Access to Electricity in Rural India

Tradeoffs and Interventions for Meaningful Electrification

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Thesis abstract

This thesis investigates the engineering economics of interventions to reduce consumer inconvenience due to unreliable electricity supply in rural India. The work introduces and applies a novel approach to estimate interruption costs as loss in consumer surplus due to restricted consumption of electricity services.

Chapter 2 reports an assessment that compares grid extension with distributed generation (DG) alternatives, based on the subsidies they will necessitate, and costs of service interruptions that are appropriate in the rural Indian context. Despite the inclusion of interruption costs, standalone DG does not appear to be competitive with grid extension at distances of less than 17 km. However, backing up unreliable grid service with local DG plants is attractive when reliability is very poor, even in previously electrified villages. Introduction of energy efficient lighting changes these economics, and the threshold for acceptable grid unreliability significantly reduces.

Chapter 3 analyzes supply rostering (alternatively, "load shedding") in metropolitan, small town and rural feeders in and around Bangalore city. The inequity in load shedding is analyzed through transfers due to differential tariffs between the urban and rural residential consumers, and the relief provided to BESCOM, through avoided procurement of additional supply from generators, because rural and small town feeders are load shed higher than Bangalore city. The values of the load shedding transfers are estimated to be in the range of Rs. 120-380/consumer-year from the rural consumers, and Rs. 220-370/consumer-year from the small town consumers. The metropolitan consumers are found to be net beneficiaries. The viability of using smart meters to provide current limited but uninterrupted supply is investigated as one alternative to outright blackouts.

Chapter 4 develops a broader theoretical framework that can be used to model consumer demand for electricity services with unreliable supply and adaptation. Demand for energy 'services' is modeled by incorporating time of use, duration and deferability. Supply reliability is disaggregated into its constituent dimensions– mean and variance of supply availability in times of high demand, and supply predictability, and their respective impacts on consumer welfare are discussed. Primary data collected from Karnataka inform the discussion, especially with backup adoption. New consumer-oriented reliability indices are proposed.

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Chapter 1: Introduction

Forty-five percent of the 168 million rural households in India remain unelectrified (Census of India, 2011). A large fraction of those that have been electrified, and have been so for decades, often receive poor quality of supply. The quality and regularity of supply vary between states, and often within a state as well. Lack of reliable supply, especially given the large durations and frequencies of outages, represent a cost to the consumers and to society. Access to electricity is a critical factor in development, and outages can have a negative impact on a household's income generation (e.g. irrigation pump-sets), children's education, and basic comforts (flexibility in cooking, ambient lighting at night, televisions).

Large government programs for subsidizing village electrification have been around, but similar government recognition and policies to improve the availability of supply has been lacking. Improving supply in rural India will require several interventions, many in parallel. Some of these are shown in Figure 1-1. While the ideal goal would be to provide uninterrupted supply, many interventions only provide limited relief from Business As Usual. These intermediate solutions tend to be more feasible in the short to medium term for the government and utilities while gradually undertaking longer term measures like tariff reforms.

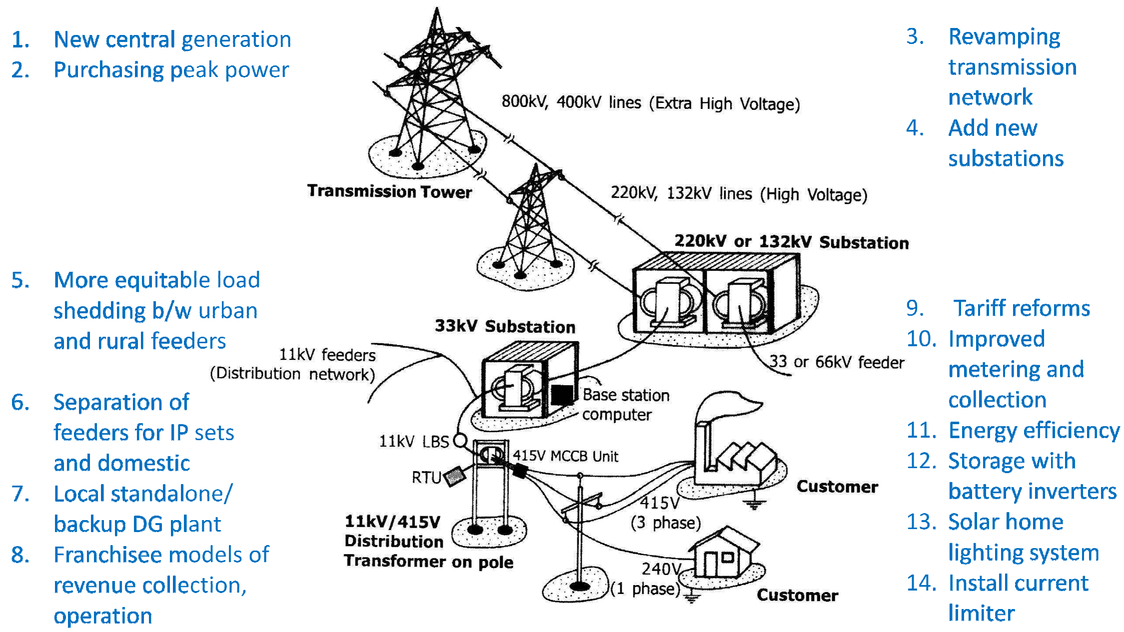

Figure 1-1: Many interventions to improve service reliability[1]

Interventions at different stages of the network involve different stakeholders and levels of institutional complexity. The quantum, structure and mode of delivery of the requisite subsidies or incentives will differ. From the perspective of consumer welfare, dissimilar interventions can have differing consequences on household usage and consumer surplus. As a result, there are two sets of tradeoffs to consider. For a given intervention, this could be framed as a benefit-cost problem, with the benefits accruing and costs borne by entirely different groups of stakeholders. And across interventions, we need to consider a consumer's relative preferences among dimensions of electricity use and supply like predictability and duration of supply, and adequacy.

One of the principal objectives of this thesis is to develop a framework to monetize the costs of frequent interruptions to the consumer. The analysis is primarily limited to residential consumers. Giving a rupee value to the inconveniences (or conversely to the value of actual supply received) provides a useful tool to study the tradeoffs- for the government in planning electrification, for the utility in distribution and for the consumer in evaluating alternatives. The other major objective is to formulate models that articulate these tradeoffs.

[1] Image adapted from http://www.iitk.ac.in/infocell/Archive/dirmar1/power_distribution.html

For the central government, that coordinates and provides the subsidies for the national rural electrification program, there is an implicit tradeoff between project costs (and hence, costs or supply) and reliability. Consumer tariffs are regulated and are usually significantly lower than supply costs. In this context, distributed generation, which could be in principle more reliable (during times of high demand) than the central grid, tends to be overlooked because of its higher costs. Incorporating the value of the additional reliability through the interruption costs would help in making this comparison fairer. The first investigation (Chapter 2) in this thesis develops a framework to estimate interruption costs, and then applies it to explore this tradeoff.

For the utility, the tradeoff is between improved reliability for its rural consumers and higher losses. One clear alternative for the utility is to procure additional and likely expensive power to avoid load shedding. As the full costs of this additional power will not be recovered through the tariffs, the utility will have to incur higher revenue losses in order to provide improved reliability. However, it is anecdotally well known that urban feeders get preferential treatment from the utilities, and hence, another way to improve reliability is to load shed urban and rural consumers more equitably. The second investigation (Chapter 3) verifies whether there is any preferential treatment to urban feeders, and how the relief to the utility because of this arrangement compares with the differentials in rural and urban tariffs. The analysis uses a very granular data-set with supply data at minute-level resolution for every 11kV feeder served by the Bangalore ESCOM. The economics of installing smart meters that can be used to provide current limited supply is explored as one possible solution to outright blackouts.

In Chapter 4, the thesis elaborates on the conceptual framework for electricity demand with unreliable supply and adaptation. This chapter is simultaneously an extension of the hypotheses on consumer behavior used in the rest of the thesis as well as a statement for future research goals. The principal premise in the proposed model is that consumer values the services derived from electricity and not electricity consumption itself. Using this assumption, and by distinguishing between end uses and services, we can incorporate consumer behavior like adaptation to outages using backup energy sources, as well as the ability to reschedule certain activities (or the lack thereof). The adoption and use of backup sources could, in principle, provide information on the relative preference among services and the willingness to pay. Using primary data gathered during household surveys, the imperfections in the market for backups are discussed. The chapter concludes with an application of the energy services framework to the design of reliability indices. Metrics for defining variability and predictability of supply are demonstrated, using supply data logged in Karnataka.

