007; Restuccia et al., 2008; Herrendorf and Valentinyi, 2012; Boppart et al., 2024)
  - sector where productivity increase $\Rightarrow$ larger aggregate effects than suggested by sector's share of economy (Hirschman 1958; Kremer 1993; Jones, 2011; Baqaee-Farhi, 2019, 2020)
- Ex ante, electricity seems like a prime candidate
  - Low substitutability with other inputs (Atkeson-Kehoe 1999; Hassler, Krusell, Olavsson, 2021; Casey, 2022)
  - But provides key input to economy (Gordon, 2016)
  - Electricification ("night lights") commonly used as proxy for development.

What We Do

1. Measure electricity TFP in 131 countries using new cross-country database of electricity inputs and outputs that we assembled.
2. Build multi-sector model to study long-run aggregate effects of improving electricity

    - Variant of neoclassical growth model

    - Electricity not really substitutable with other inputs

    - Distortions in poor countries that raise electricity costs

3. Simulate long-runeffects of raising TFP in electricity and removing distortions in electricity

Summary of Conclusions

- Electricity TFP gaps are much smaller than aggregate TFP gaps across countries.
- GDP gains from raising electricity TFP are lower than Hulten's prediction
- GDP gains from reducing 'tax-like' distortions in electricity are modest
- GDP gain $\sim$ 10% from eliminating outages in 6 countries; rest have gains ¡ Hulten's prediction

$\Rightarrow$ Not consistent with electricity being a weak link in development today — or different mechanisms are needed.

Defining the Outputs and Inputs in Electricity Sector

- Need to specify the form of production function $E = G(K_E, L_E, F)$
- Broad definition of electricity sector: production + distribution + self-production
- Output:

  - E: physical quantity of electricity produced

- Inputs:

  - Capital, K_E: electricity capital, defined below

  - Labor, L_E: employment in the electricity sector

  - Fuel inputs, F: natural gas + oil + coal in 'oil equivalents'

Electricity Output

- Want E to include all electricity produced and distributed ...
- ... plus any self-produced electricity from generators
- We measure $E = E^P(1-d) + E^S$
  - E = total electricity production (MWh) from International Energy Agency (IEA)
  - d = distribution losses, as fraction of total production
  - E^S = our estimated own-produced electricity from generators

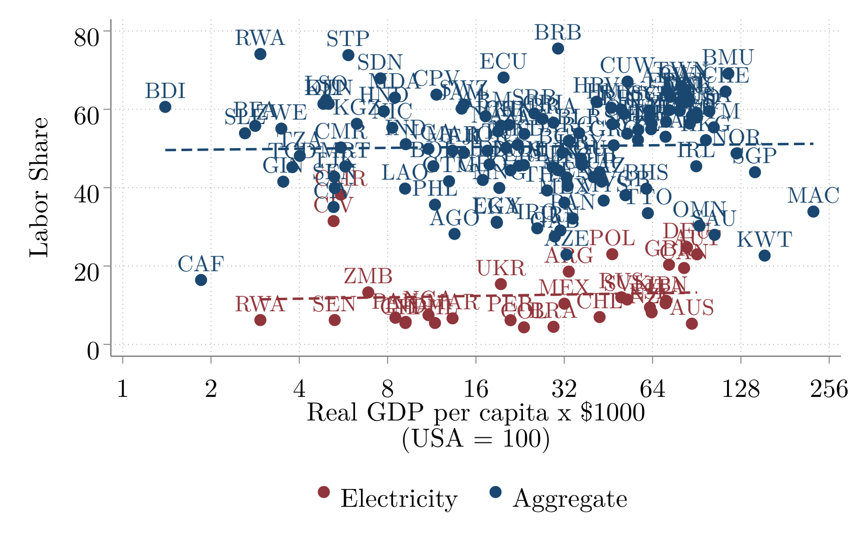
Electricity Capital

- $K_E = \min[K_E^G, \psi K_E^D]$, where K_E^P and K_E^D are generation + distribution capital
- K_E^G measured in MW as sum of
  1. Universe of large + medium scale electric power plants, from Platts
  2. Our own estimates of small-scale generation, taken from imports data (as in Caselli-Wilson, 2001)
- K_E^D captures power lines and distribution equipment

