Demand for Electricity in a Poor Economy

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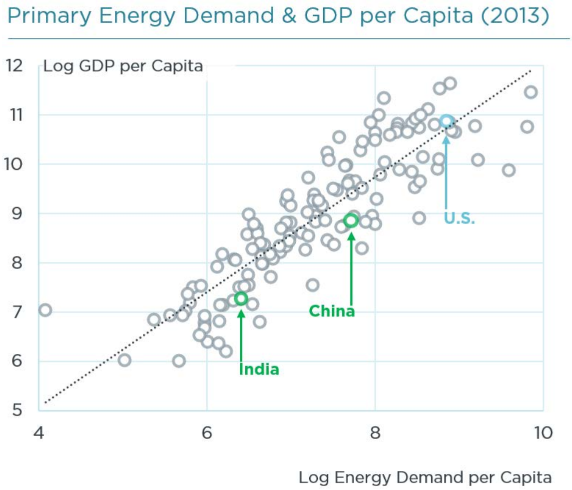
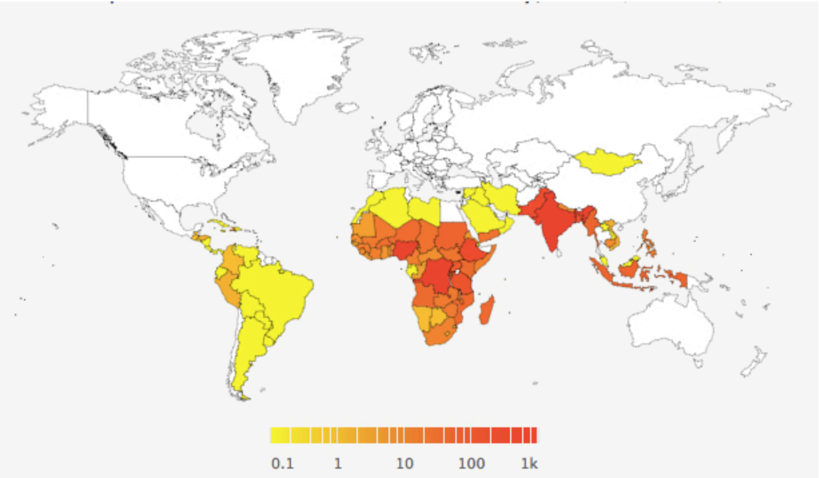
Electricity is considered critical for growth and human well-being



Over a billion people globally, nearly all in South Asia and Sub-Saharan Africa, do not have electricity in their homes

Figure: Population without electricity (millions), 2016 (IEA)

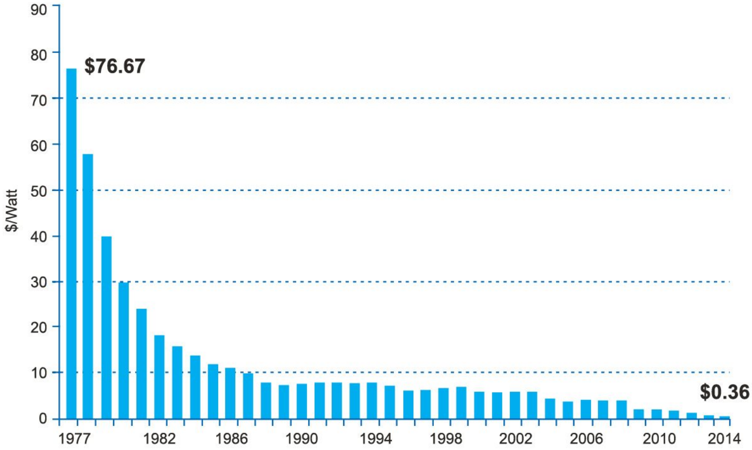


Electrification is a huge priority for policy

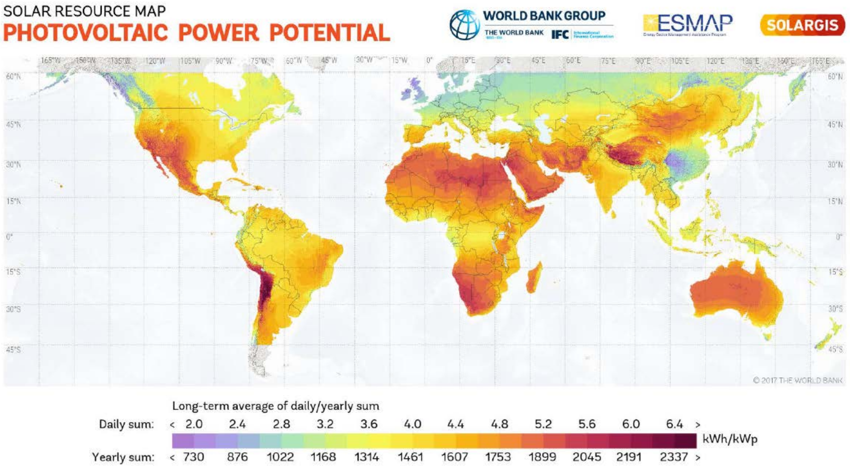
Location	Organization	Project	Cost	People
Africa	US AID, country governments	Power Africa	$32 billion	60 million
Global	United Nations	Sustainable Energy 4All		Targeting “universal access” to modern energy
India	Govt. of India, Rural Electrification Corp.	Saubhagya Yojana (“Good luck program”)	$2.5 billion	40 million households
United States	U.S. Govt.	Rural Electrification Act of 1936	$210 million in 2 years	220,000 farms connected
Bangladesh	World Bank	Rural Electrification and Renewable Energy Development Project	$290 million	650,000 connections and 2 million solar systems
Ethiopia	Ethiopian Electric Power Corporation, World Bank	Electricity Access Rural Expansion Project	$160 million	130,000 households
Rwanda	Govt. of Rwanda, World Bank, Netherlands	Electricity Access Rollout Program	$712 million	226,000 households connected to date
Uganda	African Development Bank, Govt. of Uganda	Uganda Rural Electricity Access Project	$121 million	157,000 household connection goal

Solar has gotten a lot cheaper

Figure: Price history of silicon PV cells (Bloomberg)



And, places with low electrification rates also have lots of solar availability



Cheap solar makes distributed power easier

Figure: Grid electrification

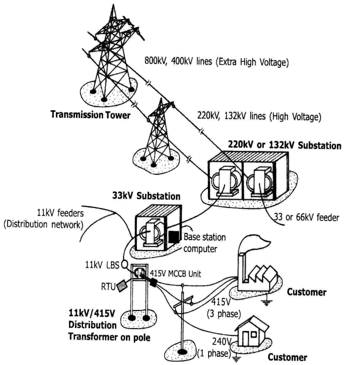


Figure: Distributed electrification

Optimism over electrification via solar, particularly from Western donors

"I have seen for myself how people's lives can be transformed with the installation of a simple solar panel system . . . It has the power to help millions of Africans **lift themselves** *out of poverty and transform the prospects of an entire continent."*

Grant Shapps, former UK Minister of State for International Development

At the same time, others make the case for grid electrification

> *"Affordable and reliable grid electricity allows factory owners to increase output and hire more workers...Societies that are able to meet their energy needs become wealthier, more resilient, and better able to navigate social and environmental hazards like climate change and natural disasters."*

Executive Summary, Our High Energy Planet, The Breakthrough Institute

This paper conducts an experiment to measure willingness to pay for electricity by randomizing the price of solar micro-grids

- We ran a randomized experiment in partnership with a micro-grids solar company, Husk Power Systems (HPS).
- Sample of 100 villages in Bihar, India
- 3 randomly assigned prices
    - 34 control villages where HPS system was not offered
    - 33 treatment 1 villages where system was offered at market price of 200 INR (later cut to 160 INR)
    - 33 treatment 2 villages where system was offered at below market price of 100 INR
- Surveyed households before and after, and collected administrative payment data

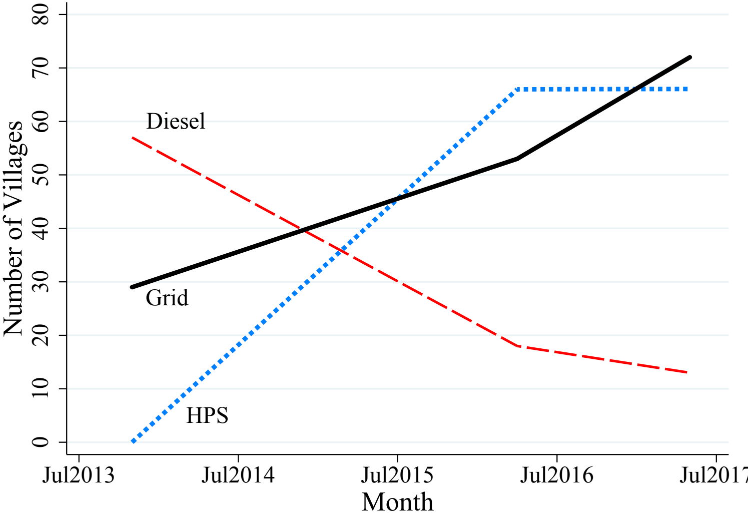
But we found there is a surprisingly competitive retail power sector in Bihar, India

Source attributes

Table: Summary of electricity sources, baseline

	Grid	Diesel	HPS	Own solar
Monthly price (INR)	73.84	126.6	200	100.5
Peak hours (5pm - 10pm)	2.076	3.375	4.300	4.717
Off peak hours	10.58	0	1	2.714
Load (watts)	327.93	139.06	28.28	258.53

Dynamic period of electricity supply in sample villages where suppliers are entering and exiting



Rich data with information on households and all energy sources that characterizes the retail electricity market

- **Household survey.** Baseline (Nov, 2013) and endline 1 (Apr, 2016) and endline 2 (May, 2017) surveys of 3,000 households in 100 rural villages of Bihar.
- **Administrative 1.** Payments data from solar provider.
- **Administrative 2.** Supply and payment records from state utility.
- **Supplier survey.** Survey all diesel generators on hours of supply.

