Experimental Evidence on the Economics of Rural Electrification

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Introduction

- Experiment randomized expansion of electric grid infrastructure in rural Kenya (2013-2016)
- In Sub-Saharan Africa, roughly 600 mio. people without electricity (IEA, 2014)
- Infrastructure investments (transportation, water/sanitation, telecommunications, electricity systems) are primary UN/ODA targets (1/3 of total World Bank lending in 2015)

$\Rightarrow$ High FC, low MC, long investment horizons, often regulated (since electricity supply is a natural monopoly)

- Recent research on economic impacts:
  - Transportation (Donaldson 2013; Faber 2014)
  - Water and sanitation (Devoto et al. 2012; Patil et al. 2014)
  - Telecommunications (Jensen 2007; Aker 2010)
  - Electricity systems (Dinkelman 2011; Lipscomb, Mobarak, and Barham 2013; Burlig and Preonas 2016; Chakravorty, Emerick, and Ravago 2016; Barron and Torero 2017)

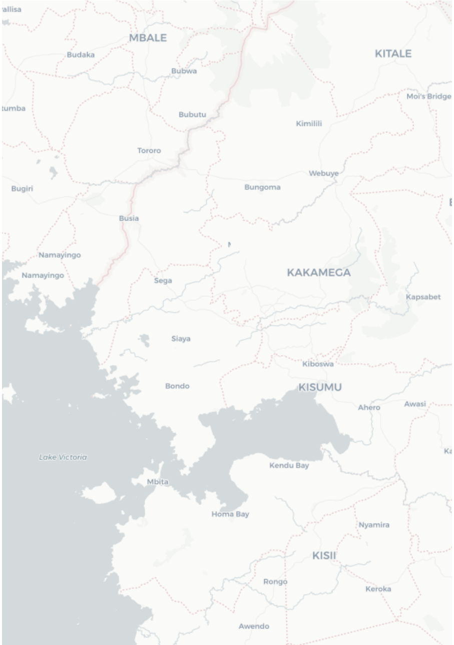
$\Rightarrow$ Strong correlation between energy consumption and economic development at the macroeconomic level, but less evidence on how energy drives poverty reduction, and how industrial energy access compares to impacts of electrifying households

$\Rightarrow$ Still limited empirical evidence that links the demand-side and supply-side economics of infrastructure investments

$\Rightarrow$ Rural access debates: Grid connections vs. solar lanterns

- **Setting**: 150 rural communities in Kenya, a country where grid coverage is rapidly expanding (last-mile grid connections)
- **Design**: With Kenya's Rural Electrification Authority (REA) $\rightarrow$ introduced randomly differing price subsidy and scale of electricitic grid construction at clusters of households level

$\Rightarrow$ Estimate demand curve + MC and AC (supply) curves, and impact on various development outcomes and welfare measures (i.e. compare consumer surplus to total cost)


MBALE
KITALE
Budaka
Bubwa
Mois Bridge
tumba
Bubutu
Kimilili
Tororo
Webuye
Bugiri
Bungoma
Busia
Namayingo
Namayingo
KAKAMEGA
Sega
Kapsabet
Siaya
Kiboswa
Bondo
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Awasi
Lake Victoria
Kendu Bay
Mbita
Homa Bay
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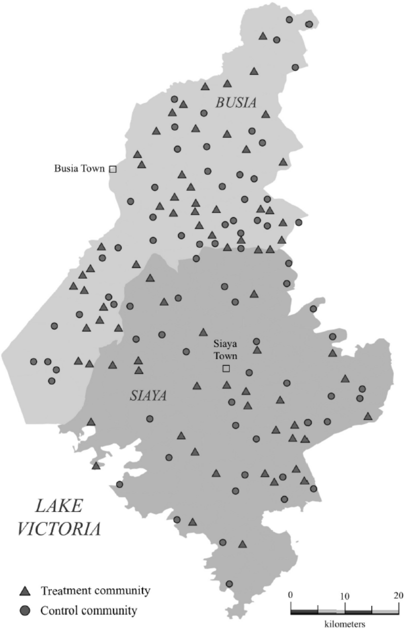
KISII
Rongo
Keroka
Awendo