Chapter 5 concludes the dissertation with a summary of the major findings and contributions. This dissertation has taken a novel approach in framing the problem of reliable electricity access in rural India- with a focus on formulating the tradeoffs from the perspective of the 'planners', but accounting for the values of the households. Given the nature of electricity as a public good, the households are often simultaneously consumers, voters, and the targeted beneficiaries of the electrification policies. There is an urgent need to extend the objectives of the government programs and the utilities' priorities, formally, beyond merely physical infrastructure access, to the provision of predictable and reliable supply of electricity based services. To implement such a paradigm shift in priorities requires a paradigm shift in the design of the government's programs in the power sector from one that relies on centralized planning and the conventional electricity grid to one where decentralized energy sources and institutions are utilized.

Chapter 2: When does unreliable grid supply become unacceptable policy? Costs of power supply and outages in rural India

Abstract

Despite frequent blackouts and brownouts, extension of the central grid remains the Indian government's preferred strategy for the country's rural electrification policy. This study reports an assessment that compares grid extension with distributed generation (DG) alternatives, based on the subsidies they will necessitate, and costs of service interruptions that are appropriate in the rural Indian context. Using cross-sectional household expenditure data and region fixed-effects models, average household demand is estimated. The price elasticity of demand is found to be in the range of -0.3 to -0.4. Interruption costs are estimated based on the loss of consumer surplus due to reduced consumption of electric lighting energy that results from intermittent power supply. Different grid reliability scenarios are simulated. Despite the inclusion of interruption costs, standalone DG does not appear to be competitive with grid extension at distances of less than 17 km. However, backing up unreliable grid service with local DG plants is attractive when reliability is very poor, even in previously electrified villages. Introduction of energy efficient lighting changes these economics, and the threshold for acceptable grid unreliability significantly reduces. A variety of polices to promote accelerated deployment and the wider adoption of improved end-use efficiency, warrant serious consideration.

1 Introduction

About 45% of the 168 million rural households in India remain unelectrified (Census, 2011). Since the adoption of the Electricity Act of 2003 and the Rajiv Gandhi *Grameen Vidyutikaran Yojana* (Rural Electrification Program) (RGGVY) in 2005, rural electrification (RE) has received renewed attention with significant government funding and ambitious targets. When it was launched, the goal of the RGGVY was to electrify *all* villages by 2012, although at the time 26% of the 600 thousand villages in the country and 56% of rural households were unelectrified (Prayas, 2011). The apparent discrepancy between the village and household figures is because a village is deemed electrified if 10% of its households are electrified and the basic infrastructure installed. Using this metric, 'village electrification' levels have now increased to almost 93% (Ministry of Power (MOP) website).

However, the quality and reliability of electricity supply remains poor in many parts of the country. Even the limited goal of guaranteeing at least 6 hours of daily supply has not been met in some states (Udupa et al., 2011). For example, Oda and Tsujita (2010) estimated that villages surveyed in the state of Bihar in 2008-09 received, on average, 6.3 hours of daily supply in "good months" and 1.3 hours in "bad" ones. The extension of the central grid has been the primary route of electrification under the RGGVY, despite the known limitations with the supply. As the intended targets have not been achieved, the program is very likely to get extended beyond 2012. In parallel, the Ministry of New and Renewable Energy (MNRE) has begun extending support to solar lighting systems under the National Solar Mission (MNRE, 2010), and is also looking to revamp the Remote Village Electrification (RVE) program (MNRE, 2012).

Much of the analysis on rural electrification routes has focused on costs of supply and the distance beyond which extension of the grid feeders is more expensive than distributed generation plants (e.g. Sinha and Kandpal (1992), Banerjee (2006), Nouni et al. (2009)). Here we ask when the standard mode of grid extension is not the optimal choice if the costs of unreliable supply are included. There are two related research questions: 1) for villages that have not been electrified, how unreliable must conventional grid be, both currently and in the foreseeable future, for one to consider an alternative, local source of generation; 2) for villages that are already electrified by the grid, how unreliable must the supply be before one should consider augmenting it with an additional local source of power.

We compare conventional grid extension with standalone distributed generation (DG) plants as well as "grid-plus" options which involve augmenting the central grid with local DG plants. The alternatives are compared based on 'societal costs'- the sum of the necessary subsidies borne by the government, and the costs incurred by customers that result from unreliable supply. This societal cost framework is analogous to estimating the 'cost' of subsidizing more reliable supply that has the 'benefit' of reducing consumer interruption costs, with the aim of identifying the 'optimal' alternative with the highest net benefit to society. We explore which alternatives, if any, have higher net benefits when compared to conventional grid extension with erratic supply.

Section 2 discusses the problem formulation in this study- the decision makers (2.1), alternatives (2.2) and metrics (2.3). Section 3 describes the estimation of electricity demand and its price elasticity from sample survey data. Section 4 elaborates the methods for estimating subsidy and consumer interruption costs. Section 5 discusses the results of our analysis and explores the sensitivity of the choice of each alternative to different levels of grid supply availability as well as demand side measures such as policies encouraging efficient lighting. Section 6 concludes the paper with a discussion on the implications of the results for rural electrification policy.

2 Problem Formulation

2.1 The decision maker(s)

Electricity falls under the jurisdiction of the central (federal) and state governments. As a result, multiple decision makers with different perspectives on the objective have to be considered.

Under the rural electrification (RE) policy currently operationalized by RGGVY, the central MOP funds 90% of the capital costs of the infrastructure in electrifying a new village. Grid extension is the "normal way of electrification" (MOP, 2006). The choice of which villages are to be electrified by the grid, and implementation, are both left to the state governments and the state-owned distribution utilities. State governments may choose to support the remaining 10% of the infrastructure costs; otherwise, the remaining costs can be passed down to the consumers. Villages deemed too remote or unviable for grid extension, can be covered under RGGVY's DG program or under the central MNRE's RVE program. Both these programs cover 90% of the (higher) costs of the DG plants. As the capital costs are funded upfront, the tariffs in the case of grid extension or DG reflect only the costs of operation and maintenance, fuel, and power purchase, as applicable.

The federal government has a limited role in the subsequent supply of electricity. In the case of DG plants, it supports the difference between the recurring costs of supply and tariffs set by the project developers in consultation with state government authorities. With grid extension, for a utility to receive capital subsidies from the Center, the federal government only requires that utilities provide a minimum of 6-8 hours of supply per day to villages chosen for grid electrification. Further, there are no apparent penalties when this condition is not met.

Tariffs are proposed by distribution utilities and regulated by state regulatory boards. With most of the generation sourced within a given state, power purchase costs differ by state. Tariffs are subsidized for domestic and agricultural consumers, partly due to equity concerns and partly due to their populist appeal. The domestic tariffs are cross-subsidized by charging commercial and industrial consumers tariffs that are greater than costs of supply. Subsidies for the poorest domestic consumers and agricultural consumers are funded by the state governments. Agricultural pump-sets, that are large loads, form a particularly problematic category. Even when they are charged for supply, they only pay flat annual charges, and typically unmetered. As a result, distribution utilities, facing both power deficits and financial losses, have an incentive to "load shed" rural areas more than urban or industrial consumers.

While this study considers the priorities of these different stakeholders, our analytic formulation adopts the perspective of a single composite decision maker who is trying to achieve an optimal social outcome that minimizes the subsidies required over a long term, while providing reliable supply. Following the RGGVY's priorities, we focus only on residential and communal loads. Agricultural loads are not considered.

2.2 Alternatives

In recent years, with the dramatic drop in photovoltaic (PV) prices (Aanesen et al., 2012), solar home lighting systems and village level micro-grids have become more popular. The current RE program allows for DG, using micro-hydro, biofuel, biomass gasification or solar PV based generation, to be used where grid supply is deemed infeasible (MOP, 2006). These have been recognized because they are relatively mature, both technologically and commercially. In this study, only biomass gasification and solar PV have been included as the resources are available in most parts of the country, and several private microgrid firms already use these technologies.

In our analysis, we consider five electrification routes:

1) Grid extension involves installing pole-mounted 11 kV feeder lines, local transformers (11 kV/ 400V) and a low voltage distribution network. Setting up sub-stations is sometimes necessary while electrifying new areas but these are assumed to exist in the analysis

2) A biomass gasification plant converts waste products from agricultural processes, or energy crops grown for the purpose, into producer gas which is then used in an internal combustion engine. There are two primary parts of the gasification system- the gasifier which includes fuel processing and preparation units- and the generator engine.

3) Solar PV systems consists of PV modules which convert solar energy into electrical energy, a charge controller that regulates the system to prevent damage, a battery to store the energy, and a power conditioning unit or an inverter to convert the DC to AC. While DC could be used directly, especially for lighting, this has not been common practice.

4) The diesel DG plant has a generator that runs on diesel alone. The price of diesel is regulated in the country and is subsidized. Diesel generators, while widely used, are not encouraged under RGGVY as a primary DG source because of their environmental and fiscal implications.

