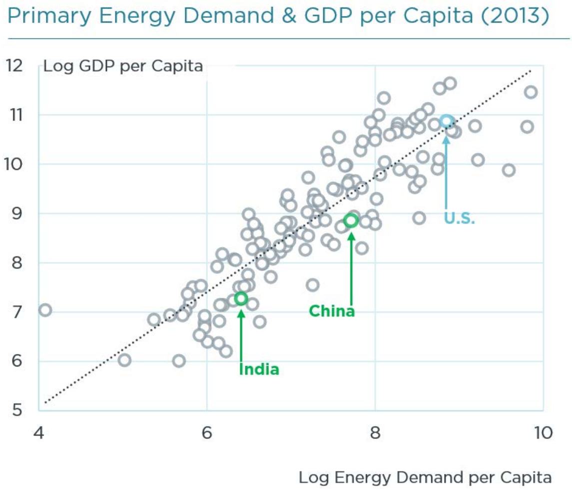
Demand for Electricity in a Poor Economy

Michael Greenstone (Chicago) with Robin Burgess (LSE), Nicholas Ryan (Yale), and Anant Sudarshan (EPIC–India)

July 20, 2018

Electricity is considered critical for growth and human well-being

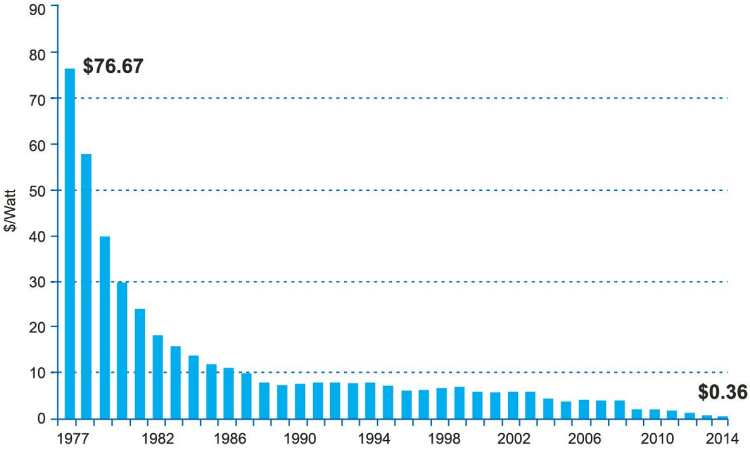


Electrification is a huge priority for policy

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)



Cheap solar makes distributed power easier

Figure: Grid electrification

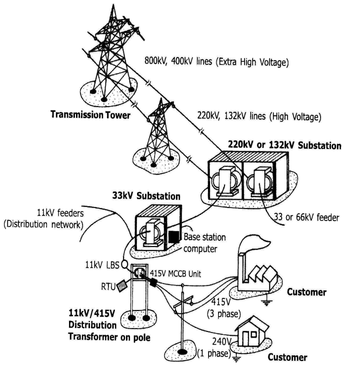


Figure: Distributed electrification

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

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

Outline

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

Outline

1. **Energy Environment in Bihar**
   A. **Electricity Sources**
      i. **Husk Solar Microgrids**
      ii. State-Owned Grid Distribution
      iii. Diesel Electricity
      iv. Own Solar
   B. Summarizing Electricity Source Attributes and Availability
   C. Experimental Design
2. Demand for Solar Microgrids
3. Demand Model for Alternative Energy Sources
4. Counterfactual Analysis

Experiment partner is Husk Power Systems, in the vanguard of solar electrification in India

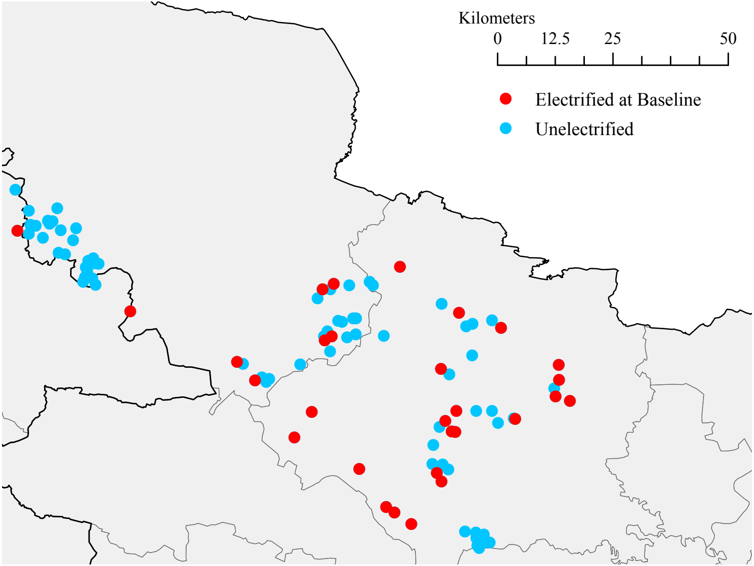
HUSK POWER SYSTEMS
हस्क पावर सिस्टम्स
तमसो मा ज्योतिर्गमय

- 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.