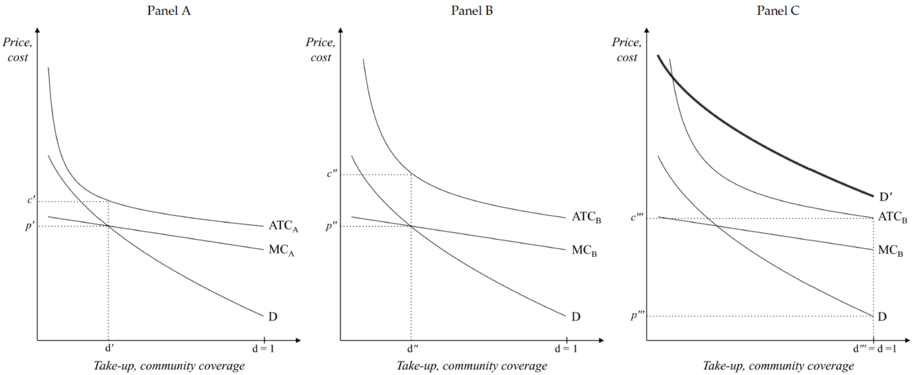

BUSIA
Busia Town
Siaya Town
SIAYA
LAKE VICTORIA
Treatment community
Control community
0
10
20
kilometers

Theoretical Framework

- **Natural monopoly**: Production by single firm minimizes cost
- Electric utility provides communities of households with grid connections, and incurs a (high) fixed cost (FC)
- As coverage increases, MC of additional household decreases
- Household demand for grid connection = expected difference between consumer surplus (CS) and monthly price
- Social planner's solution: P' = MC
- But because of high fixed cost: Subsidy (rectangle P'C')
- Social benefit if CS (area u. demand) > TC (rectangle C'D')

3 Scenarios: A: Social benefit (CS > TC) | **B**: High FC → TC > CS | **C**: Externalities → D' (social demand) > D (private demand) → full electrification + social benefit

Figure 1—The electric utility as a natural monopoly



Notes: In panel A, the electric utility is a natural monopoly facing high fixed costs, decreasing marginal costs (MC_A), and decreasing average total costs (ATC_A). MC_A intersects demand at d′. At d′, a government-subsidized mass electrification program would increase social welfare since consumer surplus (i.e., the area under the demand curve) is greater than total cost. Panel B illustrates an alternative scenario with higher fixed costs. In this case, consumer surplus is less than total cost at all quantities. A mass electrification program would not increase welfare unless there are, for instance, positive externalities from private grid connections. Panel C illustrates a scenario in which social demand (D′) is sufficiently high for the ideal outcome to be full coverage, subsidized by the government.

Rural Electrification in Kenya

- *Vision 2030*: Installed capacity to increase 10-fold by 2031 at $\approx$ constant shares (35% fossile, 36% hydro, 26% geothermal)

- Dramatic increase in coverage in recent years: 2003: 3% of public schools connected, 2012: 100% connected

- Establishment of REA in 2007 boosted progress, especially schools & hospitals, but in 2014 national HH elec. still 32%

- Since 2004: HH within 600m of electric transformer could apply for electrification at fixed price of 398$

- May 2015: Gov. Received $364M from World Bank and ADB to launch *Last Mile Connectivity Project* (LMCP): Subsidized mass electrification program that plans to connect 4M 'under grid' HH $\rightarrow$ lower the fixed connection price to $171

Experimental Design and Data

- Field experiment takes place in 150 'transformer communities'