This paper addresses 3 sets of questions

1. Experimental estimates of the demand for solar microgrids and their benefits.

- Trace out demand curve.
  - At 2013-2016 unsubsidized prices, near zero demand.
  - Demand is very elastic and at prices about 1/2 of true cost, HPS microgrids capture 7% of the market.
  - Traditional analysis
    - Users experience increase in light bulb ownership, hours of electricity use and mobile phone ownership
    - No meaningful effect on health, children's test scores, or income

This paper addresses 3 sets of questions

2. Estimate nested logit with IV model of electricity source demand with 4 sources to account for heterogeneity in sources and substitution opportunities.

- Households are price sensitive– increasing the monthly price by 10 INR ($0.16) reduces...
  - HPS market share by 0.6 percentage points
  - Own solar market share by 0.8 pp
  - Diesel market share by 0.35 pp
  - Grid market share by 1.3 pp
- Night time electricity is valued highly: annual WTP for an additional hour of peak period electricity is 473 INR, compared to annual household income of roughly 90,000 INR.

This paper addresses 3 sets of questions

3. **Counterfactuals: Improvements in the Grid are Valued Highly**
   - **Extending the grid everywhere** decreases unelectrified (from 42 pp to 23 pp), increases WTP by 89 INR per household annually, and greatly increases utility losses
   - **Introduction of solar to market.**
     - Solar's market share is highly dependent on grid availability
     - WTP for introducing solar into the market declines from about 400 INR per year per household when the grid isn't available to 90 INR when it is available everywhere
   - **Optimistic solar innovation scenario.**
     - Decreases the share of households that are unelectrified by only 2 percentage points
     - Low WTP for solar innovation, approximately equal to 63 INR per household annually

This paper addresses 3 sets of questions

3. Counterfactuals (cont.): Improvements in the Grid are Valued Highly

- **Distribution reforms.**
  - A 1 hour increase in night time supply of electricity decreases unelectrified by 6 pp, increases annual WTP by 415 INR, and greatly increases distribution company losses.
  - Ending theft increases unelectrified from 42 pp to 47 pp, reduces annual WTP by 536 INR, and greatly reduces losses
  - Budget neutral increase to full supply of night time hours to 5 and reduction in theft decreases unelectrified by 6 pp and increases annual WTP by 381 INR.

Previous literature

1. Effects of grid electrification on labor supply, productivity, and socioeconomic welfare outcomes (Rud 2012; Dinkelman 2011; Lipscomb, Mobarak and Barham 2013; Barron and Torero 2017)
2. Demand for off-grid solar power (Aklin et al. 2017; Grimm et al. 2016)
3. Willingness to pay for grid connections (Lee, Miguel, and Wolfram 2018)

This paper's contribution

1. First welfare analysis of markets for rural electrification that recover demand primitives and account for substitution opportunities
2. Medium-term subsidies (1-2 years) on solar technology that mimic real-world price variation and track households and their decisions for 3.5 years
3. Can conduct counterfactual welfare analysis of alternative policies that lay beyond the experiment

Outline

1. Context: Energy environment in Bihar
   - Electricity Sources
     - Husk Solar Microgrids
     - State-Owned Grid Distribution
     - Diesel Electricity
     - Own Solar Electricity
   - Summarizing Electricity Source Attributes and Availability
2. Demand for solar microgrids
3. Demand model for alternative energy sources
4. Counterfactual analysis

Sample villages located in two districts of Bihar

Biharis consume a small amount of electricity

Table: Electrification context, 2014 data

Location	US	India	Sub-Saharan Africa	Bihar
GDP per capita, PPP (USD 2017)	54,599	5,678	3,660	1,505
kWh per capita	12,985	765	481	122
Electricity access (%)	100	79	37	25
kWh per capita / US level	1	0.059	0.037	0.009

Source: World Bank and EPW

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   C. Experimental Design
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Experiment partner is Husk Power Systems, in the vanguard of solar electrification in India

HUSK
POWER SYSTEMS
हस्क
पावर सिस्टम्स
तमसो मा ज्योतिर्गमय

- Conceived in 2008, winning business plan competitions at UVA, U. of Texas, Cisco-Draper Fisher Jurvetson (DFJ) Global Business Plan Competitions.
- Funded by US Overseas Private Investment Corporation (OPIC), Shell Foundation, International Finance Corporation (World Bank), Acumen Fund, LGT Philanthropy, Bamboo Finance
- Moved to solar subscription model to reach villages that could not support biomass plant, and to adapt to rising fuel costs.

HPS solar product: A 240 watt micro-grid typically shared among 6 households

- Provides 25-40 watts of power, 5-7 hours of supply per day
- Each household gets a meter with keypad, two LED bulbs, socket to charge mobile phone
- Payment is 200 INR (later reduced to 160 INR) monthly and customers recharge their connection by buying a code

Figure: HPS Panel

India alight with similar product offerings

Company	Where?	People	Product	Price
Boond Energy	UP and Rajasthan, India	10,000 units as of 2014	Microgrid	INR 13000-47000 for 40-200 Watt units
Mera Gao Power	Barabanki, UP, India	150,000	Microgrid	INR 100 per household, per month
Simpa Networks	UP, India	153,512	Home system	INR 13000-26000 unit cost, financed through INR 50 monthly installments
OMC Power	Northern India	NA	Solar lanterns	INR 150 per month for solar lanterns, 350 for power boxes
Minda Nexgentech	Northern India	16,600 as of 2013	Microgrid	INR 160 per household per month

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Grid electricity

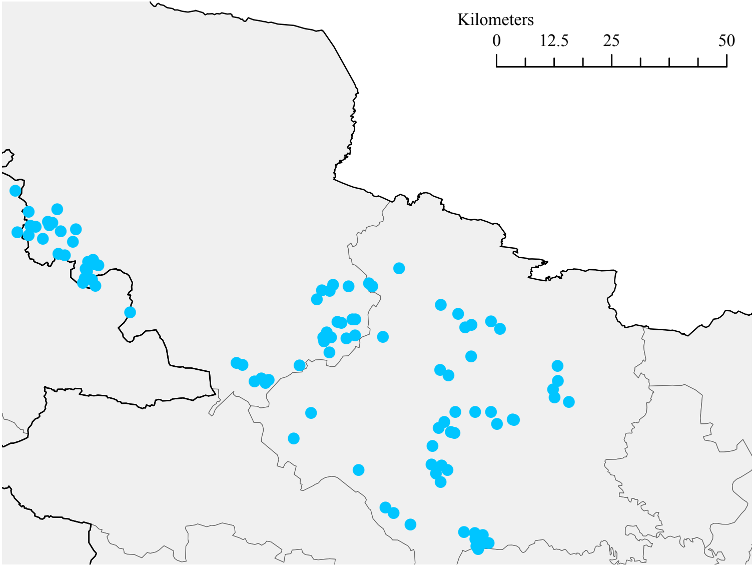
- Load is practically unlimited with respect to appliances that these households own
- Supply is unpredictable due to extensive load shedding, or supply rationing but averages 13 hours per day in connected villages
- Our best estimate is that these consumers use about 60-100 kWh per month
- Formal tariffs set by distribution companies
- Very poor bill collection in practice
  - **Distribution companies lose about 43 INR for every 100 INR of costs**

Grid price schedule

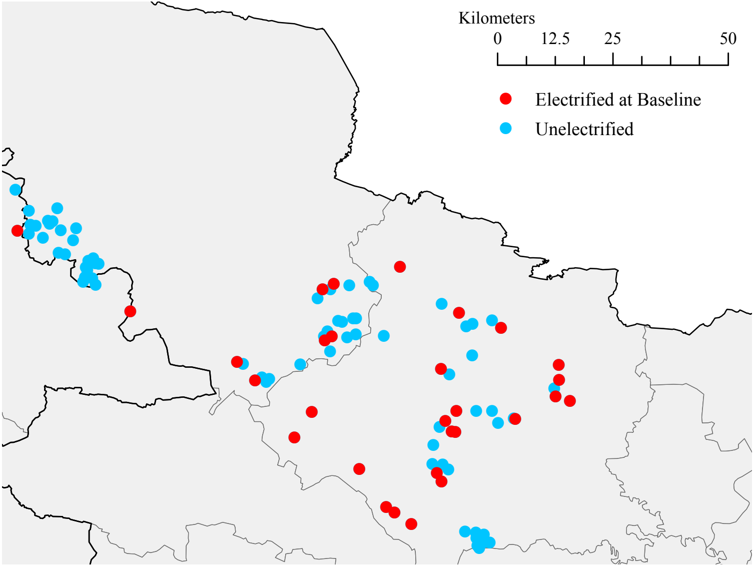
Table: North Bihar Distribution Company Electricity Tariffs (FY '16-'17)

Category	*Value*
Tariffs	
BPL Consumers: Unmetered	Rs. 60 / month
BPL Consumers: Metered	
First 30 kWh	170 Ps. / kWh
Remaining units	As per DS-1
DS-1: Unmetered	Rs. 170 / month
DS-1: Unmetered	
First 50 units	210 Ps. / kWh
51-100 units	240 Ps. / kWh
Above 100 units	280 Ps. / kWh
Avg. Consumption	
BPL: Mean consumption	60.89 kWh
Corresponding (metered) tariff	119.14 INR
DS-1: Mean consumption	106.05 kWh
Corresponding (metered) tariff	241.94 INR