Labor Shares in Electricity + Sample Restrictions

- Labor payments / value added, from 69 private producers in 31 countries
- Drop economies that are big importers or exporters of power (e.g. Paraguay)
- Final database covers 131 countries

Labor Shares Much Lower in Electricity than in Aggregate



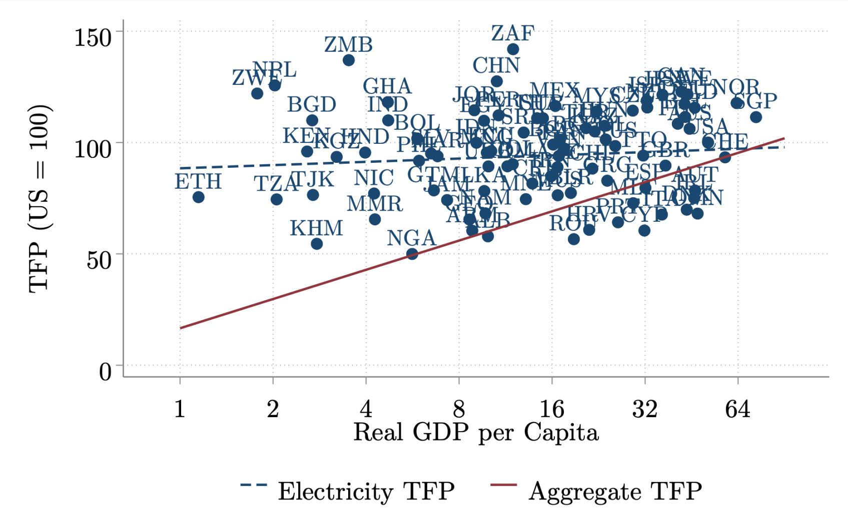
Measuring TFP in Electricity

- Need electricity aggregate production function for electricity, $E = G(K_E, L_E, F)$
- Assume $G()$ has CRS (but similar results when assuming modest DRS or IRS)
- Constant labor share suggests Cobb-Douglas in labor and $H(K_E, F)$
- Micro estimates: very low substitutability between K_E and F (Berndt-Wood, 1975)
- Thus, our production function:

$$Y_E = A_E \left(\min\left[K_E, \chi F\right]\right)^{\theta_E} L_E^{1-\theta_E}$$

- Back out A_E and χ for each country as residuals

TFP in Electricity Sector: Not Too Correlated with GDP per capita



Growth Model with an Electricity Sector

Households

- One final goods used for consumption and investment
- Representative household with preferences

$$\sum_{t=0}^{\infty} \beta^t U(C_t)$$

- Household supplies one unit of labor inelastically
- Law of motion for capital

$$K_{t+1} = (1-\delta)K_t + I_t$$

Electricity Sector

- Electricity sector production function

$$E_t = A_E K_{E,t}^{\theta_E} L_{E,t}^{1-\theta_E}$$

- Firms buying electricity pay distorted price $(1+\tau_E)P_{E,t}$
    - Stands in for generators being more expensive than grid power
- Electricity sector pays $(1+\tau_E^K)R_t$ for grid capital
    - Captures e.g. ineffective government partnerships in building a hydro dam

Non-Electricity & Final Goods Sector

- Final goods production function

$$Y_t = \left[\alpha E_t^{\frac{\sigma-1}{\sigma}} + (1-\alpha) X_t^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$$

- 'Non-electricity' sector production function

$$X_t = A_X K_{X,t}^{\theta_X} L_{X,t}^{1-\theta_X}$$

What are the GDP Gains from Raising A_E?