Figure B2—Example of a "transformer community" of typical density

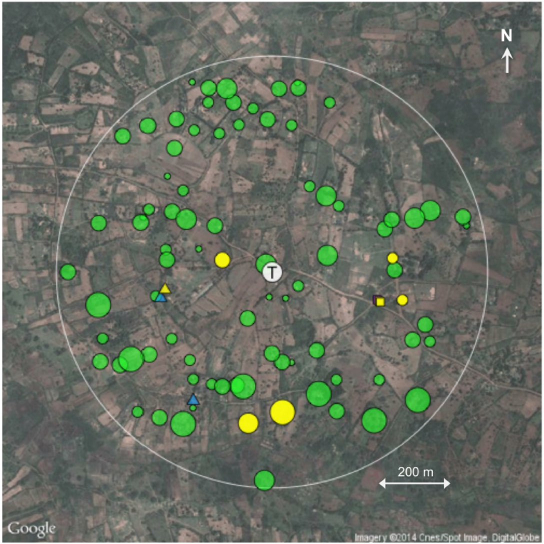
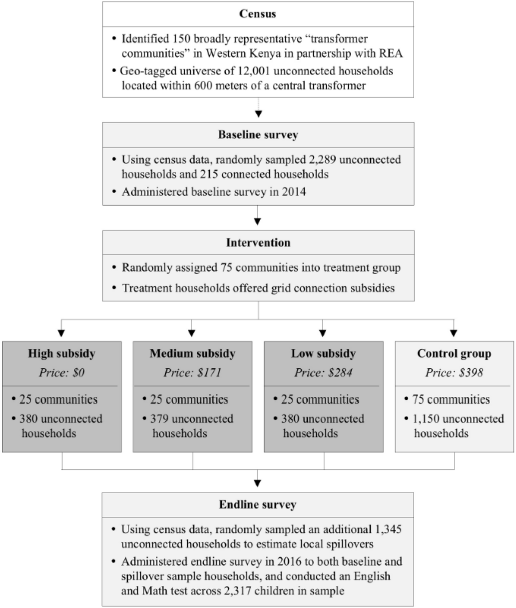


Table B1—Comparison of social and economic indicators for study region and nationwide counties

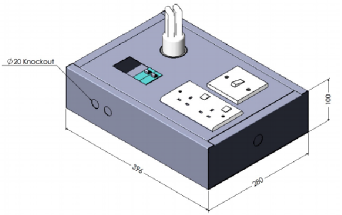
		Nationwide county percentiles		
	Study region	25th	50th	75th
Total population	793,125	528,054	724,186	958,791
per square kilometer	375.4	39.5	183.2	332.9
% rural	85.7	71.6	79.5	84.4
% at school	44.7	37.0	42.4	45.2
% in school with secondary education	10.3	9.7	11.0	13.4
Total households	176,630	103,114	154,073	202,291
per square kilometer	83.6	7.9	44.3	78.7
% with high quality roof	59.7	49.2	78.5	88.2
% with high quality floor	27.7	20.6	29.7	40.0
% with high quality walls	32.2	20.3	28.0	41.7
% with piped water	6.3	6.9	14.2	30.6
Total public facilities	644	356	521	813
per capita (000s)	0.81	0.59	0.75	0.98
Electrification rates				
Rural (%)	2.3	1.5	3.1	5.3
Urban (%)	21.8	20.2	27.2	43.2
Public facilities (%)	84.1	79.9	88.1	92.6

Figure B3—Experimental design



Notes: The 150 transformer communities in our sample covered 62.2 percent of the universe of REA projects in Busia and Siaya counties in August 2013. See appendix A for details on the community selection procedure. At baseline, roughly 15 unconnected households in each community were randomly sampled and enrolled into the study. Census data on the universe of unconnected households were used as a sampling frame. Baseline surveys were also administered to a random sample of 215 households already connected at baseline. Communities were randomly assigned into three treatment arms and a control group. Treatment offers were valid for eight weeks. At endline, roughly nine additional households in each community were randomly sampled and enrolled into the study in order to measure local spillovers. Census data on the universe of unconnected households were again used as a sampling frame.

Figure B5—*Umeme Rahisi* "ready-board" designed by Power Technics



Notes: Treatment households received an opportunity to install a certified household wiring solution in their homes at no additional cost. 88.5 percent of the households connected in the experiment accepted this offer, while 11.5 percent provided their own wiring. Each ready-board, valued at roughly $34 per unit, featured a single light bulb socket, two power outlets, and two miniature circuit breakers. The unit is first mounted onto a wall and the electricity service line is directly connected to the back. The hardware was designed and produced by Power Technics, an electronic supplies manufacturer in Nairobi.