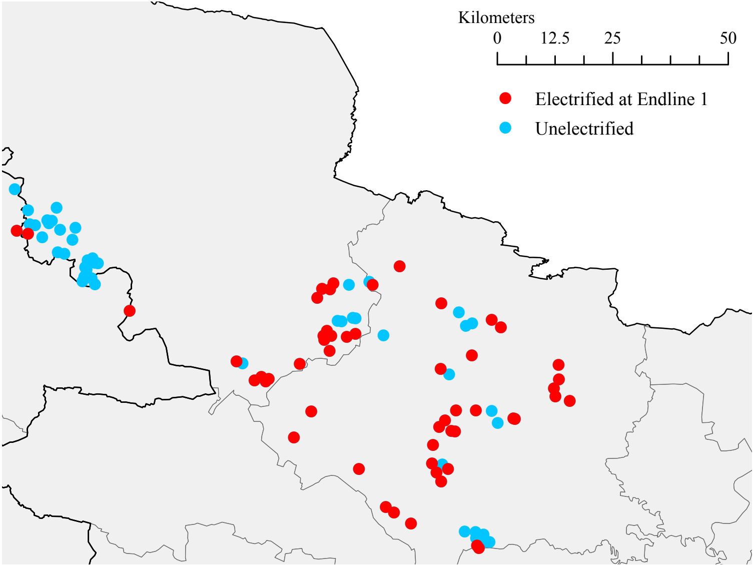
Outline

1. **Energy Environment in Bihar**
   - A. **Electricity Sources**
     - i. Husk Solar Microgrids
     - ii. **State-Owned Grid Distribution**
     - iii. Diesel Electricity
     - iv. Own Solar
   - B. Summarizing Electricity Source Attributes and Availability
   - C. Experimental Design
2. Demand for Solar Microgrids
3. Demand Model for Alternative Energy Sources
4. Counterfactual Analysis

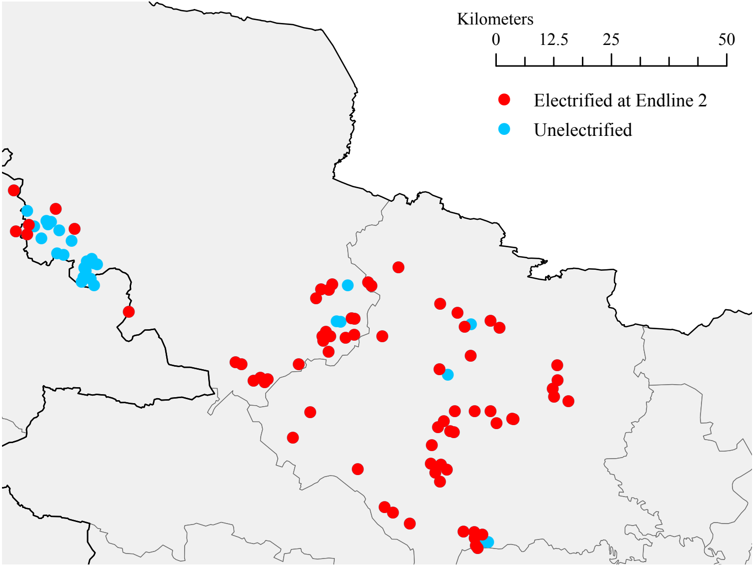
Electrification in Dec. 2013



Electrification in May 2016



Electrification in June 2017



Payments and supply on the grid

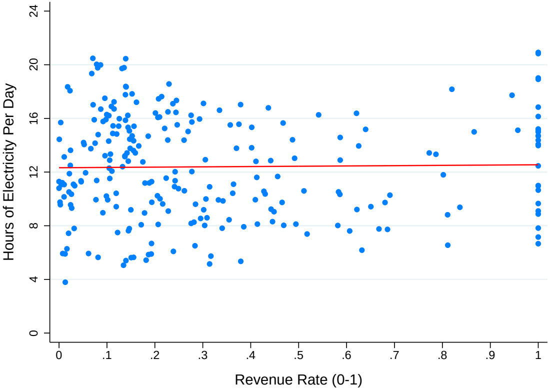
"Whenever I feel like paying the bill."

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

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?"