5) In addition, we consider grid extension backed up with local DG plants. The generators are sized to meet the entire daily load of the village. The supply mix from the central grid and the DG plant is optimized to minimize the costs of supply. Power generated by the DG is not exported to the grid.

In this analysis, the biomass and solar PV standalone plants are assumed to have diesel backup generators to mitigate constraints in fuel supply or insufficient sunshine. The sizing of backup generators are for the aggregate daily peak load and this redundancy ensures that the standalone DG plants are close to perfectly reliable.

2.3 Metrics- Societal costs

The alternatives are compared based on societal costs computed as the sum of the capital subsidies received by the utilities, and supply interruption costs experienced by the consumers. These two costs are borne by two very different groups of stakeholders. Weighting them equally prioritizes reliable energy access in a very different way than that implied by current policy. We are essentially assuming that society should value the reliability of the supply to the consumer to the same degree as consumers themselves (although perhaps with a different time value of money).

Subsidy costs

Subsidy costs are computed as the present value of the unrecovered costs of supply. To do this, we consider a constant, flat tariff. Monthly household demand is estimated as a function of this tariff using a cross-sectional dataset as described in sections 3.1 and 3.2. The estimates of load profiles are based on assumptions regarding the distribution of demand through the average day as well as village size and community facilities. The plants are sized to match the peak aggregate demand in the village. Estimates of supply costs are a function of cost schedules of the alternatives and the assumed aggregate load profile. The costs of supply depend on the tariffs, the costs of components and fuel, the village size, as well as the nature of the household demand. For example, the efficiency of the lighting appliances used may dramatically affect the supply costs of the alternatives, as described in Section 5.

Interruption costs

The method adopted to assess interruption costs is based on an estimate of forgone consumer surplus, rather than an elicitation of willingness to pay (WTP) which has become the more standard approach (Lawton et al., 2009; Woo and Pupp, 1992). As ability to pay is the primary constraint in an RE context and rural households tend to overestimate their WTP, survey responses may be misleading (Cust et al., 2004). With uninterrupted supply, consumption will be a function of tariff. The value of the forced decrease in usage will then be the area under the demand curve between this reduced usage and the estimated usage with uninterrupted supply (i.e., demand). The interruption cost is then the lost surplus, if there is no alternative for the foregone service. If a back-up service is used, the interruption cost would be the net of lost surplus and the surplus associated with the back-up source.

Woo and Pupp (1992) identify three broad techniques for estimating interruption costs- proxy based, consumer surplus and contingent valuation methods. The approach used here combines the consumer surplus method of estimating interruption costs, with the proxy method of considering costs of backup. Service unreliability and its implications on rural residential loads in the developing world have not witnessed a significant body of work. The exceptions are Sarkar (1996) (contingent valuation) and Kanase-Patil et al. (2010) (proxy based). In the RE context, consumer surplus methods have been used by Munasinghe (1988), van den Broek and Lemmens (1997) and World Bank (2008) to quantify the benefits of rural electrification.

While we believe it is superior for our purposes, the approach of using consumer surplus involves a number of limitations. First, reduction in planned consumption due to tariff increases is not equivalent to forced reduction in consumption due to outages (Munasinghe, 1979; Woo and Pupp, 1992). Estimating lost surplus based on the former underestimates the latter. Second, non-linear demand curves, especially double log functions, can overestimate the lost surplus because the demand reduces to zero only when the cost per unit tends to infinity (Woo and Pupp, 1992; IAEA, 1984). Third, Munasinghe (1979) suggests that the consumer surplus method inherently assumes that electricity is a product, and not an intermediate service for a productive activity. Fourth, the demand curves used must correspond to the periods of loss for the outage costs for the estimated costs to be appropriate. In our analysis, while the first limitation remains, intermediate modifications and assumptions are made to mitigate the other three.

To differentiate outages of different durations and frequencies starting from an aggregate monthly demand curve, we need to define the smallest interval of time for which there is an 'independent' demand curve. Such an interval should satisfy two conditions.

1. Consumption in this interval is valued independently of consumption in any other period.
2. Demand in a subset of this interval is valued as a function of consumption in the rest of the interval.

If there is an order of priority for the activities that require electricity within this interval, there will be a diminishing marginal utility for electricity consumed. This formulation requires the consumers to be able to reschedule their activities dynamically in this order of priority such that any consumption denied, due to outages, will be treated as the marginal unit denied. We assume that this interval is a day- that is, a monthly demand curve is composed of 30 identical, ‘independent’ daily demand curves. While the values of forced reduction in usage due to a daylong outage is estimated as in Figure 2-1(a), the values of outages within a day aggregate as shown in Figure 2-1(b). Appendix 1 formalizes this discussion further.

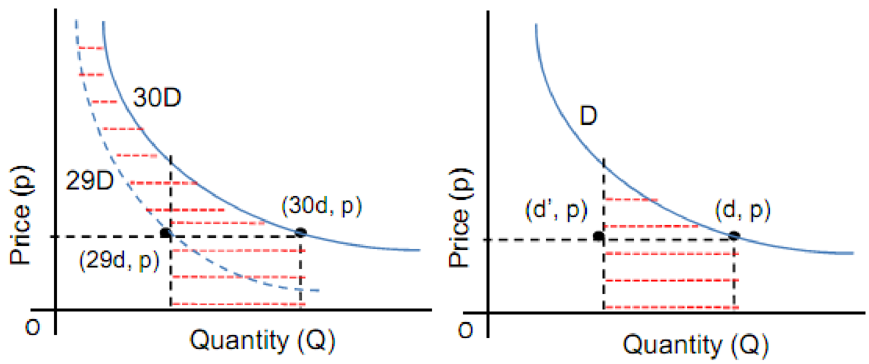

Figure 2-1: Illustration of (a) the assumed valuations of day long outages (left) and (b) for a few hours during the day (right)

The demand curve required for calculating these interruption costs is estimated based on the household data and regressions discussed in section 3. Additional assumptions and modifications are also made as discussed in section 4.2.

3 Estimating electricity demand

The principal objective of this part of the analysis is to estimate household demand as a function of tariff. The analysis is based on household data collected by the National Sample Survey Organization (NSSO) in their 2009-10 surveys. These sampling surveys are conducted every five years. They collect data on consumption expenditure from over 100,000 households, including about 59,000 rural households) from all the districts in the country. The analysis uses district level mean values for the relevant variables, resulting in 593 data points for the regression.

3.1 Summary of data used

The surveys were done by NSSO over the course of a year, and the electricity consumption data were based on a 30 day recall period. Each respondent was surveyed only once, but sampling was done in each district throughout the year. To check whether there are discernible seasonal patterns that are missed while using district means, the dates of surveys were used to categorize the observations into different seasons. The average consumptions across the four seasons (as per the Indian Meteorological Department) are reported in Figure 2-2. Average monthly household consumption in most of the states is less than 60 kWh per month. While, the national averages are almost constant across the seasons, some spikes in consumption during winters occur in a few states in the north and north-east. Cross state variations in consumption of power are neglected in the rest of the analysis.

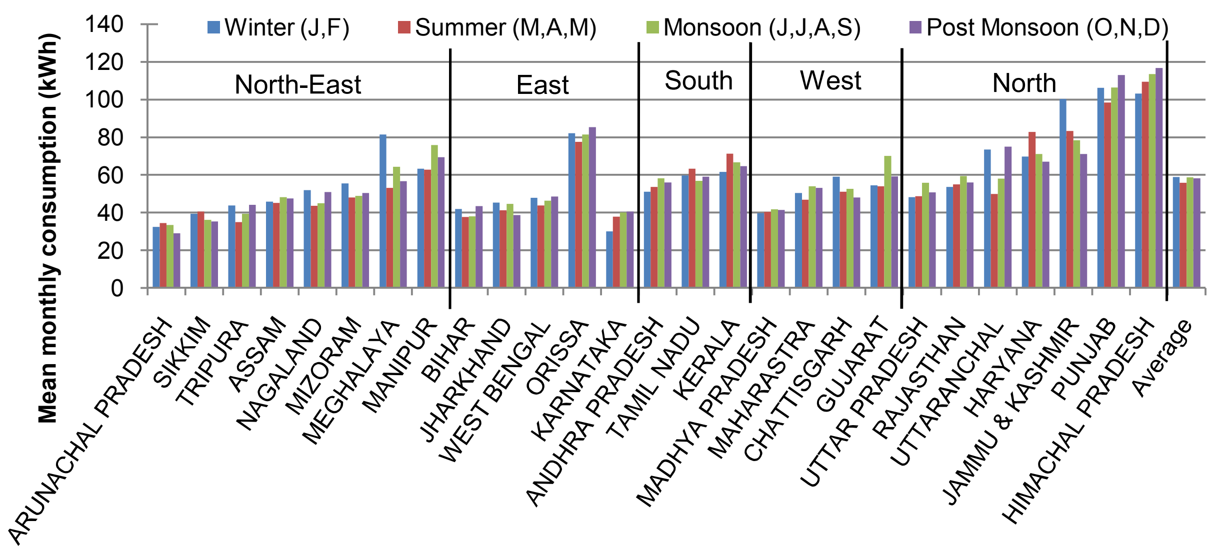

Figure 2-2: Mean reported household consumption over the four seasons for different states

Tariff structures are regulated by bodies at the state level, and cross state variations in tariffs facilitate the cross-sectional analysis here. The national mean is Rs.2.4/kWh, and the average tariffs range from Rs.0.7/kWh in Pondicherry to Rs.3.8/kWh in Rajasthan.