- First treatment HH metered in September 2014, average connection time 7 months. Final HH metered in October 2015

- May and September 2016: Endline survey to 2,217 study households, or 96.9% of the baseline sample + short English and Math tests to all 12 to 15-year olds in the endline sample HH's, or 2,317 children in total

- **Data**: Community characteristics data (N=150), baseline HH survey data (N=2,504), experimental demand data (N=2,289), administrative community construction cost data (N=77), endline HH survey data (N=3,770), and children's test score data (N=2,310) (all collected and compiled between August 2013 and December 2016)

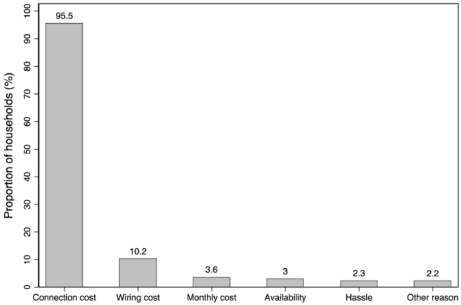
- Tests reveal 4 study arms are comparable in basic control characteristics → Randomization succesfull

Table 1—Differences between electricity grid unconnected vs. grid connected households at baseline

	Unconnected (1)	Connected (2)	p-value of diff. (3)
Panel A: Household head (respondent) characteristics			
Female (%)	62.9	58.6	0.22
Age (years)	52.3	55.8	< 0.01
Senior citizen (%)	27.5	32.6	0.11
Attended secondary schooling (%)	13.3	45.1	< 0.01
Married (%)	66.0	76.7	< 0.01
Not a farmer (%)	22.5	39.5	< 0.01
Employed (%)	36.1	47.0	< 0.01
Basic political awareness (%)	11.4	36.7	< 0.01
Has bank account (%)	18.3	60.9	< 0.01
Monthly earnings (USD)	16.9	50.6	< 0.01
Panel B: Household characteristics			
Number of members	5.2	5.3	0.76
Youth members (age ≤ 18)	3.0	2.6	0.01
High-quality walls (%)	16.0	80.0	< 0.01
Land (acres)	1.9	3.7	< 0.01
Distance to transformer (m)	356.5	350.9	0.58
Monthly (non-charcoal) energy (USD)	5.5	15.4	< 0.01
Panel C: Household assets			
Bednets	2.3	3.4	< 0.01
Sofa pieces	6.0	12.5	< 0.01
Chickens	7.0	14.3	< 0.01
Radios	0.35	0.62	< 0.01
Televisions	0.15	0.81	< 0.01
Sample size	2,289	215	

- **Unconnected HH's**: 77% primarily farmers, overwhelmingly poor HH's, as evidenced by the fact that only 15 percent have high-quality walls. HH's have 5.3 members on average, and spend \$5.55 per month on (non-charcoal) energy sources, primarily kerosene

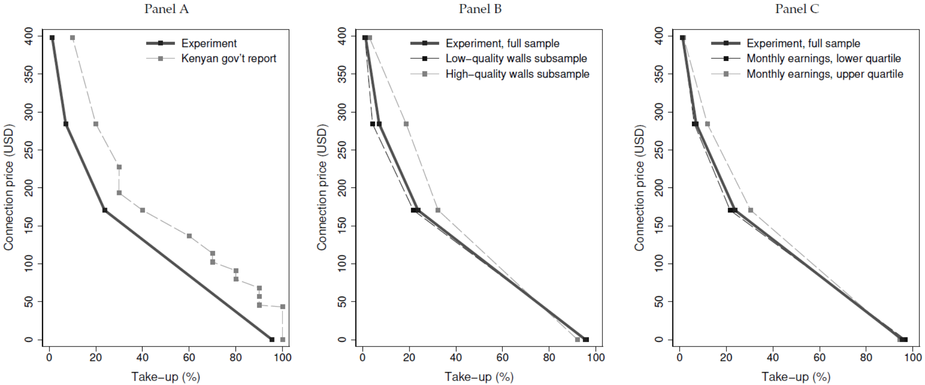
Figure B6—Stated reasons why households remain unconnected to electricity at baseline



Notes: Based on the responses of 2,289 unconnected households during the baseline survey round.