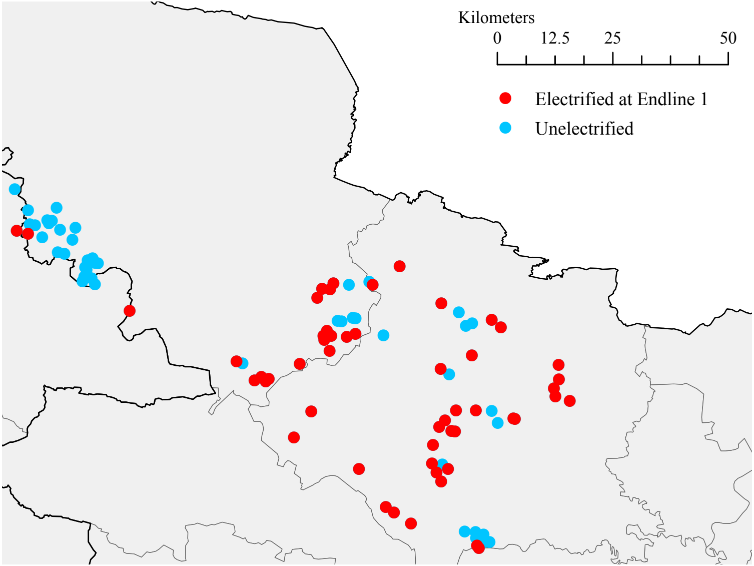
Location of Villages



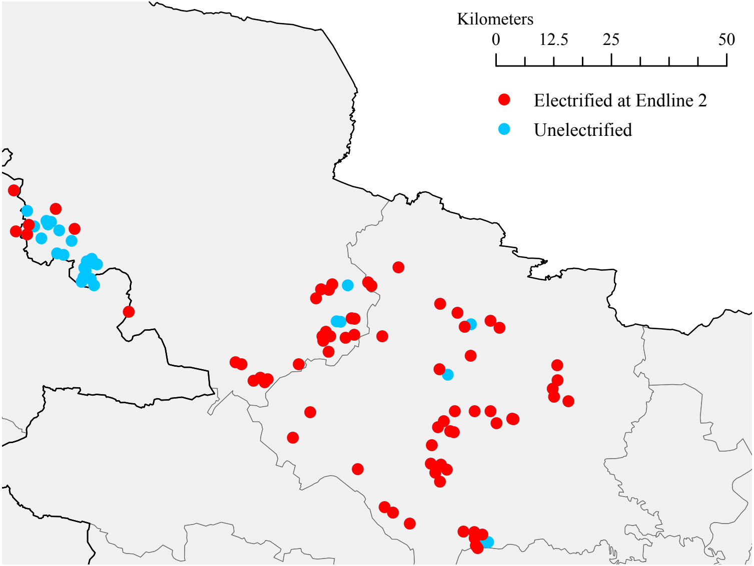
Electrification in Dec. 2013



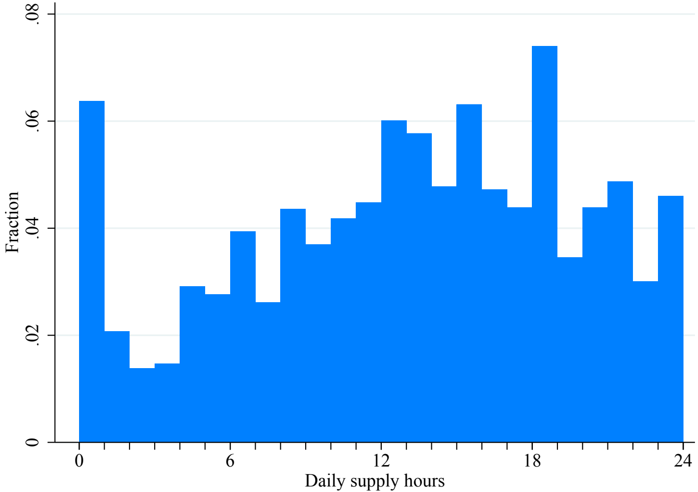
Electrification in May 2016



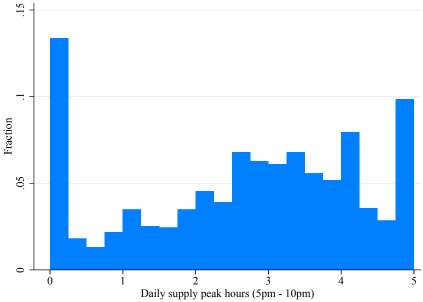
Electrification in June 2017

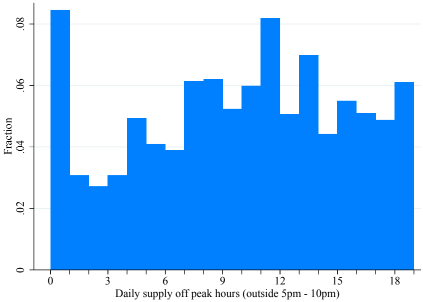


Variation in grid supply available to sample villages, March - May 2017



Variation in grid supply, peak (5pm - 10pm) hours and off peak (else) hours





Payments and supply on the grid

"Whenever I feel like paying the bill."

- Bihar villager in response to survey question "How often do you pay your bill?"

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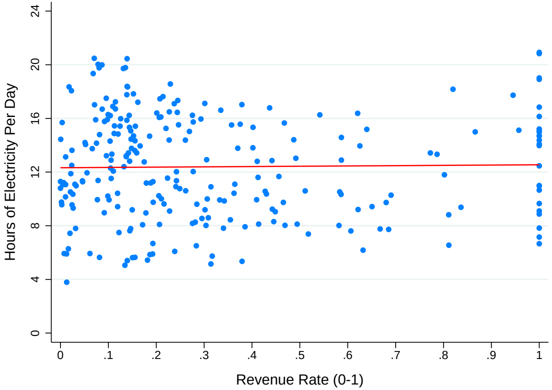

Is it possible to divide grid customers?

Grid users are defined as formal if they could provide a consumer ID that can be matched with the administrative consumer database

Table: Balance in grid formality, endline 2 grid households

	Formal	Informal
Pays bills (=1)	0.95	0.40
Has meter (=1)	0.84	0.73
Meter installed formally (=1)	0.36	0.35
Formal connection process	0.81	0.81
Informal connection process	0.14	0.054
Sum of connection fees	1235.2	973.0
Number households	109	614

Outline

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   A. **Electricity Sources**
      i. Husk Solar Microgrids
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      iii. **Diesel Electricity**
      iv. Own Solar
   B. Summarizing Electricity Source Attributes and Availability
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Diesel electricity

- Village members own and run diesel generators, sell electricity within village
- Most operators offer at least one standard plan, of 100 INR / month for 100 watts
- Turned on for predictable hours during peak demand, averaging about 3.5 hours per day (all during night time hours)
- Need a sufficient number of customers to cover fixed costs, so the availability of diesel is highly dependent on the number of local customers

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Own solar electricity

- Off-grid solar option, as opposed to micro grid HPS
- Most panels are small and service lightbulbs and mobile phone chargers
- Provide similar hours of supply to HPS micro grid
- We amortize own solar one-time costs to monthly payments assuming 7 year panel life and 20% interest rate

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Source attributes

Table: Summary of electricity sources

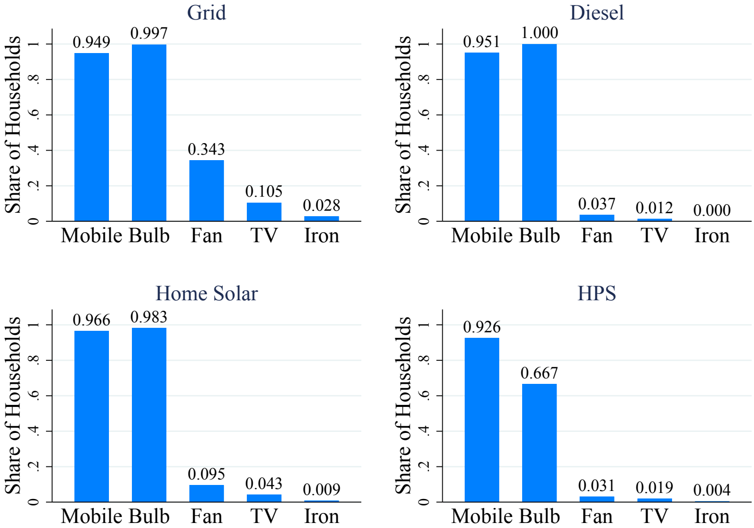
	Grid	Diesel	HPS	Own solar
Monthly price (INR)				
Baseline	73.84	126.6	200	100.5
Endline 1	61.64	104.8	163.8	99.55
Endline 2	61.64	104.8	170	90.95
Peak hours (5pm - 10pm)				
Baseline	2.076	3.375	4.300	4.717
Endline 1	2.497	3.083	5	5
Endline 2	2.952	3.083	5	5
Off hours				
Baseline	10.58	0	1	2.714
Endline 1	10.62	0	0.714	0.808
Endline 2	10.59	0	0.714	0.808

What does load mean practically?