These average tariffs have been estimated using reported monthly expenditure on, and consumption of, electricity. As state level tariffs have a multi-part structure, the average tariffs may depend on the consumption. However, the standard deviations were less than 5% of estimated mean tariffs in most states, and within 10% for all. As the estimated tariffs fall within a narrow range, it seems reasonable to treat the tariffs as independent of consumption, and ignore simultaneity issues.

3.2 Regressions

A simple population model should suffice in estimating price elasticity as long as there are no omitted variables that are correlated with the tariffs. For example, while average monthly per capita total expenditure (*MPCE*) is positively correlated with average monthly electricity consumption, it has close to zero correlation (0.01) with the average tariffs. Hence, MPCE need not be included in our regression models. On the other hand, the fraction of rural households owning televisions (*PropTV*) is both positively correlated with consumption and moderately negatively correlated with tariffs, and hence, has to be included.

To estimate demand based on usage data, we need to control for unreliability in the supply. For demand estimation, we use state-wise estimates of deficits as a fraction of demand at peak loading (*PeakDeficit)*, as estimated by the Central Electricity Authority (CEA) for the months of May 2009- April 2010 (the period of the surveys). On average, only 87% of the peak demand was met. In the state of Bihar, only 66% of the demand was met, while supply in states like Gujarat and Himachal Pradesh met peak demand. As the rural residential peaks coincide with the aggregate peaks, and as utilities "load shed" more from rural areas during these times, *PeakDeficit* is a reasonable proxy for the supply availability.

Regressions using Ordinary Least Squares (OLS) and fixed effects by region (region FE) have been used to estimate the demand curve. The 'regions' identified are as defined by the CEA. The region FE model helps avoid biases due to omitted variables that are constant in a given region. This includes weather conditions and electrification levels over time. A double log formulation has been used, implicitly assuming a constant price elasticity of demand. The population model assumed is:

$$\ln(\mathit{Elec.\ Usage})_{ij} = \alpha_0 + \alpha_t \ln(\mathit{Tariff})_{ij} + \alpha_{pd}(\mathit{PeakDeficit})_{ij} + \sum \alpha_i X_{ij} + r_j + \epsilon_{ij} \quad \text{Eq. (1)}$$

where, X_{ij} are average demographic characteristics or electrical appliance ownership in district i of region j. r_j are regional unobservables, and ϵ_{ij} are idiosyncratic errors. We use district level means of the variables (except for *PeakDeficit*). Since the primary variable of interest is the tariff, only those variables that were found to be correlated with it have been included. The results are shown in Table 2-1.

Table 2-1 Results of the OLS and region fixed effects regression models for ln(*Elec. Usage*)- coefficients with robust standard errors (n=592) (*p<0.01, **p<0.05, *p<0.1)**

	OLS		Region FE		
	Model 1	Model 2	Model 3	**Model 4**	Model 5
ln*(tariff)*	-0.181*** (0.037)	-0.199*** (0.035)	-0.384** (0.118)	**-0.343** (0.098)**	-0.324** (0.078)
PropTV	0.558*** (0.075)	0.396*** (0.077)	0.521*** (0.089)	**0.540*** (0.087)**	0.413*** (0.061)
ln*(mpce)*		0.354*** (0.053)			0.342** (0.095)
PeakDeficit	0.663*** (0.178)	0.511*** (0.163)		**0.869* (0.358)**	0.826 (0.420)
Constant	3.861** (0.069)	1.508*** (0.359)	3.977*** (0.133)	**4.043*** (0.113)**	1.734* 0.666)
R^2	0.19	0.28	0.31	0.34	0.42

All coefficients have the appropriate sign. The price elasticity of demand is estimated to be about -0.2 with the OLS approach and between -0.3 to -0.4 with the FE model. The latter is slightly higher (that is, more elastic) than estimates in literature in the developed country context (for example, Azevedo et al., 2010). Price elasticities of demand have been previously estimated for Indian households by Filippini and Pachauri (2004) (-0.29 to -0.51), Tiwari (1997) (-0.7) or Gundimeda and Kohlin (2008) (-0.59 to -0.72). Of these, only the last estimate corresponds to rural households. An increase in deficits by 10 percent reduces consumption by about 10 percent.

Subsequent analysis will use results from model 4 in Table 2-1 using region FE (with *Tariff*, *PropTV*, and *PeakDeficit*). We adjust for reliability using the PeakDeficit proxy variable. The estimated demand curve, juxtaposed with state level means of consumption and tariff, is shown in Figure 2-3. The estimated demand at Rs.2.5/kWh is about 58 kWh, close to the national mean consumption.

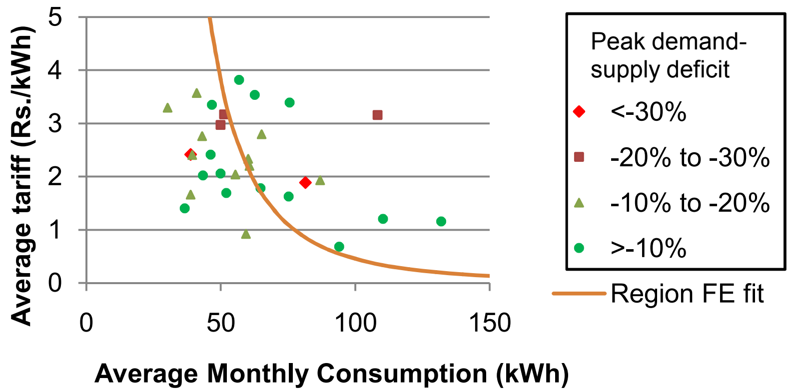

Figure 2-3: Estimated demand curve, along with state level means of consumption and peak deficit

4 Estimating societal costs- methods

4.1 Subsidy costs

Subsidy costs are a function of the costs of supply, the tariffs charged and the consumption.

Aggregate load profiles are required for sizing the plants, and affect significantly the costs and profitability of providing supply. In the rural Indian context, the residential demand tends to be greatest in the early mornings and evenings. The two primary uses of electricity is for lighting and televisions. The demand is assumed equal (on average) for each day of the month, and monthly or seasonal variations are not considered. Hourly load profiles are assumed constant on average during the course of a year. The data used for making the estimates are not restricted to newly electrified households; the sampled households are likely to have been electrified at different times. Hence, demand growth over time has not been included here. Inputs for *Tariff* and *PropTV* were based on NSSO data. To estimate aggregate load profiles, some additional community facilities with representative loads have been included. The detailed assumptions are documented in Appendix 2-1.

The required plant size is estimated using the peak aggregate demand and an approximate distribution loss. The actual size of the plant for a given alternative would also be constrained by the available module sizes of generators, batteries or transformers. For solar PV, the required panel size and battery capacity need to be estimated using additional inputs on component efficiencies and losses. The formulae and assumptions are listed in Appendix 2-2.

It is assumed that outages are a characteristic of the alternative. For DG, fuel availability (or in the case of solar, sufficient sunshine) throughout the year could be a problem. Hence, we assume that biomass and PV DG plants are backed up by a diesel generator so that the combined design is reliable. In the case of the central grid, it is assumed that outages are independent of the local consumption. This is reasonable since rural domestic consumption is a very small fraction of the overall demand (in contrast to agricultural demand that we are not considering here).

In the absence of more detailed data, the availability of grid power is characterized in terms of daily hours of supply, number of days of blackouts per month, and number of years in the future when grid-power is likely to become reliable. There are some data reported to support the estimates for the first two (for example, Udupa et al., 2011), the third is treated as an uncertain parameter. While unreliable supply is a consequence of limited generation capacity, it also depends on political priorities and the incentives faced by utilities. The availability scenarios (besides that of uninterrupted supply) are summarized in Table 2-2. RGGVY mandates a minimum of 6-8 hours of supply per day. However, there is no requirement for this to coincide with the times of maximum demand. Often, grid supply is provided late in the night or in the afternoon hours, when there is little or nothing that a household can usefully do with the power.