A: Experiment vs. Ministry of Energy and Petroleum's internal predictions for take-up in rural areas. Area under experimental demand curve is \$12,421. Based on average community density of 84.7 HH's → average valuation is just \$147 per HH | **B**: High Quality Walls HH's show larger takeup | **C**: Upper Quantile HH's show larger takeup

Figure 2—Experimental evidence on the demand for rural electrification



Notes: Panel A compares the experimental results to the assumptions in an internal government report shared with our team in early-2015. Panel B plots the experimental results separately for households with low- and high-quality walls. Panel C plots the results separately for households in the lower and upper quartiles of monthly earnings, which is defined as the respondent's profits from businesses and self-employment, salary and benefits from employment, and agricultural sales for the entire household.

Empirical Model:

$$y_{ic} = \alpha + \beta_1 T_c^L + \beta_2 T_c^M + \beta_3 T_c^H + \mathbf{x}_c' \gamma + \mathbf{x}_{ic}' \lambda + \epsilon_{ic} \qquad (1)$$

Where:

- y_{ic}: Take-up decision of HH i in community c
- $T_c^{L,M,H}$: Low, medium, or high subsidy arm dummies
- $\mathbf{x}_c'$: Community-level characteristics (variables used for stratification during randomization)
- $\mathbf{x}_{ic}'$: HH-level baseline characteristics
- Standard errors are clustered by community, the unit of randomization

Table 2—Impact of grid connection subsidy on take-up of electricity connections

			Interacted variable					
			High-quality walls	Monthly earnings (USD)	Attended secondary school	Baseline electrification rate	Baseline neighbors connected	Report of blackout in past 3 days
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
T1: Low subsidy—29% discount	5.8***	5.9***	3.6**	4.8***	4.5***	5.6**	4.8**	6.1**
	(1.4)	(1.5)	(1.5)	(1.5)	(1.4)	(2.2)	(1.9)	(2.6)
T2: Medium subsidy—57% discount	22.4***	22.9***	21.3***	20.9***	19.8***	21.4***	21.4***	18.7***
	(4.0)	(4.0)	(4.4)	(4.1)	(3.8)	(6.2)	(3.5)	(5.1)
T3: High subsidy—100% discount	94.2***	95.0***	95.6***	95.6***	95.2***	97.5***	96.1***	95.1***
	(1.2)	(1.3)	(1.2)	(1.3)	(1.3)	(1.7)	(1.3)	(2.4)
Interacted variable			0.3	-0.0	-1.0	0.1	0.1	-0.9
			(1.4)	(0.0)	(1.5)	(0.1)	(0.1)	(1.3)
T1 × interacted variable			12.3**	0.1*	10.2	0.1	0.2	-0.2
			(6.1)	(0.0)	(7.0)	(0.2)	(0.2)	(3.1)
T2 × interacted variable			8.8	0.1*	19.5***	0.3	0.3	7.6
			(7.8)	(0.1)	(4.6)	(1.2)	(0.2)	(7.8)
T3 × interacted variable			-5.5	-0.0	-4.3	-0.5*	-0.2	-0.2
			(3.9)	(0.0)	(4.9)	(0.3)	(0.1)	(2.8)
Household and community controls	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2289	2176	2176	2164	2176	2176	2176	2176
R^2	0.68	0.69	0.69	0.70	0.70	0.69	0.69	0.69

Notes: The dependent variable is an indicator variable (multiplied by 100) for household take-up, with a mean of 21.6. Take-up in the control group is 1.3. Robust standard errors clustered at the community level in parentheses. Pre-specified household controls include the age of the household head, indicators for whether the household respondent attended secondary school, is a senior citizen, is not primarily a farmer, is employed, and has a bank account, an indicator for whether the household has high-quality walls, and the number of chickens (a measure of assets) owned by the household. Pre-specified community controls include indicators for the county, market status, whether the transformer was funded and installed early on (between 2008 and 2010), community electrification rate at baseline, and community population. Monthly earnings (USD) includes the respondent's profits from businesses and self-employment, salary and benefits from employment, and agricultural sales for the entire household. Interacted variables in columns 7 and 8 are the proportion of neighbors (i.e., within 200 meters) connected to electricity and an indicator for whether any households in the community reported a recent blackout, respectively. Asterisks indicate coefficient statistical significance level (2-tailed): * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.