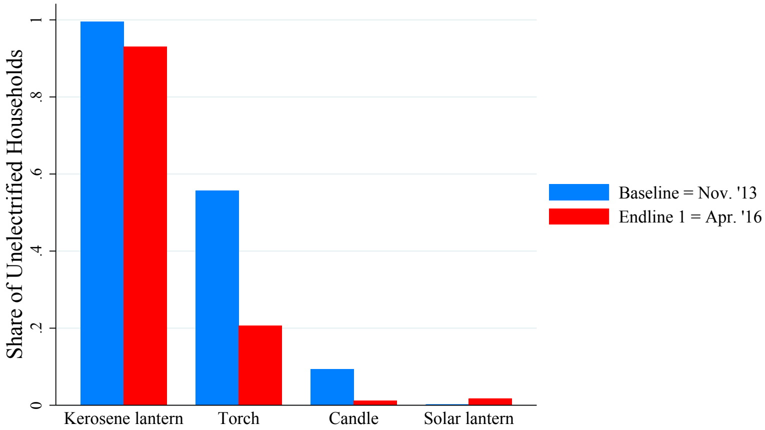
Table: Electricity source capacity

	Mobile	Bulb	Fan	Radio	TV	Fridge
HPS	x	x				
Grid	x	x	x	x	x	x
Diesel	x	x	x	x	x	
Own solar	x	x	x			

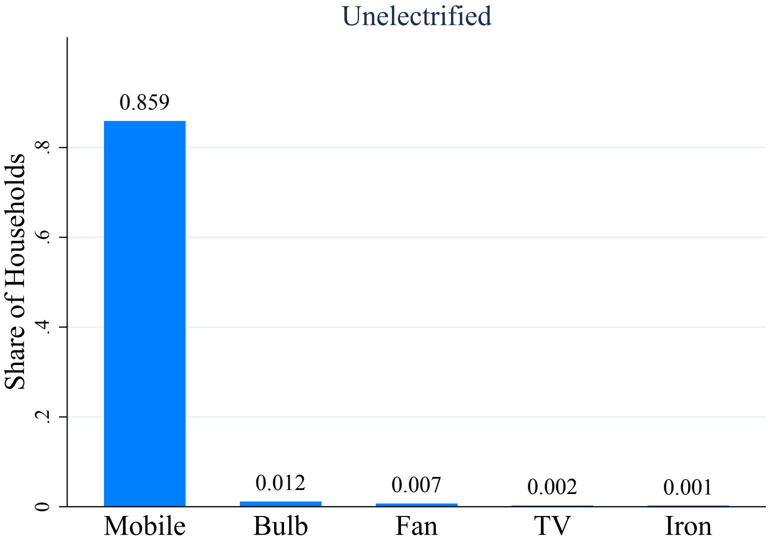
Appliance use by source



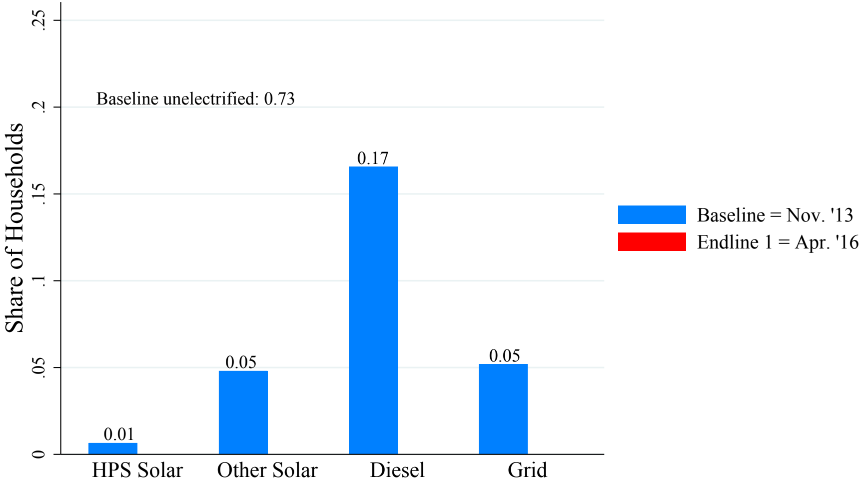
The outside option: What do unelectrified homes do for lighting and energy?



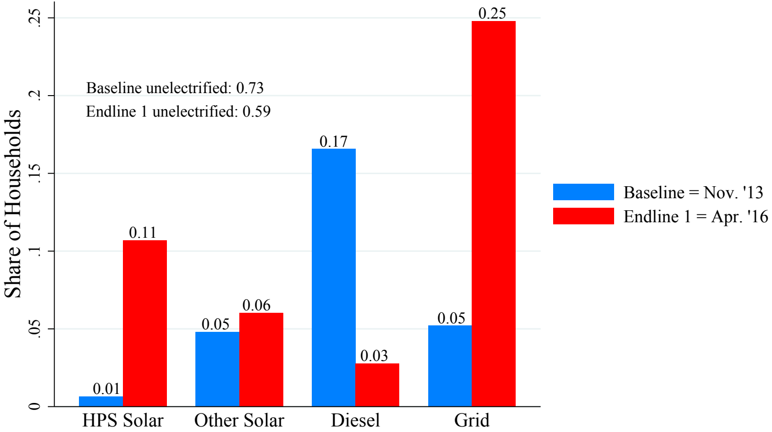
Unelectrified households own mobile phones



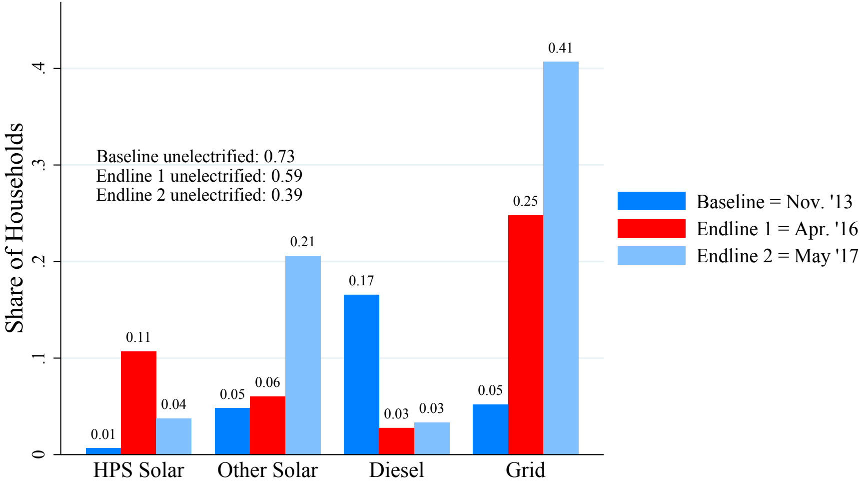
Substantial variation in sources over time: At baseline, diesel is the primary electricity source



2.5 Years Later: Big Changes in Market Shares Due to Government Policy of Grid Expansion, Declining Solar Prices, and the Exit of Diesel Generators



Continued grid and solar expansion in 2017



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Sample of marginally non-electrified villages

- **Village selection**. HPS staff and project field staff visited 130 villages and found 102 with population of 48,979 that met four criteria.
  1. Within 15 km of existing HPS villages
  2. Less than 50 households with solar and less than 50 households with biomass electricity
  3. Less than 25% of households with grid electricity
  4. At least one tola (neighborhood) in village without grid connections

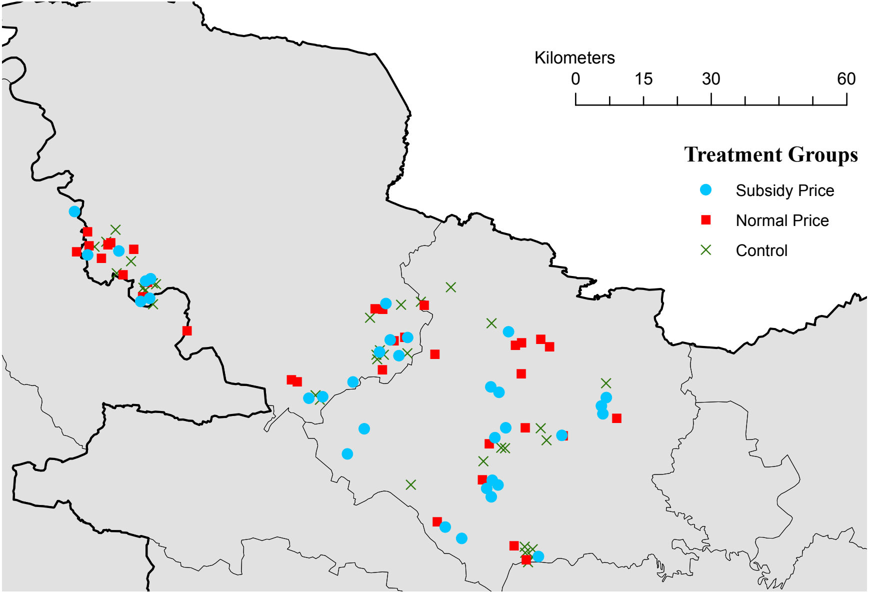
- **Household selection**
  - HPS and survey team jointly conducted customer identification survey to create sampling frame of households that expressed interest in adopting solar
  - In practice, this was not restrictive, as no deposit was required
    - 93% of 18,000+ enumerated households stated interest at 100 INR
  - About 30 households were surveyed in each village for a sample of approximately 3,000 households

Village-level experimental design to estimate solar demand curve

Cluster-based randomized design with three treatment arms

1. **Control**. HPS does not offer solar in village.
2. **Normal price**. HPS offers solar at 200 INR (USD 3.33) and 160 INR (USD 2.67) per month, the prevailing pre-experiment price.
3. **Subsidized price**. HPS offers solar at 100 INR (USD 1.67) per month with subsidies paid by researchers for experiment.

All households could sign up in treated villages, regardless of prior expression of interest or survey status. Sales began in January 2014. In practice, a HPS installation required about 4 interested households that could be connected to the same panel.