- We focus on steady-states
- Compare model's predictions to two frames of reference

1. Hulten

$$d \ln Y = \lambda_E d \ln A_E$$

2. Baqaee-Malmberg

$$d \ln Y = \lambda_E d \ln A_E + \frac{RK}{Y} d \ln K$$

... where λ_E is electricity's Domar weight

Analytical Special Case of Model

- Suppose Leontief production function in E and X

$$Y_t = \min\{E_t, X_t\}$$

  ... and electricity production only using capital

$$E_t = A_E K_{E,t}$$

  ... and no distortions $\tau_E = \tau_E^K = 0$

- Then can compute gains from raising A_E in closed form

GDP Gains in Analytical Model vs Hulten

- Steady-state aggregate output is:

$$Y = \left[\left(\frac{1}{R} - \frac{1}{A_E}\right)\theta_X\right]^{\frac{\theta_X}{1-\theta_X}} A_X^{\frac{1}{1-\theta_X}}$$

- With dynamic responses in capital accumulation,

$$\frac{d\ln Y}{d\ln A_E} = \frac{\theta_X}{1-\theta_X}\frac{R}{A_E - R}$$

- Domar weight of electricity

$$\lambda_E = \frac{P_E E}{Y} = \frac{R}{A_E}$$

- Long-run gains greater than Hulten's prediction when

$$A_E < R\frac{1-\theta_X}{1-2\theta_X}$$

GDP Gains in Analytical Model vs Baqaee-Malmberg

- Baqaee-Malmberg (2025) formula in our setting

$$\frac{d \ln Y}{d \ln A_E} = \lambda_E + \frac{RK}{Y} \frac{\partial \ln K}{\partial \ln A_E}$$

where

$$\frac{\partial \ln K}{\partial \ln A_E} = \frac{1}{1-\theta_X} \left[-1 + \theta_X \left(\frac{A_E}{A_E - R} + \frac{(1-\theta_X) A_E}{\theta_X A_E + (1-\theta_X) R} \right) \right]$$

- Can show $\lim_{A_E \to \infty} \frac{\partial \ln K}{\partial \ln A_E} = 0$ and $\lim_{A_E \to R} \frac{\partial \ln K}{\partial \ln A_E} = \infty$

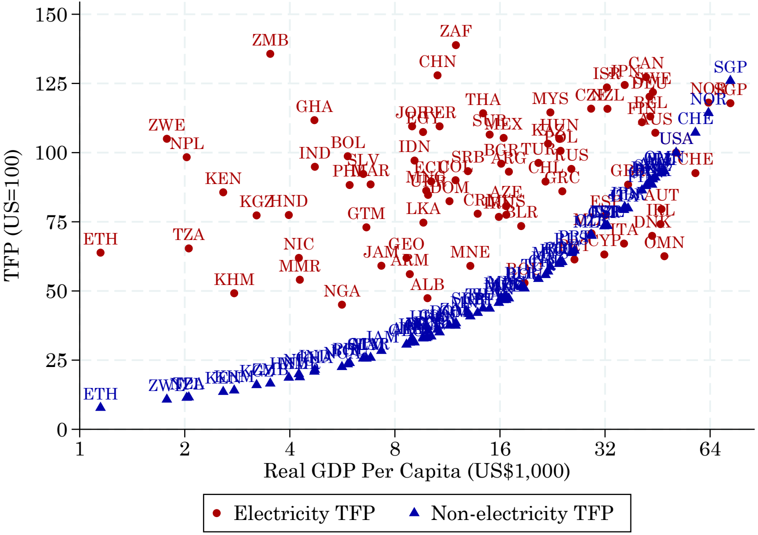
- Punchline: GDP gains biggest when A_E smallest