Outline

1. **Energy Environment in Bihar**
   A. **Electricity Sources**
      i. Husk Solar Microgrids
      ii. State-Owned Grid Distribution
      iii. **Diesel Electricity**
      iv. Own Solar
   B. Summarizing Electricity Source Attributes and Availability
   C. Experimental Design
2. Demand for Solar Microgrids
3. Demand Model for Alternative Energy Sources
4. Counterfactual Analysis

Diesel electricity

Outline

1. **Energy Environment in Bihar**
   A. **Electricity Sources**
      i. Husk Solar Microgrids
      ii. State-Owned Grid Distribution
      iii. Diesel Electricity
      iv. **Own Solar**
   B. Summarizing Electricity Source Attributes and Availability
   C. Experimental Design
2. Demand for Solar Microgrids
3. Demand Model for Alternative Energy Sources
4. Counterfactual Analysis

Own solar electricity

Outline

1. **Energy Environment in Bihar**
   A. Electricity Sources
   B. **Summarizing Electricity Source Attributes and Availability**
   C. Experimental Design
2. Demand for Solar Microgrids
3. Demand Model for Alternative Energy Sources
4. Counterfactual Analysis

Outline

1. **Energy Environment in Bihar**
   A. Electricity Sources
   B. Summarizing Electricity Source Attributes and Availability
   C. **Experimental Design**
2. Demand for Solar Microgrids
3. Demand Model for Alternative Energy Sources
4. Counterfactual Analysis

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.

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*

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

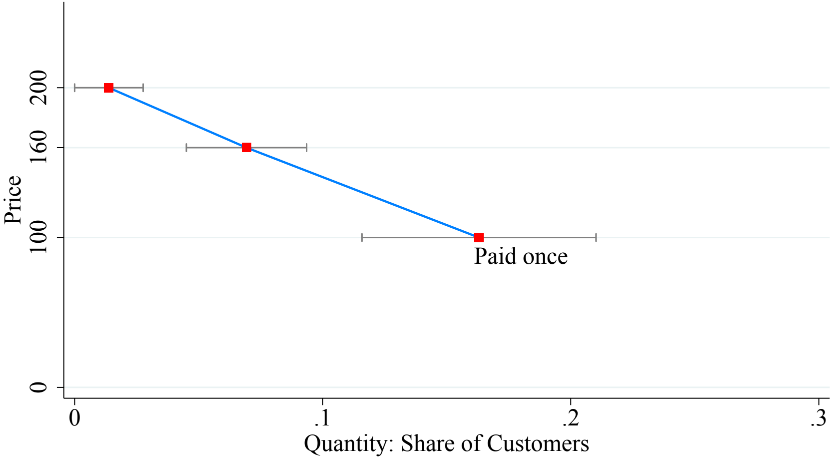
Baseline covariate balance

	Control	Normal	Subsidy	FTest
Panel C. Energy Access				
Any elec source (=1)	0.25	0.31	0.27	0.63
	[0.43]	[0.46]	[0.44]	(0.54)
	1052	983	1001	
Uses gov. elec (=1)	0.030	0.036	0.091	2.53*
	[0.17]	[0.19]	[0.29]	(0.085)
	1052	983	1001	
Uses diesel elec (=1)	0.17	0.21	0.11	1.70
	[0.38]	[0.41]	[0.31]	(0.19)
	1052	983	1001	
Uses own panel (=1)	0.034	0.050	0.061	1.81
	[0.18]	[0.22]	[0.24]	(0.17)
	1052	983	1001	
Uses HPS solar (=1)	0.0067	0.0081	0.0050	0.14
	[0.081]	[0.090]	[0.071]	(0.87)
	1052	983	1001	

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

Outline

Demand curve for HPS solar (administrative data)



Outline

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:

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

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

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)

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

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
2. Households highly value night time hours
    - Annual MWTP for an additional hour of night time electricity is 473 INR.
    - Annual household income is roughly 90,000 INR

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
2. Households highly value night time hours
    - Annual MWTP for an additional hour of night time electricity is 473 INR.
    - Annual household income is roughly 90,000 INR
3. Wealth proxies increase demand for electricity, particularly the grid

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
2. Households highly value night time hours
   - Annual MWTP for an additional hour of night time electricity is 473 INR.
   - Annual household income is roughly 90,000 INR
3. Wealth proxies increase demand for electricity, particularly the grid
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 $\hat{\sigma}$.

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 $\hat{\sigma}$.

2. Calculate the inclusive value of each nest k

$$IV_{ik} = \ln \sum_{j \in B_k} \exp(\widehat{V}_{vtij}/(1 - \sigma_g)).$$

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 $\hat{\sigma}$.

2. Calculate the inclusive value of each nest k

$$IV_{ik} = \ln \sum_{j \in B_k} \exp(\widehat{V}_{vtij}/(1-\sigma_g)).$$

3. Given the inclusive value of each nest, calculate the value of the choice over nests as

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

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 $\hat{\sigma}$.
2. Calculate the inclusive value of each nest k

$$IV_{ik} = \ln \sum_{j \in B_k} \exp(\widehat{V}_{vtij}/(1-\sigma_g)).$$

3. Given the inclusive value of each nest, calculate the value of the choice over nests as

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

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)