Table 2-2 Reliability scenarios considered

	'Poor' quality	**'Intermediate' quality**
Daily hours of supply	6 hours in all: 3 in the peak period- 1 in the evening, 2 morning; 3 hours in the rest	18 hours in all: Single phase: 6 PM-6 AM; Three phase: 6 AM- 12 noon
Average day-long outages/ month	5	2
Years required for grid to become reliable	10 (2-10)	5 (2-10)

For grid supply, consumption in year t will be constrained by availability as

$$c_t = \sum_{h=1}^{24}(D^k_{agg,h} * s^k_{h,t}) * (365 - num^k_{blackout,t} * 12) \qquad \text{Eq. (2)}$$

where, $D^k_{agg,h}$ is the estimated aggregate load at hour h in the supply scenario k and $s^k_{h,t}$ is a binary variable (0 or 1) representing whether grid supply is available then or not. $num^k_{blackout,t}$ is the number of entire days of no supply per month in year t . The k scenarios include the uninterrupted, 18-hour and 6-hour scenarios as described in Table 2-2. With DG, consumption will be identical to uninterrupted grid availability scenario. Appliance ownership is assumed to be unaffected by the intermittency in supply.

The cost estimation methodology follows from prior literature. A detailed description of the cost inputs and assumptions for each alternative is provided in Appendix 2-3. The subsidy costs are estimated over a 10 year period, using a real discount rate of 10%. As the lifetimes of some of the components are higher, their capital costs are annualized.

The Levelized Cost of Energy (LCOE) is estimated as,

$$LCOE = \sum_{t=1}^{10} \frac{x_{cap-ann} + x_{O\&M} + x_{fuel,t}(or\ x_{gridpower,t})}{(1+r)^t} / \sum_{t=1}^{10} \frac{c_t}{(1+r)^t} \qquad \text{Eq. (3)}$$

$x_{cap\text{-}ann}$ are the annualized capital costs of the infrastructure for a given alternative, $x_{O\&M}$, the annual operation and maintenance costs, $x_{fuel,t}$ the costs of the fuel in the plants in year t and $x_{gridpower,t}$ the costs of supply for the utilities. r is the discount rate used.

Although the LCOEs could be computed for the unreliable grid supply scenarios as well, comparisons are not entirely meaningful when their denominators vary. As a result, the analysis here considers the subsidy costs instead.

$$Cost\ of\ Subsidy = (LCOE - Tariff) \sum_{t=1}^{10} \frac{c_t}{(1+r)^t} \qquad \text{Eq. (4)}$$

Interestingly, in terms of subsidy costs, providing unreliable grid supply is cheaper for the utilities than providing uninterrupted supply from the grid or through DG. As the costs of power purchased contribute a significant amount to the LCOE of grid supply, and because the tariffs tend to be lower than costs of supply, subsidy costs favor extending the grid, over DG alternatives, despite the former's poor reliability. To make reasonable comparisons, interruption costs must be considered.

4.2 Interruption costs

Following the earlier discussion, interruption costs are estimated based on loss of consumer surplus using daily demand curves. As a simplification, the interruption costs are estimated based on lighting in the 'peak' hours alone. Hence, the consumption in this case could alternatively be measured using kilolumen-hour, i.e. total light output 'used' over time. While such an estimate would at best be a lower bound, lighting is the primary domestic end-use of electricity in rural India. In the absence of reliable electricity, different back-up sources of lighting are used which help in understanding the willingness to pay and validating the estimates.

While the demand curves from section 3.2 provide the foundation of the interruption costs estimate, modifications are made at low consumption where the double-log curve will overestimate the consumer surplus. Two constant expenditure lines of Rs. 200/ month and Rs. 300/ month are used as bounds. These correspond to estimated expenditures at Rs. 4/kWh and Rs. 8/kWh, and are in the ballpark of the amortized costs of solar lanterns and lighting systems that are becoming increasingly popular as primary and backup lighting. [i]

It is assumed that during outages, kerosene lanterns are used. As the light output is very low, the value of consumption of kerosene will be very low but bound the interruption costs from going to infinity. As a result, the interruption costs will now comprise the value lost by consuming kerosene lighting and not electricity, and net costs of the backup lighting energy source (that is, expenditure on kerosene less the saved expenditure on unconsumed electricity).

Based on demand as a function F of tariff, annual interruption cost is estimated as,

$$x_{interruption,t} = \left(\frac{\left(30 - num^{k}_{blackout,t}\right)}{30}\int_{e'_T}^{e_T} F^{-1}(l)dl + \frac{\left(num^{k}_{blackout,t}\right)}{30}\int_{e_{kerosene}}^{e_T} F^{-1}(l)dl + x_{kerosene,t} - \left(e_T - e'_T\right)p_e\right) * 12 \quad \text{Eq. (5)}$$

where, e_T, e'_T and $e_{kerosene}$ are the consumption of lighting energy (in klm-hr, say) with uninterrupted supply at tariff p_e, with unreliable supply, and forced usage of kerosene due to outages respectively

$$x_{kerosene,t} = \left(6num^{k}_{blackout,t} + \left(30 - num^{k}_{blackout,t}\right)\left(6 - \sum\nolimits_{h\epsilon peak} s^{k}_{h,t}\right)\right) * p_{kerosene} * \eta_{kerosene} * lanterns \quad \text{Eq. (6)}$$

$p_{kerosene}$ is the price of kerosene. Up to 4l/month, subsidized kerosene at Rs. 15/l is available, and beyond that kerosene must be purchased in the market at Rs. 25/l

$\eta_{kerosene}$ is the fuel efficiency of kerosene lanterns. A mass-manufactured "hurricane" lantern consumes 0.03 l/hour (Mills, 2003).

The variable *lanterns* is the number of kerosene lamps. It is assumed that two lamps are used during outages. With higher numbers, kerosene consumption becomes impracticably high, especially in the 6 hour supply scenario

By design, the interruption cost will be zero in the case of uninterrupted grid and decentralized plants. For unreliable grid supply, these costs will be positive. The estimated consumption in the base-case with the different unreliable scenarios is shown in Figure 2-4. Table 2-3 summarizes estimated costs for a few blackout events. Because of our assumptions, the interruption cost per unit time (or per unit consumption denied) increases with the cumulative duration of the outages within a single day.

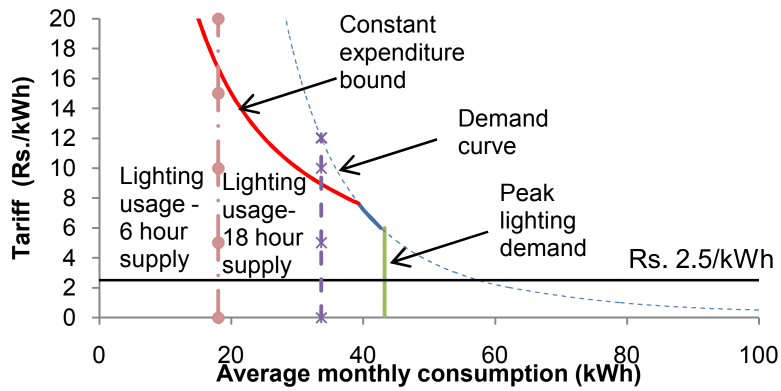

Figure 2-4: Lighting usage with intermittent supply

Table 2-3: Estimated interruption costs for a few examples

Event	Estimated interruption cost Rs.	Estimated interruption cost Rs./kWh denied
Any frequency of any duration of outages in the non 'peak' hours	0	0
30 minutes at peak	0.6-0.8	4.8-6.6
1 hour during peak	1.2- 1.7	5.1-7.3
2 hours during peak	2.7-4	5.6-8.3
1 day (or all 6 hours of peak)	29-79	20-55

5 Results

Table 2-4 summarizes the inputs for the 'base case'. Based on these inputs, the peak aggregate demand is 63kW, and the total daily consumption is about 420 kWh.

Table 2-4: Assumptions used for the base case

Average tariff, *Tariff*	Rs. 2.5/kWh
PropTV	60%
PeakDeficit	0% (Perfectly reliable)
Lighting usage threshold, *L*	43.2 kWh (4 X 60W lamps)
Average TV usage, *TV*	5.8 kWh (80W load)
Peak hours	5-7 am; 6-10 pm
Evening hours	6-10 pm
Night hours	10 pm- 5 am
Number of households	200
Distance of village from grid (Length of 11kV line needed)	3 km

Combining the interruption costs with the subsidy costs, the alternatives are compared in Table 2-5. The present value of subsidy, interruption and societal costs are expressed per electrified household.