- All three subsidy levels lead to significant increases in the likelihood of takeup:
  - The 100% subsidy increases of take-up by 95%
  - The 57% subsidy increases of take-up by 23%
  - The 29% subsidy increases of take-up by 6%

- Take-up is differentially higher in low and medium subsidy arms for HH with wealthier and more educated respondents

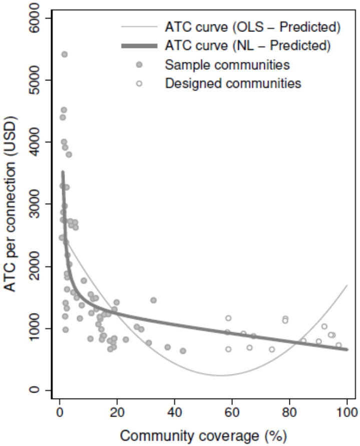
Next Step: Estimate the economies of scale in grid extension

$$\Gamma_c = \frac{b_0}{Q_c} + b_1 + b_2 Q_c \quad (2)$$

- (2): Non-linera function, Γ_c = Average Total Cost per connection (ATC), Q_c = community coverage (%)

- ATC = \$1813 (Ministry of Energy ATC = \$1602), $AC_{Q_c=100}$ = \$658 $\rightarrow$ Strong scale economies

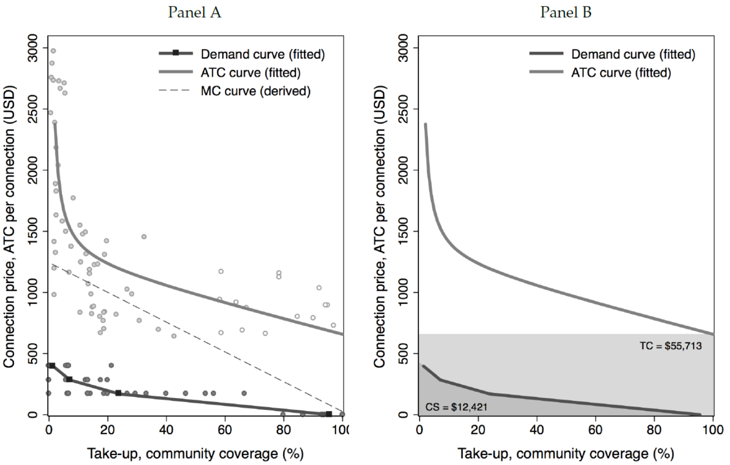
Figure 3—Experimental evidence on the costs of rural electrification



Notes: Each point on the scatterplot represents the community-level, budgeted estimate of the average total cost per connection (ATC) at a specific level of community coverage. The light-grey curve is the fitted curve from the IV regression reported in appendix table A1B, column 3. The dark-grey curve corresponds to the predicted vaues from the nonlinear estimation of $ATC = b_0/Q + b_1 + b_2Q$.

- Total Cost (TC) in particular community $= Q_c \times$ ATC
- $\mathrm{MC} = \frac{dTC}{dQ_c} = b_1 + b_2 Q_c = \$1244.30 - (\$12.20) Q_c$

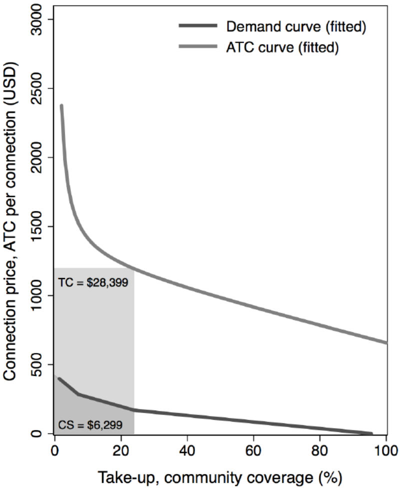
Figure 4—Experimental estimates of the welfare implications of rural electrification



- Estimated demand curve for an electricity connection does not intersect estimated MC curve
- At 100% coverage, estimated TC of connecting a community of \$55,713 (based on mean community density of 84.7 HH's)
- CS $\approx$ \$12400 $<< TC$ at all quantity (Q_c) levels $\rightarrow$ Rural electrification seems to reduce social welfare $\rightarrow$ welfare loss of \$43,292 per community
- To justify such a program, discounted future social welfare gains (and externalities) of \$511 per HH would be required
- But: Credit constraints and imperfect information may also contribute to lower demand