Kilometers
0
15
30
60
Treatment Groups
Subsidy Price
Normal Price
Control

Baseline covariate balance

	Control	Normal	Subsidy	F-Stat
Panel A. Demographics				
Literacy of hh head (1-8)	2.44	2.69	2.60	1.33
Number of adults	3.31	3.50	3.49	2.19
Panel B. Wealth Proxies				
Income (Rs. '000s/month)	7.46	7.32	7.28	0.068
Number of rooms	2.40	2.55	2.53	1.29
Permanent house (=1)	0.24	0.27	0.31	2.79*
Owns agricultural land	0.67	0.69	0.67	0.045
Solid Roof (=1)	0.42	0.46	0.51	3.08*

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Baseline covariate balance

	Control	Normal	Subsidy	F-Stat
Panel C. Energy Access				
Any elec source (=1)	0.25	0.31	0.27	0.63
Uses gov. elec (=1)	0.030	0.036	0.091	2.53*
Uses diesel elec (=1)	0.17	0.21	0.11	1.70
Uses own panel (=1)	0.034	0.050	0.061	1.81
Uses HPS solar (=1)	0.0067	0.0081	0.0050	0.14

* p <0.10, ** p <0.05, *** p <0.01

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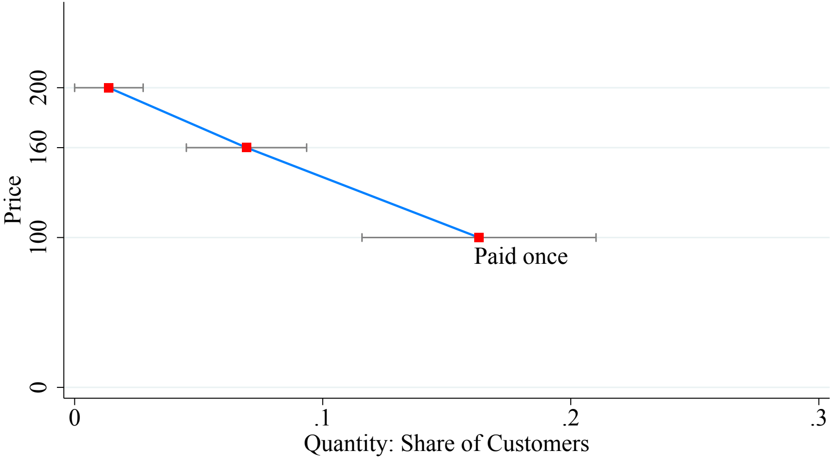
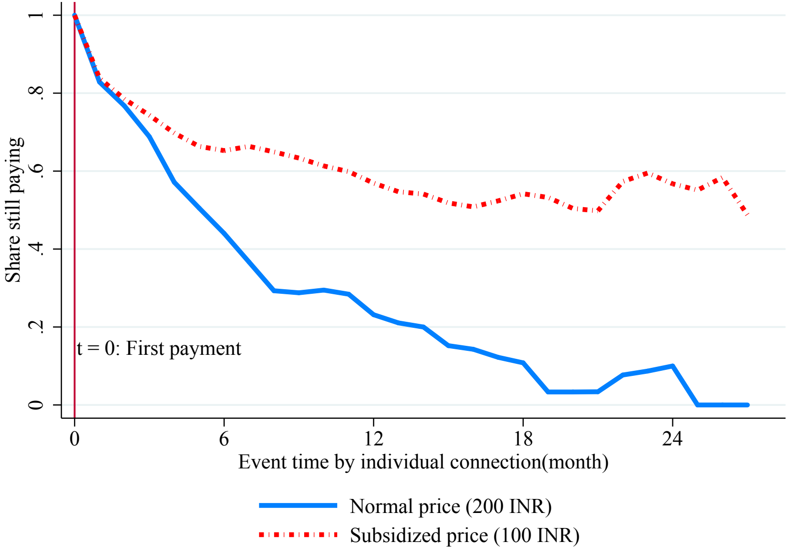
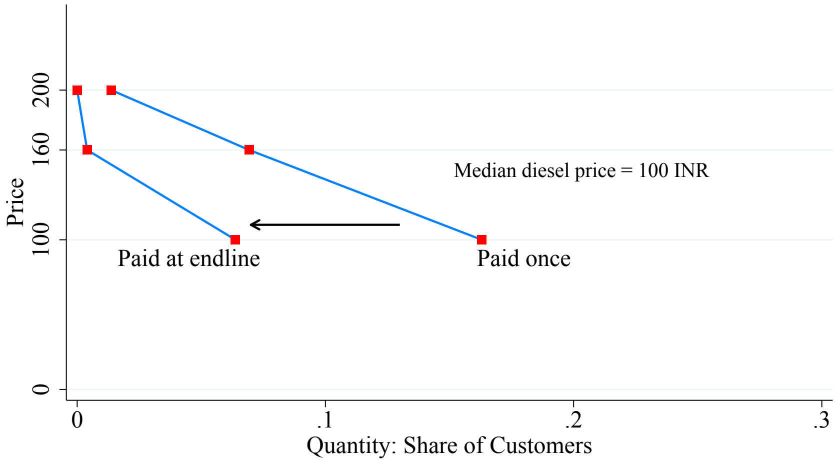
Demand curve for HPS solar (administrative data)



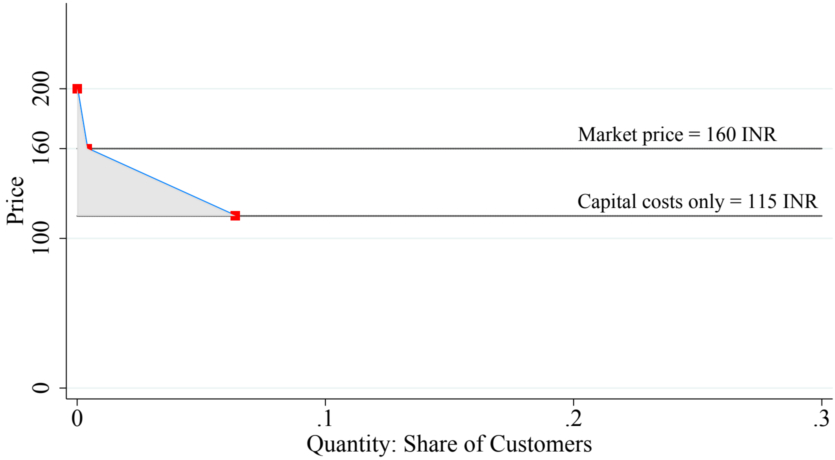
But, solar microgrid take-up declines over time



Demand curve for HPS solar



HPS consumer surplus at current price and price that could prevail with substantial innovation



ITT Reduced-form effects of Offering and Subsidizing HPS Microgrids

Table: Endline 1 electricity and asset outcomes

	HPS Electricity (=1) (1)	Daily Hours of Electricity Use (2)	Light Bulb Ownership (=1) (3)	Mobile Phone Ownership (=1) (4)
Subsidy treatment village (=1)	0.066***	0.94***	0.15***	0.034**
	(0.021)	(0.24)	(0.047)	(0.014)
No subsidy treatment village (=1)	0.0001	0.52**	0.098**	0.022
	(0.016)	(0.20)	(0.044)	(0.013)
Baseline Controls	Yes	Yes	Yes	Yes
Control mean	0.026	1.16	0.32	0.88
Observations	3036	2868	3001	3001

Includes baseline electricity source indicators, baseline monthly income, and baseline equivalent of outcome variable controls. Standard errors clustered at the village level in parentheses.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

ITT Reduced-form effects of Offering and Subsidizing HPS Microgrids

Table: Endline 1 welfare outcomes

	Monthly Inc. (INR '000s) (1)	Night study time (minutes) (2)	Adult Resp. Problems (3)	Children Resp. Problems (4)
Instrumental Variables				
Hours of electricity	0.15	0.51	0.027	0.014
	(0.35)	(3.40)	(0.027)	(0.012)
Reduced Form				
Subsidy treatment village (=1)	0.18	-0.60	0.026	0.012
	(0.31)	(3.15)	(0.021)	(0.008)
No subsidy treatment village (=1)	0.63*	7.00**	0.017	0.004
	(0.33)	(2.93)	(0.018)	(0.008)
Baseline Controls	Yes	Yes	Yes	Yes
Control mean	7.5	54.7	0.14	0.024
Observations	2692	2021	2710	2669

Includes baseline electricity source indicators, baseline monthly income, and baseline equivalent of outcome variable controls. Standard errors clustered at the village level in parentheses.

Summary of reduced-form results

1. Demand for solar
   - Near zero at 2013 to 2016 unsubsidized prices
   - Demand is very elastic and solar microgrids capture $\approx$ 7% of the market at prices about 1/2 of true cost
2. Sources of demand
   - Users experience increase in light bulb ownership, hours of electricity use and mobile phone ownership
   - No statistically meaningful effect on health, children's test scores, or income
   - **Appears related to availability and attributes of other products. We now turn to a model of demand for electricity sources to investigate.**

Outline

What are the determinants of demand for electricity sources?

We estimate a demand system, using the experiment, to answer a rich set of possible counter-factual questions.

Today: Nested logit with IV

- **Data**. Households choose one of $\{Grid, Diesel, Own\ Solar, HPS\ Solar\ Microgrid, None\}$.
  - Prices and availability at village-level.
  - Extraordinarily detailed household covariates.
- **Model**. Nested logit model with three nests of
  1. $\{Grid\}$
  2. $\{Diesel, Own\ Solar, HPS\ Solar\ Microgrid\}$
  3. $\{None\}$
- **Variation**.
  - Use experimental price variation for HPS solar
  - Treat availability and price of other sources as exogenous

Nested logit model

- Indirect utility for household i in village v and time t from electricity sources j is given by

$$
\begin{aligned}
U_{vtij} &= \delta_{vtj} + z_{tir}\beta_{rj} + \sum_g d_{jg}\zeta_{gi} + (1-\sigma_g)\epsilon_{vtij} \\
\delta_{vtj} &\equiv \sum_k x_{vtjk}\bar{\beta}_k + \xi_{vtj}.
\end{aligned}
$$

- x_{vtjk} are source characteristics.
- z_{tir} are household characteristics (income, number of adults, ownership of agricultural land).
- $\zeta_{gi} + (1-\sigma_g)\epsilon_{vtij} \sim$ EV-I, $\epsilon_{vtij} \sim$ EV-I (nested logit model)
- ξ_{vtj} is the mean unobserved utility of a source.