Table 2-5: Summary of societal costs in the base case

Alternative		Cost of subsidy (Rs.)	Outage cost (Rs.)	Societal costs (Rs.)
Uninterrupted grid supply		7,800	-	**7,800**
18 hours grid supply	Without backup	7,400	5,100-7,200	**12,500-14,600**
	With diesel backup	27,000	-	**29,300**
6 hours grid supply	Without backup	6,100	26,200-36,700	**32,300-42,800**
	With biomass backup	38,200	-	**38,200**
	With diesel backup	49,800	-	**49,800**
Biomass- Diesel DG plant		55,400	-	**55,400**
Diesel DG plant		79,600	-	**79,600**
Solar- Diesel DG plant		147,000	-	**147,000**

Even after including interruption costs, the DG plants are still too expensive from a societal standpoint. While subsidy costs of grid extension are sensitive to distance, biomass-diesel (the cheapest of the three DG plants) is competitive with the 6-hour supply only beyond 17 km. However, RGGVY project reports (from MOP's RGGVY website) suggest that grid extension beyond 5 km is very rare- required for less than 10% of unelectrified villages in the three most poorly electrified states. On the other hand, the backup alternatives look more attractive. As grid costs are common for both, the outage costs of unreliable supply are compared with the additional cost of backing-up. As a result, these comparisons are independent of grid extension distance and would also apply to villages already connected, whether the grid infrastructure is considered as a sunk cost or not.

Figure 5 compares the societal costs of grid extension with and without backup. Because 6 hours/day is used as a benchmark in rural electrification planning, the alternatives compared here all assume 6 hours of grid availability but differ in the number of hours in the peak period. Biomass capital costs are high, and hence for optimum operations, if installed it should be used as much as possible, subject to fuel availability. Biomass alone (assuming sufficient fuel availability) costs Rs.27,000 per household, or in terms of LCOE, Rs. 8.2/kWh. That will be cheaper than any grid-biomass backup combination. When being used as a backup as well, the optimal operations entail using the available grid supply only to spread the availability of biomass throughout the year. Hence, in Figure 2-5, societal costs of the grid-biomass alternative are independent of reliability.

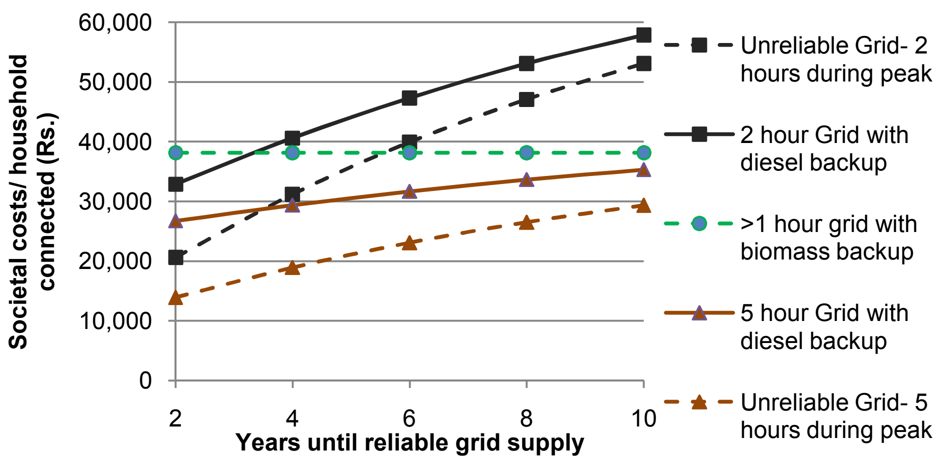

Figure 2-5: Sensitivity of societal costs of grid supply, with and without backup, to reliability (receiving 6 hour grid supply on average per day but differing in number of hours of supply in the peak hours)

Table 2-6 summarizes the least expensive alternative for different grid availability combinations. If grid extension is suboptimal, all alternatives preferable to grid are listed. Once again, the results in Table 2-6 are for the 6 hour supply case alone. As the interruption costs are being estimated only based on availability in the peak demand period, they will not be affected with greater grid availability through the day. However, subsidy costs will increase, and hence, so too will the total societal costs of grid power. Grid-biomass costs should remain unaffected, and hence become marginally more attractive.

The results in Table 2-6 assume the base case daylong outages per month for 6 hour supply, but the results are sensitive to these as shown in Table 2-7.

Table 2-6: Alternative with least societal cost for different reliability scenarios (grid availability for 6 hours/day on most days, but differing availability during peak demand)

		Years for reliable grid supply			
		<4	6	8	10
Hours of grid availability in peak demand period (6 hours)	2	Grid	Biomass backup (Grid)	Biomass backup (Grid)	Biomass backup (Grid)
	3	Grid	Grid	Grid	Biomass backup (Grid)
	≥4	Grid	Grid	Grid	Grid

Table 2-7: Sensitivity to number of daylong outages per month- alternative with least societal cost for different reliability scenarios (grid availability for 6 hours/day on most days; differing availability during peak demand; supply becoming reliable after 6 years)

		Number of daylong outages/ month				
		Upper bound of interruption costs			Lower bound of interruption costs	
		0-2	5	10	0-5	10
Hours of supply in peak demand period	2	Grid	Biomass backup	Biomass or Diesel backup	Grid	Biomass backup
	3	Grid	Grid	Biomass or Diesel backup	Grid	Grid
	≥4	Grid	Grid	Diesel backup	Grid	Grid

Because of low initial cost, at present most rural lighting uses incandescent bulbs. Replacing them with energy efficient lighting could have a substantial impact on the economics of the alternatives. Hence, we study how a switch to compact fluorescent lamps (CFL) affects the costs through a reduction in demand. While incandescent lamps are assumed to have a luminosity of 12 lm/W, CFL are assumed to provide 50 lm/W (based on Azevedo et al. (2009) and Bureau of Energy Efficiency (2009)). Rebound in consumption is parameterized. With zero rebound, the estimated monthly household demand in the base case reduces from 58 kWh to 25 kWh. Similarly, the aggregate peak demand reduces from 63 kW to 25 kW.

The inclusion of energy efficient lighting, leads to lower estimated peak demands and higher load factors. Because of the lower consumption, the subsidy costs for all the alternatives decrease, but the interruption costs are unaffected. The alternative most significantly affected by the change is standalone biomass. While the improvement in plant load factor improves the efficiency of power production, the reduction in demand leads to a reduction in the requirement for backup; in some cases, the backup generator is no longer required, reducing capital costs. The biomass alternative becomes much more competitive as a result, as shown in Table 2-8.

Table 2-8: Alternative with least societal cost for different reliability scenarios with CFL lighting (grid availability for 6 hours/day on most days, but differing availability during peak demand). Biomass DG plant is not competitive with the grid at reasonable distances (*) or is optimal beyond 1km (^{1}), 3km (^{3}) and 5km (^{5}) or at any distance (^{0})

		Years for reliable grid supply 2	4	6	8	10
		Upper bound of interruption costs				
Hours of grid availability in peak demand period (6 hours)	2	Diesel backup^{1}	Diesel backup^{0}	Biomass or Diesel backup^{0}	Biomass or Diesel backup^{0}	Biomass or Diesel backup^{0}
	3	Grid^{5}	Diesel backup^{0}	Diesel backup^{0}	Diesel backup^{0}	Biomass or Diesel backup^{0}
	4	Grid*	Diesel backup^{0}	Diesel backup^{0}	Diesel backup^{0}	Biomass or Diesel backup^{0}
	5	Grid*	Diesel backup^{3}	Diesel backup^{0}	Diesel backup^{0}	Diesel backup^{0}
		Lower bound of interruption costs				
	2	Grid*	Grid^{0}	Biomass or Diesel backup^{0}	Biomass or Diesel backup^{0}	Biomass or Diesel backup^{0}
	3	Grid*	Grid^{3}	Grid^{0}	Diesel backup^{0}	Biomass or Diesel backup^{0}
	4	Grid*	Grid^{5}	Grid^{3}	Grid^{1}	Diesel backup^{0}
	5	Grid*	Grid*	Grid*	Grid^{5}	Grid^{3}

The two most sensitive parameters for these results will be the amount of rebound and the biomass fuel availability. Note that in this case, rebound in consumption should not be viewed as a bad thing because it implies that low income energy-limited rural consumer are able to increase consumption and experience greater utility. Biomass becomes less preferable as fuel availability decreases and as rebound increases. Table 2-9 captures this two-way sensitivity. With 50% rebound and low fuel availability, biomass is competitive with grid extension of 1 km or more only when grid supply is available for 2 hours at peak and will become reliable only after 10 years.