Evaluate LMCP programme ($171 per HH nationwide): 23.7% of HH's would take up connection, welfare loss of $22,100 per community, or $1,099 per connected HH

Figure B12—Estimated net welfare of a government program



Evaluating Economic Impacts 18 months post-connection:

- First only high subsidy group vs. control group, estimate intention-to-treat (ITT):

$$y_{ic} = \beta_0 + \beta_3 T_{Hc} + \mathbf{x}_c' \Lambda + \mathbf{z}_{1ic}' \Gamma + \epsilon_{ic} \tag{3}$$

- Then estimate treatment-on-treated (TOT) results using data from all three of the subsidy treatment groups:

$$y_{ic} = \beta_0 + \beta_1 E_{ic} + \mathbf{x}_c' \Lambda_2 + \mathbf{z}_{1ic}' \Gamma_2 + \epsilon_{ic} \tag{4}$$

- $E_{ic} = 1[\text{Electrified}]$, instrumented by $T_{Lc},\ T_{Mc}$ and T_{Hc}

Results: No substantial economic or other impacts stemming from household electrification, only small, marginally statistically impacts on total hours worked (P5) and life satisfaction (P8), which do not survive the FDR multiple testing adjustment[1]

[1] Column 4 reports the false discovery rate (FDR)-adjusted q-values corresponding to the coefficient estimates in column 3, which limit the expected proportion of rejections within a hypothesis that are Type I errors (i.e., false positives).

Table 3—Estimated treatment effects on pre-specified and grouped outcomes

	Control	ITT	TOT	FDR q-val
	(1)	(2)	(3)	(4)
Panel A: Treatment effects on pre-specified outcomes				
P1. Grid connected (%)	5.6	89.7***	–	–
	[23.0]	(1.4)		
P2. Monthly electricity spending (USD)	0.16	2.00***	2.20***	.001
	[1.29]	(0.18)	(0.20)	
P3. Household employed or own business (%)	36.8	5.1	4.5	.416
	[38.8]	(3.1)	(3.4)	
P4. Total hours worked last week	50.9	-2.8*	-3.6**	.167
	[32.8]	(1.5)	(1.7)	
P5. Total asset value (USD)	888	109	110	.540
	[851]	(108)	(120)	
P6. Ann. consumption of major food items (USD)	117	-3	-5	.548
	[92]	(6)	(7)	
P7. Recent health symptoms index	0	-0.03	-0.05	.548
	[1]	(0.06)	(0.07)	
P8. Normalized life satisfaction	0	0.12**	0.13*	.179
	[1]	(0.06)	(0.07)	
P9. Political and social awareness index	0	-0.03	-0.02	.731
	[1]	(0.05)	(0.05)	
P10. Average student test Z-score	0	-0.08	-0.10	.540
	[0.99]	(0.10)	(0.10)	
Panel B: Mean treatment effects on grouped outcomes				
G1. Economic Index (P3 to P6 outcomes)	0	0.06	0.03	–
	[1]	(0.08)	(0.08)	
G2. Non-Economic Index (P7 to P10 outcomes)	0	-0.01	-0.02	–
	[1]	(0.06)	(0.07)	

Alternative approach to estimate CS doesn't change result:

Table 4—Alternative estimates of household (HH) consumer surplus based on monthly consumption

	Monthly consumption *Benchmark*			
Consumer demand elasticity	5 kWh *Newly connected HH in sample* (1)	5 kWh + 10% annual growth (2)	40 kWh *Baseline connected HH in sample* (3)	75 kWh *Median connected HH in Nairobi* (4)
-0.45	49	110	391	733
-0.30	73	164	587	1,100
-0.15	147	329	1,173	2,200

Notes: Estimates of consumer surplus based on monthly electricity consumption levels ranging from 5 kWh to 75 kWh, and consumer demand elasticities ranging from -0.15 to -0.45. Common assumptions include a discount rate of 15%, an asset life of 30 years, a price of $0.12 per kWh, linear demand, zero consumer surplus from electricity without a grid connection, and a 188 day delay before obtaining an electricity connection (as illustrated in appendix figure A1). The 40 kWh level in column 3 corresponds to median consumption level reported by connected households at baseline. See appendix table B7 for details on the benchmark electricity consumption levels.