Quantitative Analysis

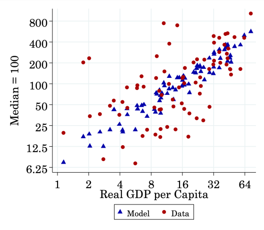
Calibration of Full Model

Parameter	Interpretation	Value	Source/Target
A. Externally Determined			
β	Discount factor	0.96	Comin et al. (2021)
δ	Depreciation rate of capital	0.06	BEA
σ	EoS between power & non-power input	0.2	Berndt & Wood (1975)
θ_X	Capital share in non-electricity	1/3	Gollin (2002)
θ_E	Capital share in electricity	0.9	Our data
A_{Ei}	TFP in electricity sector	Various	Our data
τ_E, τ_E^K	Wedges of electricity sector	0	By assumption
B. Internally Calibrated			
α_i	Weight on electricity inputs	Various	Domar weight of the grid
A_{Xi}	TFP of non-electricity sector	Various	GDP per capita

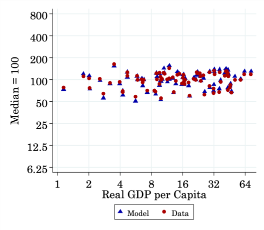
Calibrated TFP Terms in Model



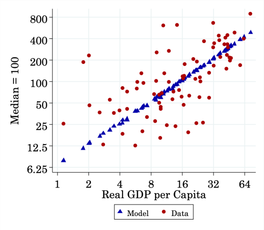
Fit of Model – Non-targeted Moments



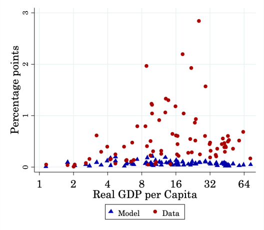
(a) E/L_E



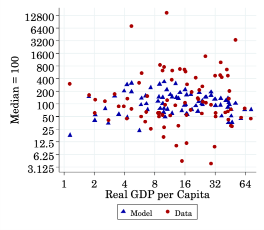
(b) E/K_E



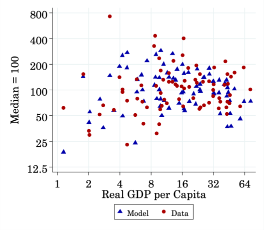
(c) K_E/L_E



(d) L_E

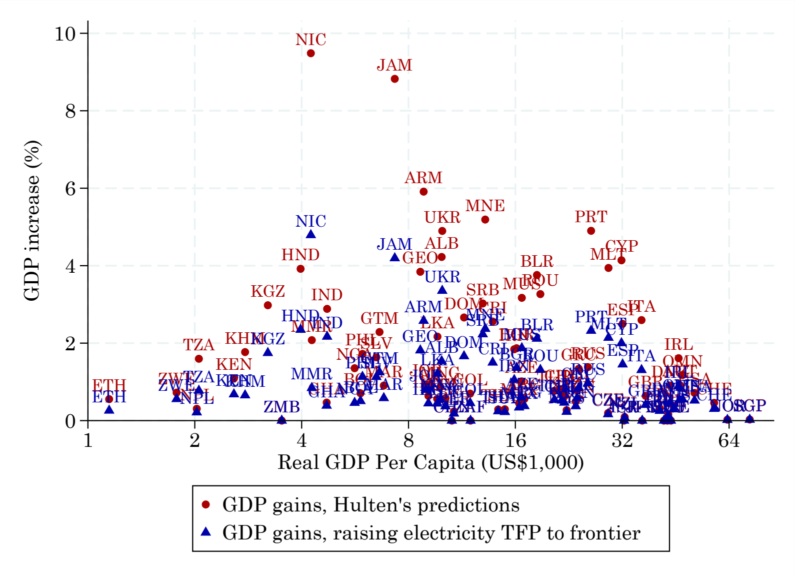


(e) K_E/Y

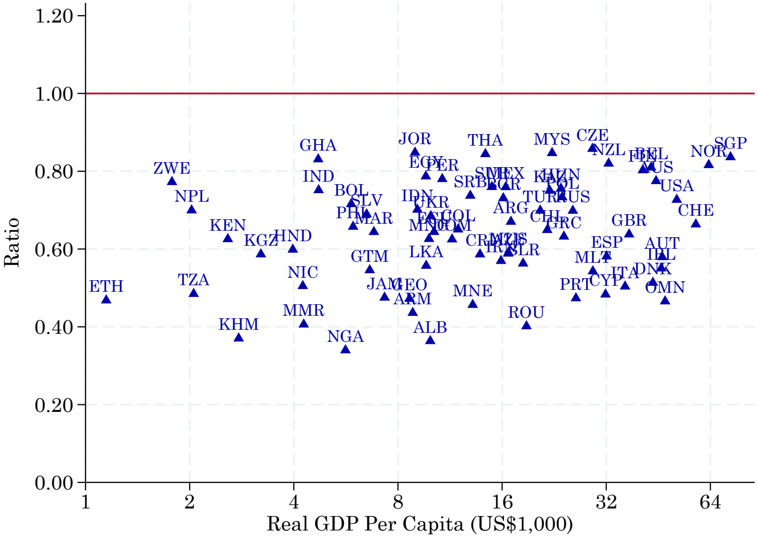


(f) K_E/K

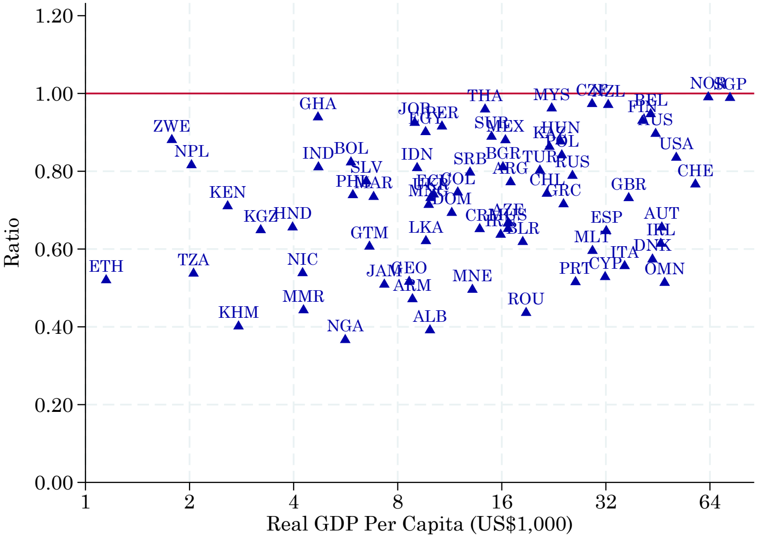
Not A Weak Link: Gains from Raising A_E to World Frontier



Ratio, Gains from Raising A_E to Hulten's Predictions



Ratio, Gains from Raising A_E to Baqaee-Malmberg Predictions



Electricity Does Not Behave Like A Weak Link

- When CAN electricity be a weak link?
  - When dealing with negative electricity TFP shocks
  - When the electricity TFP is counterfactually MUCH lower
- What about the non-electricity sector?
  - Non-electricity is the actual weak link
- How do frictions affect the results?
  - Similar results to raising A_E
- What about “power outages” rather than standard macro distortions?
  - Widespread outages in developing countries not in form of wedges
  - Extension with regulated prices and rationing of power
  - Find 6 countries for which A_E increases beat Hulten; find 74 that don’t

Conclusions so far

- Went looking for evidence that electricity is a ‘weak link’ in development
- Didn’t find it in cross-country data: electricity TFP not too far behind frontier
- Didn’t find it in multi-sector model with ‘tax-like’ distortions: GDP gains similar to predictions of Hulten and David’s work with Hannes
- Policy takeaway: probably over-emphasizing electricity spending
- Acadamic takeway: need more work on channels by which electricity drives development