Table 2-9: Sensitivity of results for CFL lighting to fuel availability and rebound

<table>
<tr><td colspan="2" rowspan="2">Zero Rebound</td><td colspan="5">Years for reliable supply</td></tr>
<tr><td>2</td><td>4</td><td>6</td><td>8</td><td>10</td></tr>
<tr><td rowspan="3">Hours of supply</td><td>2</td><td colspan="5" rowspan="2">Biomass</td></tr>
<tr><td>3</td></tr>
<tr><td>4,5</td><td>Grid</td><td colspan="4">For all fuel availability scenarios considered</td></tr>
<tr><td colspan="2" rowspan="2">50% Rebound</td><td colspan="5">Years for reliable supply</td></tr>
<tr><td>2</td><td>4</td><td>6</td><td>8</td><td>10</td></tr>
<tr><td rowspan="3">Hours of supply</td><td>2</td><td rowspan="3">Grid</td><td colspan="2">Biomass</td><td colspan="2">Low fuel</td></tr>
<tr><td>3</td><td></td><td colspan="3" rowspan="2">Base case fuel</td></tr>
<tr><td>4,5</td><td></td></tr>
</table>

An obvious barrier to large-scale adoption of energy efficient lights is the higher upfront cost relative to ICL. Over the lifetimes, CFLs, are significantly less expensive. In fact, the payback period is 6-7 months (with a 15 W CFL costing Rs. 150-200 compared to Rs. 15 for a 60W ICL), assuming a daily usage of 6 hours. To encourage the replacement of incandescent bulbs with CFL, the government initiated a policy, Bachat Lamp Yojana ("Efficient Lighting Program"), under which households could purchase CFLs at the price of incandescent bulbs. The difference was to be financed using Clean Development Mechanism (CDM) fund. While the program eventually ran into trouble when the market for Certified Emission Ratings crashed, some of the states have reportedly achieved some success (Forbes India, 2012; Hindu Business Line, 2011). Previous attempts by some of the utilities could not be sustained due to the limited financial resources available to them (CDM PoA document- Bureau of Energy Efficiency (2009)). LED lighting for residential purposes is still nascent, and its upfront costs are more than four times that of CFL lights and 40 times that of ICLs. Reportedly, the Delhi government is encouraging the adoption of LED lights by providing a 50% subsidy on upfront costs (The Economic Times, 2011, 2012).

Upfront capital subsidies have been the preferred approach (CDM PoA document- Bureau of Energy Efficiency (2009)), where the funding is provided by a centralized body and the utilities are not stretched financially. However, given the quick payback in the case of CFL, subsidies may not be necessary and the costs could be amortized over the course of a few months. For instance, utilities could replace CFL without any upfront fees and charge an extra Rs. 30-40/ month for about 6 months. With similar usage, the electricity bills should reduce by about Rs. 20/ month for each replaced lamp. Given the high mercury content, a mechanism for the safe disposal of used CFL bulbs must be put in place as well.

6 Discussion and concluding remarks

We began the paper with two questions- 1) when is conventional grid extension unadvisable for connecting unelectrified villages and 2) when is grid supply in electrified villages unreliable enough to look beyond the conventional route of supply. The best solution for a given village will depend on the nature of the demand in the village, the presence of local resources, the village economy, and incentives for and presence of micro-grid developers among many other factors. Broadly, we find that backing up unreliable grid with local DG based on biomass or diesel is an attractive strategy for a range of scenarios. Further, these results depend only on grid reliability and hold for both unelectrified and previously electrified villages. In the base case with conventional lighting, standalone DG plants do not seem to be optimal at distances within 17km and this makes them appropriate only for small or remote villages. The analysis here does not account for fuel subsidies provided for kerosene and diesel. If these are included, the societal costs increase for unreliable supply (due to the kerosene subsidies for backup lighting), and for the diesel based routes. Standalone biomass DG plants, despite including a diesel generator as backup, become more competitive (becoming optimal at 6km relative to 6 hour grid supply).

With chronic supply shortage, residential energy efficiency holds great potential and strategies that promote the adoption of CFL lighting can reduce the costs of subsidy for all alternatives. The threshold for acceptability of unreliable grid supply reduces substantially when energy efficient lighting is incorporated- biomass standalone plants in particular become preferable to extending the grid over very short distances. For instance, the analysis recommends disconnecting an already electrified village from the 11kV line and distribution transformer and replacing them with a standalone biomass plant for domestic supply, rather than continuing to provide the 'poor' grid supply described in Table 2-2.

The sizing of the alternatives is based on a rigid demand target. In practice, meeting the demand in the peak hours, or perhaps even limiting it to the lighting demand, could have immense value to the consumers. Conversely, subsidizing the purchase of solar lighting systems as backups for unreliable supply could be a promising approach. Solar home lighting systems (SLS) have small rooftop panels and batteries that can support 2-3 lights. The outage costs can be considered as an upper bound for the subsidies that could be provided to support SLS adoption. These subsidies could take different forms- in general, it has been found that systems with high capital subsides are not maintained well. Interestingly, abandoning its previous focus on unelectrified remote villages alone, MNRE's draft Remote Village Lighting policy proposes to support the use of local DG plants and solar lighting systems in electrified villages receiving less than 6 hours of grid supply per day (MNRE, 2012). This is certainly a step in the right direction.

Beyond the economic arguments made in this paper, two more fundamental considerations are relevant to providing reliable electric power in rural India. First, citizens of a modern democracy should enjoy a right to affordable and reliable electric power. In India at present there is no clearly defined right to "reasonable supply availability." The goal of 6 hours/day, which has become the present target for RE policies is still remarkably modest and means little if supply does not correspond to times of demand. Our analysis of different levels of availability in the peak 6 hour period produced very different results. Second, affordable and reliable electric power is a prerequisite for much economic development. Electric power is an essential input if rural India is ever to rise above its present low standard of living, and grow a range of more modern commercial and light industrial activities. Rao (2013) suggests that household enterprise incomes in India increase not just with access to electricity, but improved electricity availability as well.

Institutional constraints to implementing and sustaining electrification projects, especially DG plants, present a major hurdle. Sustainable and replicable microgrid models, especially in terms of maintenance, continue to remain elusive and there is little standardization in this space. Because of the limited (but growing) number of active commercial microgrid developers in India, the scale and rate of implementation is a concern. The solar lighting systems market is relatively better equipped in this regard with the presence of a large number of companies as well as financial institutions with some experience in structuring loans. However, in both cases, well deployed technical advice and resources from both the Center and from State Governments could considerably accelerate adoption.

A number of models that have been developed elsewhere around the world might be usefully adapted to the rural Indian setting. One example is a program called Efficiency Vermont, developed by the U.S. state of Vermont (See: www.efficiencyvermont.com). By adding a charge of a few mills/kWh, the state collects a fund that is then administered by a competitively selected non-profit entity to promote improvements in end-use efficiency and subsidize things such as more efficient lamps. In India, such a program might also subsidize solar lighting. Alternatively, State Electricity Boards, or local Indian utilities, might develop strategies to help consumers amortize the cost of compact fluorescents or solid-state lights through programs such as offering slightly lower rates for the first few kWh for a limited time to those consumers who participate in bulb replacement projects.

In summary, the cost to India, and its rural citizens, of unreliable electric power is very high. The time has come for some new thinking about how to rectify this problem that, despite ambitious development goals, has continued to fester for decades.

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Appendix 1- Treatment of outages of different frequencies and durations

To differentiate outages of different durations and frequencies starting from an aggregate monthly demand curve, we need to define the smallest interval of time during which the demand is independent. 'Independence' here implies that the value of consumption (or the lack of it) in a given interval of time is independent of consumption elsewhere. Let e_i be the demand for electricity at the i^{th} period of duration t (which could be a week, a day, an hour etc.). Let T be the higher unit of time such that $nt= T$. Then, the total demand in T, e_T will be the sum of e_i over i=1 to n. We can have two distinct formulations for the value of the lost consumption as shown in Figures 2-A1.1 (a) and (b).