Estimate nested logit accounting for endogeneity

Use micro data (BLP, 2004) and account for endogeneity (Berry, 1994)

1. **Non linear search.** Search over (β, σ) to match the characteristics of the households that buy each product with GMM estimator

$$G_{tirj}(\beta,\sigma) = z_{tir}\left(\mathbf{1}\{i_j = j\} - Pr\left(i_j = j \mid \mathbf{z}_{\mathrm{ti}}, \mathbf{x}_{\mathrm{vt}}, \beta, \delta(\beta\sigma)\right)\right).$$

2. **Contraction mapping.** Use Berry (1994) contraction mapping to recover $\delta_{vtj}(\hat{\beta}, \hat{\sigma})$ for each village x wave x source.
3. **Linear instrumental variables.** Use 2SLS with specification:

$$\delta_{vtj}(\hat{\beta, \hat{\sigma}}) = \sum_k x_{vtjk}\bar{\beta}_k + \bar{\xi}_{tj} + \xi_{vtj}$$

$$\begin{aligned} x_{vtj,price} = & \mathbf{1}\left\{NormalPrice\right\} \times \mathbf{1}\{Endline1\}\,\alpha_1 + \\ & \mathbf{1}\left\{SubsidisedPrice\right\} \times \mathbf{1}\{Endline1\}\,\alpha_2 + \\ & \sum_{k \neq price} x_{vtjk}\gamma_k + \rho_{tj} + \varepsilon_{vtj} \end{aligned}$$

Experiment estimates structural parameters

Several candidate instruments for demand

1. **Supply / cost shifter.** Prices in other markets (Hausman instruments).
2. **Mark-up shifter.** Characteristics of other products in the same market (BLP instruments).
3. **Mark-up shifter.** Randomized experiment assigning price of HPS solar.

We opt to use (3)

- Perhaps the first experimental estimate of discrete choice (Kremer, Leino, Miguel and Zwane (2011) identify mixed logit model with travel cost, not experiment)

Household characteristics z_{vti}

Table: Household Attributes

	mean	sd
Demographics		
Literacy of household head (1-8)	2.57	2.10
Number of adults	3.43	1.70
Wealth Proxies		
Income (Rs. '000s/month)	7.36	6.98
Number of rooms	2.49	1.41
House type (pukka = 1)	0.27	0.45
Owns agricultural land	0.68	0.47
Solid roof (concrete, metal, tile, cement, asbestos)	0.46	0.50
Observations	3036	

Electricity source characteristics x_{vtj}

Table: Summary of electricity sources

	Grid	Diesel	HPS	Own solar
		Monthly price (INR)		
Baseline	73.84	126.6	200	100.5
Endline 1	61.64	104.8	163.8	99.55
Endline 2	61.64	104.8	170	90.95
		Peak hours (5pm - 10pm)		
Baseline	2.076	3.375	4.300	4.717
Endline 1	2.497	3.083	5	5
Endline 2	2.952	3.083	5	5
		Off hours		
Baseline	10.58	0	1	2.714
Endline 1	10.62	0	0.714	0.808
Endline 2	10.59	0	0.714	0.808

Variation in source characteristics

Table: Variation in source attributes

Variable	Source	Level of Variation
Price	Grid	Village x Survey wave
	Diesel	Village x Survey wave
	Own Solar	Village x Survey wave
	HPS	Village x Survey wave
Hours	Grid	Village x Survey wave
	Diesel	Village x Survey wave
	Own solar	Survey wave
	HPS	Survey wave

Estimation results: non linear part

Table: First step: Nonlinear parameters

	Non-linear stage (1)
Grid x Income	0.4876
Diesel x Income	0.3635
Own solar x Income	0.2456
HPS x Income	0.4012
Grid x Land	0.7155
Diesel x Land	0.2924
Own solar x Land	0.1481
HPS x Land	0.2049
Grid x Adults	0.8461
Diesel x Adults	0.7871
Own solar x Adults	0.2690
HPS x Adults	0.0562
Sigma offgrid	0.0848

The on-grid nest and no electricity outside good nest are degenerate and have $\sigma_g = 0$ accordingly.

Estimation results: linear part

Table: Linear Price IV

	OLS (1)	Second Stage Price IV (2)
Price (Rs. 100)	-0.26**	-1.32*
	(0.11)	(0.76)
Hours of supply on peak	0.50*	0.52**
	(0.26)	(0.26)
Hours of supply off peak	-0.12*	-0.14**
	(0.070)	(0.068)
ξ_{tj} mean effects	Yes	Yes
Observations	996	996

Standard errors cluster at the village level in parentheses. Includes mean unobserved energy source by time effects, ξ_{tj}.

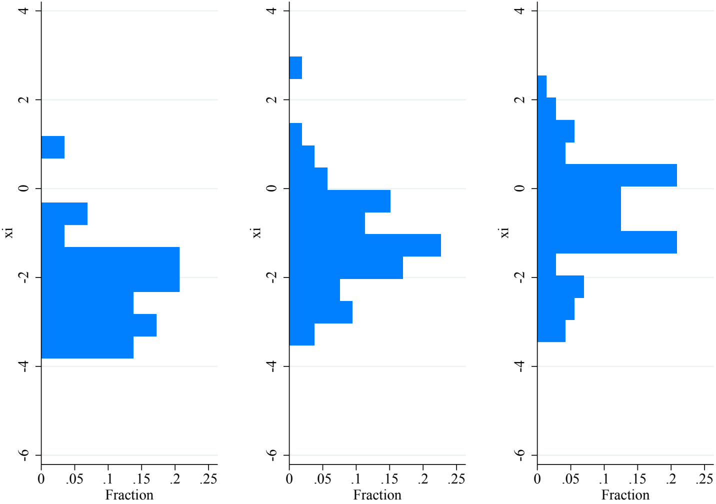
Estimation results: linear part

Table: First Stage

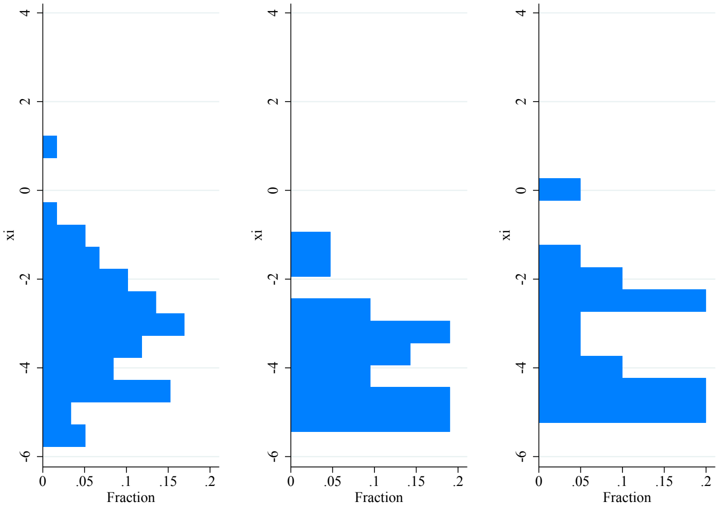
	(1) First Stage Price IV
Normal Price	0.11***
	(0.037)
Subsidy Price	-0.074**
	(0.033)
Hours of supply on peak	0.025
	(0.033)
Hours of supply off peak	-0.017
	(0.017)
ξ_{tj} mean effects	Yes
Observations	996

Standard errors cluster at the village level in parentheses. Includes mean unobserved energy source by time effects, ξ_{tj}

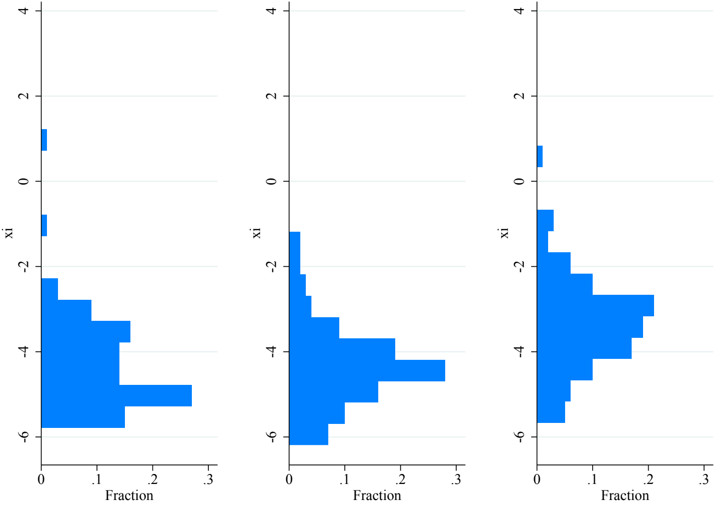
Estimate results: mean grid unobserved utilities



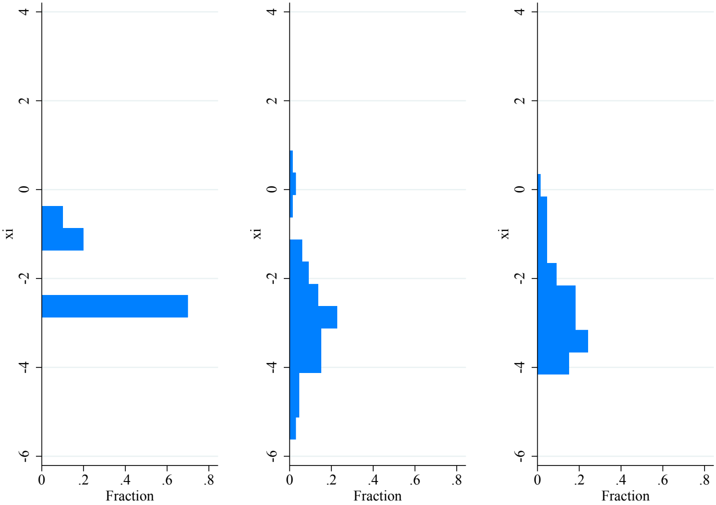
Estimate results: mean diesel unobserved utilities



Estimate results: mean own solar unobserved utilities



Estimate results: mean HPS unobserved utilities



Key Findings

1. Households are price sensitive – increasing the monthly price by 10 INR ($0.16) reduces...
    - HPS market share by 0.6 percentage points
    - Own solar market share by 0.8 pp
    - Diesel market share by 0.4 pp
    - Grid market share by 1.3 pp

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4. Estimation details
    - Load is in the constant, suggesting that it is part of the grid's appeal

Outline

Estimating the Change in Consumer Surplus or WTP

1. For a given consumer i, calculate the observable component of indirect utility $\widehat{V}_{vtij}$ for every choice j using $\hat{\delta}_j, \hat{\beta}$ and $\hat{\sigma}$.