Administrative data from Kenya Power indicates that the median connected household in Nairobi consumes 72.8 kWh per month. At roughly this level of consumption, the rural connections would appear to potentially yield positive social welfare, with consumer surplus ranging from $733 to $2,200.

External Validity

- Welfare loss surprising: Previous analyses have found substantial benefits from electrification (Dinkelman 2011, Lipscomb, Mobarak, and Barham 2013) though they have not directly compared benefits to costs
- But potentially there are factors that could drive down costs or increase demand in other settings reducing external validity:
  - **A. Excess cost from leakage**: contractors submitted invoices that were only 1.7% higher than the budgeted amount on average, but the number of observed poles was 21.3% less than budgeted, and invoiced construction travel costs were 32.9% higher than expected

  $\rightarrow$ Electric grid construction costs may be substantially inflated due to mismanagement and corruption in Kenya, but even 20-30% decline in construction cost would still entail a social welfare loss

- **B. Factors contributing to lower demand**:
  - bureaucratic red tape (HH's waited 188 days after submitting their paperwork)
  - low grid reliability (both short- and long-term blackounts: 2014/15 19% of transformers had a black out of on average 4 months, no strong statistical evidence that recent blackouts affect demand)
  - credit constraints: Experiment offers short run subsidy (8-week takeup period) (experimental demand curve is substantially lower than the stated demand without time limits (derived from baseline survey), credit constraints seem binding (+ absolute poverty) but issues with the survey cast doubt, and welfare loss would still persist)
  - unaccounted for positive spillovers
- **C. Is rural electrification a socially desirable policy?**: Cost appears 4 × higher than benefit in rural Kenya + negligible medium-run economic, health and educational impacts 18 months post-connection. But could change at different levels of institutional performance and economic development

Simulation exercisze using baseline informations and assumptions about institutional setting:

Table 5—Predicting cost (C), consumer surplus (CS), and net welfare (NW) per household using different approaches and assumptions

		Experimental approach		Alternative approach		
	C	CS	NW	CS	NW	Key assumption(s)
Main estimates	658	147	-511	147	-511	
a) Income growth (*experimental approach*);	–	+139		–		Income growth of 3 percent per annum over 30 years (based on demand curves in figure 2, panel B);
Electricity consumption growth (*alternative approach*)	–	–		+182		Electricity consumption growth of 10 percent per annum over 30 years (see table 4, column 2, row 3).
b) No credit constraints for grid connections	–	+301		–		Stated WTP without time constraints (see figure 5)
c) No transformer breakdowns	–	+33		+19		Reduce likelihood of transformer breakdowns from 5.4 to 0 percent (see appendix table B10).
d) No grid connection delays	–	+46		+26		Reduce waiting period from 188 to 0 days (see appendix figure A1).
e) No construction cost leakage	-140	–		–		Decrease total construction costs by 21.3 percent (see appendix table B8).
Ideal scenario	518	665	148	374	-144	

Notes: Main estimates of C, CS, and NW correspond to figure 4, panel B (for the experimental approach), and table 4, column 1, row 3 (for the alternative approach). Appendix table B13 includes an additional row to account for the consumer surplus associated with baseline connected households.

→ Under Ideal Scanario net welfare gain of \$148, alternative estimates using electricity consumption (and assuming rapid future consumption growth) are more negative, with ideal scenario entailing a net welfare loss of \$144

Conclusions

- Today, access to energy has emerged as a major political issue in many low-income countries
- Findings suggest that HH electrification may reduce social welfare, but do not necessarily imply that distributed solar systems are any more attractive than the grid, and external validity might be low
- (Survey) Evidence suggests that social welfare consequences of rural electrification are closely tied to organizational performance as well as institutions and poverty levels
- No sizeable development gains after 18 month, but perhaps after another decade (or two) of sustained income growth rural HH can purchase the complementary appliances needed to fully exploit electrification's promise
- Connecting rural households not necessarily an economically productive and high return activity in the world's poorest countries
- Needs to be compared to social returns to investments in transportation, education, health, water, sanitation, or other sectors