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$$\mathbb{E}[CS_i|J] = ln\left(\sum_g exp((1-\sigma_g)IV_{ig})\right)$$

5. Willingness-to-pay for the expanded choice set is

$$\sum_i -\left(\mathbb{E}[CS_i|J'] - \mathbb{E}[CS_i|J]\right)/\beta_{price}.$$

Calculating annual losses to grid utility per household

- Annual losses to the utility per capita are given by

$$\frac{\left(12 \times NumGridCustomers \times \left(60\frac{kWh}{month} \times 3.88\frac{INR}{kWh} - x_{vt,grid,price}\right)\right)}{N}$$

- $60\frac{kWh}{month}$ mean consumption among Bihar households in billing data
- $3.88\ \frac{INR}{kWh}$ power purchase cost (NBPDCL Tariff Order FY 14-15)

Counterfactuals on grid and solar policy

1. **Complete expansion of the grid**
2. Introduction of solar to market
3. Optimistic solar innovation scenario
4. Distribution reforms

Quicktake

Power for All in India! How Close Is Modi's Goal?

By Rajesh Kumar Singh
April 26, 2018, 1:30 PM CDT

In a country where about 70 percent of the 1.3 billion population live in rural areas, getting electricity to everyone in India has proved something of a challenge. Among the reasons are the dire state of the power distribution companies' finances and rampant theft from the grid. Prime Minister Narendra Modi was elected in 2014 partly on a commitment to light up every home. With a general election expected next year, and access to power a key issue for voters, Modi's plans are coming under scrutiny.

1. How bad is the power situation?

About 270 million Indians had no access <http://documents.worldbank.org/curated/en/364571494517675149/pdf/114841-REVISED-JUNE12-FINAL-SEAR-web-REV-optimized.pdf> to electricity in 2014 -- making up one third of the world's powerless. (Nigeria was second-highest with 75 million.) Access in India's rural communities has jumped since 1990, when less than half had electricity, but more than a fifth of non-city dwellers still were without power in 2016, according to World Bank <https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS?locations=IN> data. That compares with 100 percent rural coverage in China and 99 percent in neighboring Pakistan.

WTP for current policy objective

Table: Distribution company policy reform counterfactuals: market shares and WTP

	Market shares					Annual WTP per HH (INR)	Annual Losses per HH (INR)
	Grid	Diesel	Own solar	HPS	None		
Actual	0.41	0.05	0.07	0.05	0.42		861.45
Grid everywhere	0.69	0.02	0.03	0.03	0.23	89.38	1436.57

Note: Assumes Endline 1 covariates and sources available as in April 2016.

Counterfactuals on grid and solar policy

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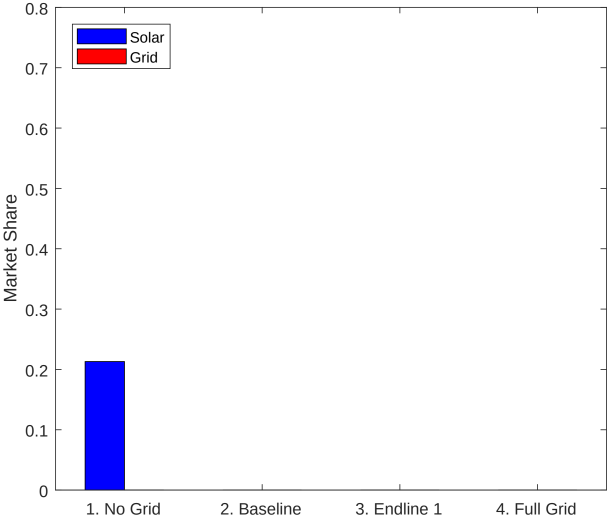
Off-grid solar market shares fall as grid expands



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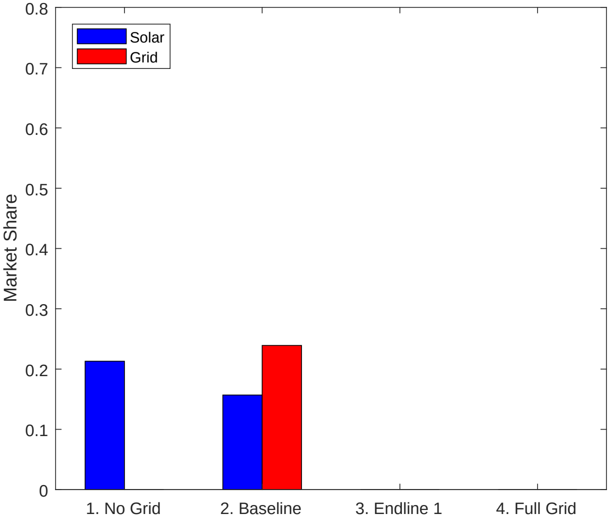

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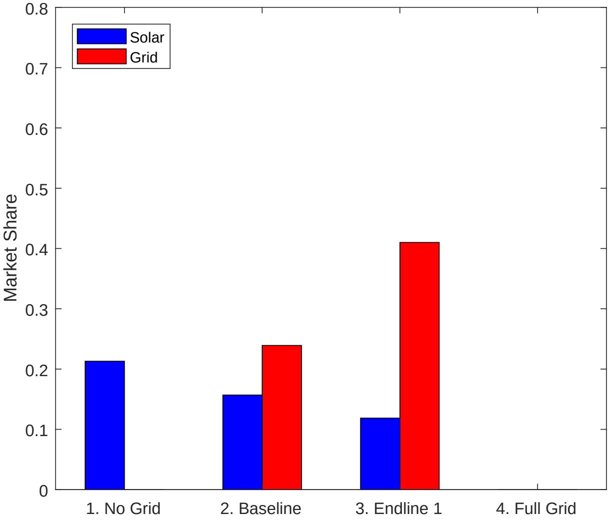

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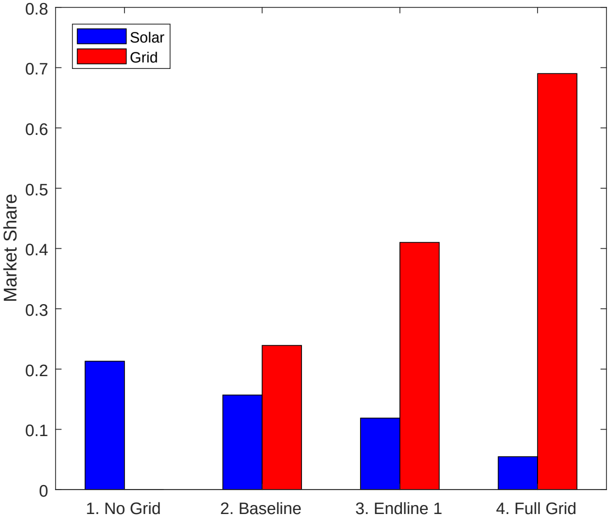
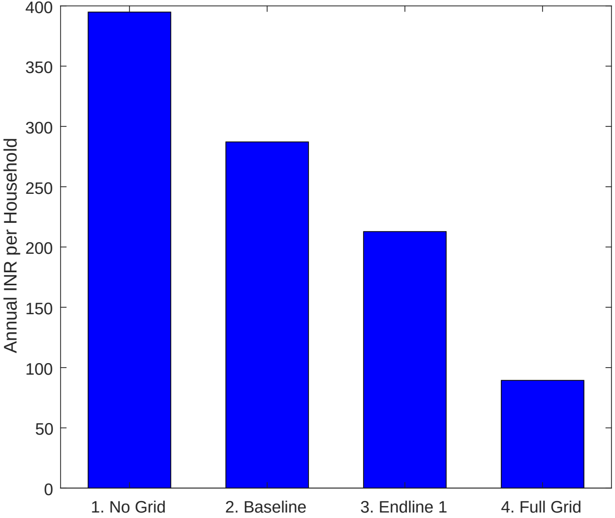


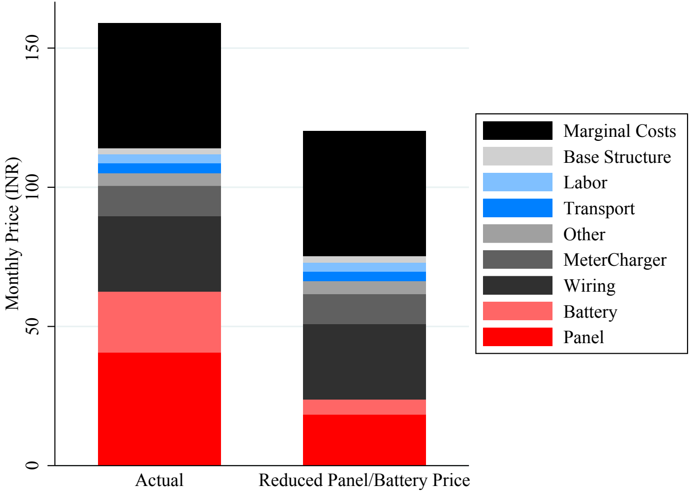
WTP for solar depends on presence of grid



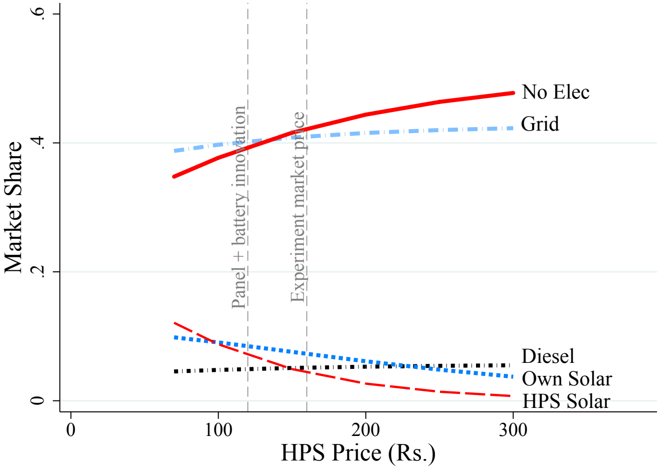
Counterfactuals on grid and solar policy

1. Complete expansion of the grid
2. Introduction of solar to market
3. **Optimistic solar innovation scenario**
    - Assume PV prices fall by 55% in accordance with NREL PV module experience curve 2022 projection.
    - Assume battery prices fall by 75% in accordance with DOE 2022 goal.
4. Distribution reforms

Projected capital costs in 2022 30% cheaper than subsidy treatment (INR 75 vs INR 115)



Solar demand limited, even at low prices



Note: Own solar prices varied proportionately to HPS price and we assume the grid is at endline 1 availability (53%).

Solar demand and addition to consumer surplus is limited, even at low prices

Table: Solar Innovation: WTP for decline in solar battery and panel costs

	Market shares					Annual WTP per HH (INR)	Annual Losses per HH (INR)
	Grid	Diesel	Own solar	HPS	None		
Actual	0.41	0.05	0.07	0.05	0.42		861.45
Optimistic Solar Innovation	0.40	0.05	0.08	0.07	0.40	63.24	846.19

Note: Assumes Endline 1 covariates and sources available as in April 2016. Assumes battery and panel costs decline according to NREL and DOE 2022 projections and that own solar prices are comprised of similar share battery and panel costs.

Counterfactuals on grid and solar policy

1. Complete expansion of the grid
2. Introduction of solar to market
3. Optimistic solar innovation scenario
4. **Distribution reforms**
    - Additional nighttime supply hours
    - Recover full tariffs (disallow theft)

Distribution company potential policy reforms

Table: Distribution company policy reform counterfactuals: market shares and WTP

	Market shares					Annual WTP per HH (INR)	Annual Losses per HH (INR)
	Grid	Diesel	Own solar	HPS	None		
Actual	0.41	0.05	0.07	0.05	0.42		861.45
i. Expand availability and supply							
Grid everywhere	0.69	0.02	0.03	0.03	0.23	89.38	1436.57
Extra 1 Hour	0.45	0.05	0.08	0.06	0.36	414.97	1042.04
Extra 2 Hours	0.51	0.04	0.07	0.06	0.32	1041.80	1287.86
ii. Remove theft							
Grid INR 140	0.29	0.06	0.10	0.08	0.47	-535.93	321.74
iii. Budget neutral reduction in theft and 5 peak hours							
Grid INR 120	0.45	0.05	0.08	0.06	0.36	381.13	843.04

We model removing theft by raising the grid price to reported survey bill values, assuming payment rate is 100%. In the budget neutral theft reduction with increased supply hours, we set peak hours equal to its maximum of 5 and raise the grid price until annual losses are equivalent to actual annual losses.

Bihar village clamours for real electricity

The residents of Dharnai are far from satisfied to see lights for the first time in 33 years, courtesy a solar-powered micro-grid set up by the environment watchdog Greenpeace India.

Giridhar Jha
Patna, August 6, 2014 | UPDATED 09:07 IST

A+ A-

The least you would expect when you bring electricity to an entire village, ending over three decades of darkness, is a 'thank you' from its residents. But no such niceties here in Dharnai, a nondescript village tucked away in the Naxal heartland of Bihar.

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Counterfactuals on grid and solar policy

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Note: Assumes Endline 1 covariates and sources available as in April 2016.

This paper addresses 3 sets of questions

1. Experimental estimates of the demand for solar microgrids and their benefits.

- Trace out demand curve.
    - At 2013-2016 unsubsidized prices, near zero demand.
    - Demand is very elastic and at prices about 1/2 of true cost, HPS microgrids capture 7% of the market.
    - Traditional analysis
        - Users experience increase in light bulb ownership, hours of electricity use and mobile phone ownership
        - No meaningful effect on health, children's test scores, or income

This paper addresses 3 sets of questions

2. Estimate nested logit model of electricity source demand with 4 sources to account for heterogeneity in sources and substitution opportunities.

- Households are price sensitive– increasing the monthly price by by 10 INR ($0.16) reduces...
  - HPS market share by 0.6 percentage points
  - Own solar market share by 0.8 pp
  - Diesel market share by 0.4 pp
  - Grid market share by 1.3 pp
- Night time electricity is valued highly: annual WTP for an additional hour of peak period electricity is 473 INR, compared to annual household income of roughly 90,000 INR.

This paper addresses 3 sets of questions

3. Counterfactuals: Improvements in the Grid are Valued Highly

- **Extending the grid everywhere** decreases unelectrified (from 42 pp to 23 pp), increases WTP by 89 INR per household annually, and greatly increases utility losses
- **Introduction of solar to market.**
  - Solar's market share is highly dependent on grid availability
  - WTP for introducing solar into the market declies from about 400 INR per year per household when the grid isn't available to 90 INR when it is available everywhere
- **Optimistic solar innovation scenario.**
  - Decreases the share of households that are unelectrified by only 2 percentage points
  - Low WTP for solar innovation, approximately equal to 63 INR per household annually

This paper addresses 3 sets of questions

3. Counterfactuals (cont.): Improvements in the Grid are Valued Highly

- **Distribution reforms.**
  - A 1 hour increase in night time supply of electricity decreases unelectrified by 6 pp, increases annual WTP by 415 INR, and greatly increases distribution company losses.
  - Ending theft increases unelectrified from 42 pp to 47 pp, reduces annual WTP by 536 INR, and greatly reduces losses
  - Budget neutral increase to full supply of night time hours to 5 and reduction in theft decreases unelectrified by 6 pp and increases annual WTP by 381 INR.

Lots of to-dos

- **Richer model**.
  - Additional household covariates, consider mixed logit.
- **Conduct full welfare analysis, accounting for distribution company losses.**
- ......

Appendix

Measure intra-household socio-economic benefits with health and educational outcomes

1. Self-reported health (cardio-respiratory)
2. Directly administered reading and math tests (Pratham ASER)
3. Surveyed income

Health estimates: null effect

Table: Experiences respiratory problems (=1)

	Adults (1)	Children (2)
Instrumental Variables		
Hours of electricity	0.027	0.014
	(0.027)	(0.012)
Reduced Form		
Subsidy treatment village (=1)	0.026	0.012
	(0.021)	(0.0082)
No subsidy treatment village (=1)	0.017	0.0041
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Baseline Controls	Yes	Yes
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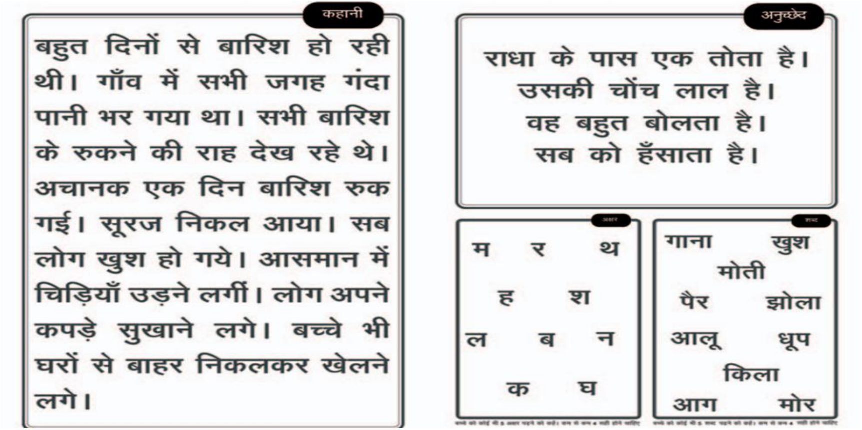
Solar and learning

Reading test instrument from Pratham: Alphabet, Words, Paragraph, Story



कहानी

बहुत दिनों से बारिश हो रही थी। गाँव में सभी जगह गंदा पानी भर गया था। सभी बारिश के रुकने की राह देख रहे थे। अचानक एक दिन बारिश रुक गई। सूरज निकल आया। सब लोग खुश हो गये। आसमान में चिड़ियाँ उड़ने लगीं। लोग अपने कपड़े सुखाने लगे। बच्चे भी घरों से बाहर निकलकर खेलने लगे।

अनुच्छेद

राधा के पास एक तोता है।
उसकी चोंच लाल है।
वह बहुत बोलता है।
सब को हँसाता है।

अक्षर

म र थ
ह श
ल ब न
क घ

शब्द

गाना खुश
मोती
पैर झोला
आलू धूप
किला
आग मोर

Learning estimates: larger null effect

Table: Child level test scores (standardized)

	Night study time (minutes)	Reading	Math
	(1)	(2)	(3)
Instrumental Variables			
Hours of electricity	0.51	0.22	0.21
	(3.40)	(0.24)	(0.23)
Reduced Form			
Subsidy treatment village (=1)	-0.60	0.11*	0.095
	(3.15)	(0.061)	(0.065)
Normal treatment village (=1)	7.00**	0.020	0.071
	(2.93)	(0.061)	(0.062)
Baseline Controls	Yes	Yes	Yes
Control mean	54.7	0	0
Observations	2021	646	637

Includes baseline electricity source indicators, baseline monthly income, and baseline equivalent of outcome variable controls. Standard errors clustered at the village level in parentheses. Study time results are at the household level where nighttime begins at 6pm. Test score results are at the child level.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Income estimate: null effect

Table: Endline monthly income

	Monthly Income (INR '000s)
	(1)
Instrumental Variables	
Hours of electricity	0.15
	(0.35)
Reduced Form	
Subsidy treatment village (=1)	0.18
	(0.31)
No subsidy treatment village (=1)	0.63^{*}
	(0.33)
Baseline Controls	Yes
Control mean	7.5
Observations	2692

Includes baseline electricity source indicators, baseline monthly income, and baseline equivalent of outcome variable controls. Standard errors clustered at the village level in parentheses.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$