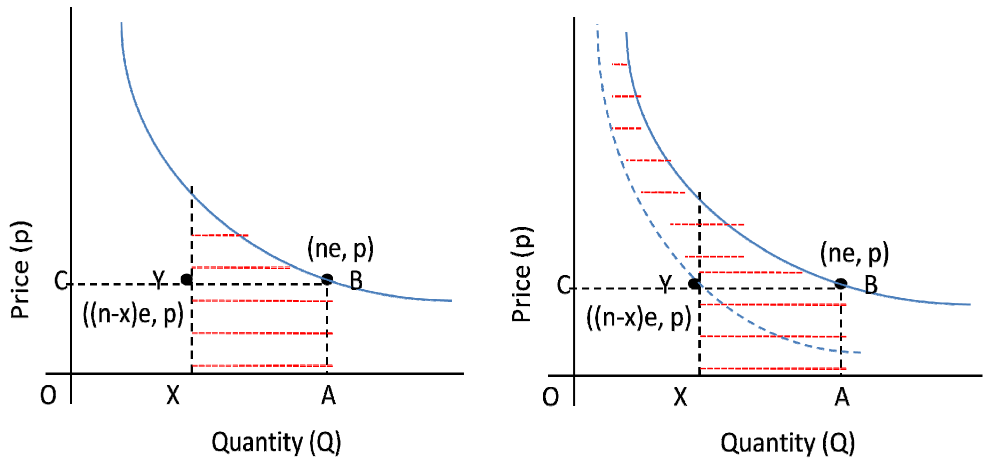

Figure 2-A1.1 (a) and (b) Illustrations of the two formulations of outage costs

Figure 2-A1.1 (a) assumes that the e_i are not independent of each other, i.e. the value of the marginal unit is equal irrespective of the time of consumption as long as it is within the period T. On the other hand, Figure 2-A1.1 (b) assumes each period t to be independent, as defined above. This distinction is significant, and it is thus necessary to define the smallest unit of t for which the demand curves can be assumed independent. Let, $e_T = F(p)$ and $e_i = f_i(p)$ for each duration of t that composes T. At price p_e, let the usage with unreliable supply, in the i^{th} period of duration t, be e_i'. Obviously, $e_i' <= e_i$, the equality holding in periods where supply is entirely uninterrupted. For formulation in Figure 2-A1.1 (a) to hold,

$$\int_{\Sigma e_i'}^{e_T} F^{-1}(e)de = \sum_{i=1}^{n} \int_{e_i'}^{e_i} f_i^{-1}(e)de \qquad \text{Eq. (A1.1)}$$

The condition holds when the demand curves are allowed to vary dynamically as a function of usage and average demand in the other (n-1) periods (hence, the individual n demand curves are not independent). These are demonstrated below for the log-log demand curve model.

$$\ln(e_T) = a + b\ln(p) \Longrightarrow e_T = ap^b \Longrightarrow p_T = (\frac{e}{a})^{1/b} \qquad \text{Eq. (A1.2)}$$

$$\sum_{i=1}^{n} e_i = e_T \text{ and } e_i = a_i p^{b_i} \Longrightarrow p_i = (\frac{e}{a_i})^{1/b_i} \qquad \text{Eq. (A1.3)}$$

Let $\sum_{i=1}^{n} e'_i = e'_T$ and $e'_i \leq e_i$

$$\int_{e'_T}^{e_T} (\frac{e}{a})^{1/b} de = \frac{1}{a^{1/b}} \frac{(e_T^{\frac{1+b}{b}} - e'^{\frac{1+b}{b}}_T)}{\frac{1+b}{b}}$$ Eq. (A1.4)

$$\int_{e'_i}^{e_i} (\frac{e}{a_i})^{1/b_i} de = \frac{1}{a_i^{1/b_i}} \frac{(e_i^{\frac{1+b_i}{b_i}} - e'^{\frac{1+b_i}{b_i}}_i)}{\frac{1+b_i}{b_i}}$$ Eq. (A1.5)

Hence, equation Eq. A1.1 holds when,

1. Each $a_i = a/n$ and $b_i = b$. And all e_i' are equal (hence, $e_i' = e_T/n$)
2. If there is no power supply available in j periods, that is, $e_i'=0$ for j periods: $e_i' = e_i = e_T'/(n-j) = e_T/n$ for the remaining periods.$b_i = b$ for all i, but a_i in all or some of the $(n-j)$ periods increase by the appropriate magnitude

There are other solutions but these justify the assumptions used here

Intuitively, the condition is met when demand curves for the periods with supply available shift to the right to accommodate for the periods with no supply. In practical terms, this requires the consumers to be able to reschedule their activities based on the availability of supply, such that consumers are forced to 'do more' when supply is available. This does not necessarily imply consuming more electricity when supply is available. In fact, it is assumed in this analysis that outages have no impact on the usage in periods with supply.

Appendix 2- Assumptions for household demand

Average daily demand, controlling for reliability (using *PeakDeficit*),

$$D_{daily} = \frac{D_{monthly}(Tariff, PropTV)}{30} \qquad \text{Eq. (A2.1)}$$

where, $D_{monthly}$ is the estimated average monthly demand and is a function of *Tariff* and *PropTV*. Naturally, the sum of hourly demands d_h will be equal to the daily demand,

$$\sum_{h=1}^{24} d_h = D_{daily} \qquad \text{Eq. (A2.2)}$$

There are two primary applications-lighting and television, with lighting being the more basic demand. After a threshold lighting demand is met, the TV is assumed to be purchased and used. Once lighting and TV loads are met in the peak demand period, electricity usage in the morning and afternoon hours is assumed to increase.

The average lighting load in the peak hours (which in this study, will be assumed to comprise six hours per day- early mornings 5-7 AM and evenings 6-10 PM) are estimated as below.

$$lighting_{h \in peak} = \frac{D_{daily}}{6} \quad \text{if, } D_{daily} < 6L$$
$$= L \text{ otherwise} \qquad \text{Eq. (A2.3)}$$

where, L is the maximum hourly electricity consumption on lighting in the six peak demand hours. It is assumed that incandescent bulbs are used for lighting. Similarly, the average load in the four evening hours (6-10 PM) due to TV usage is estimated as,

$$tv_{h \in evening} = \frac{(D_{daily} - lighting_{h \in peak})}{4} \quad \text{if } (D_{daily} - lighting_{h \in peak}) < 4TV * PropTV$$
$$= TV * PropTV, \text{ otherwise} \qquad \text{Eq. (A2.4)}$$

TV is the assumed maximum hourly household TV consumption. Residual hourly demand distributed uniformly through the day (except for nighttime) will then be,

$$any_{h \in night'} = \frac{D_{daily} - (6lighting_{h \in peak} + 4tv_{h \in evening})}{(24-7)} \qquad \text{Eq. (A2.5)}$$

To be clear,

$$d_h = lighting_h + tv_h + any_h \qquad \text{Eq. (A2.6)}$$

Average household load profiles were estimated the approach above and assumptions listed in Table 2-2. The load assumptions for community level facilities are summarized in Table 2-A2.1.

Table 2-A2.1 Community load assumptions

	Load (W)	Time of operation
Streetlights (per light)	100	6 PM- 7AM
School	600	10 AM- 4 PM
Drinking water pump	2238 (or 5 HP)	2 AM- 4 AM

Appendix 3- Plant sizing

Required plant size (for biomass and diesel DG) or transformer rating should be,

$$C = \frac{\max\left(D_h^{agg}\right)}{pf * (1 - loss_{dist})} \quad \text{Eq. (A3.1)}$$

where, D_h^{agg} is the aggregate load at hour h, pf is the power factor, and $loss_{dist}$ is the distribution loss in the local network.

In the case of solar, sizing is slightly different because of the need for battery storage. Assuming all supply is through stored energy, the required plant and battery capacities are sized as follows (following Chaurey and sKandpal, 2010).

$$C_{solar} = \frac{\sum_{h=1}^{24} D_h^{agg}}{pf * (1 - loss_{dist}) * \eta_{inverter} * \eta_{battery} * \eta_{cc} * \left(1 - f_{temp}\right) * (1 - f_{dust}) * (1 - f_{mismatch}) * EHFS} \quad \text{Eq. (A3.2)}$$

Where, $\eta_{inverter}$, $\eta_{battery}$ and η_{cc} are the efficiencies of the inverter, battery, and charge controller

f_{temp}, f_{dust} and $f_{mismatch}$ are the losses associated with ambient temperature, dust, and mismatch among cells.

EHFS is the expected hours of full sunshine- the level of solar radiation is translated in terms of hours of full sunshine that provides 1kW/m^2.

$$C_{solar-battery} = \frac{\sum_{h=1}^{24} D_h^{agg}}{pf * (1 - loss_{dist}) * \eta_{inverter} * \eta_{battery} * M_{DoD} * V} \quad \text{Eq. (A3.3)}$$

where, M_{DoD} is the maximum depth of discharge and V is the terminal voltage

Appendix 4- Capital and operations costs

Cost of grid supply is estimated as power purchase costs inflated by the reciprocal of (1- transmission and distribution losses).

The fuel costs for the biomass plant will be,

$$x^{Biomass\ DG}_{fuel,t} = \sum_{h=1}^{24}[\eta_{biomass}(d_{h,t}, C_{biomass}) * p_{biomass} * d_{h,t} * days^{biomass}_{operating} + \eta_{diesel}(d_{h,t}, C_{diesel}) * p_{diesel} * d_{h,t} * (365 - days^{biomass}_{operating})] \quad \text{(A4.1)}$$

where, $\eta_{biomass}$ and η_{diesel} are the fuel efficiencies of the biomass and diesel generators and are functions of load factors ($d_{h,t}/C_{biomass}$ or $d_{h,t}/C_{diesel}$), $C_{biomass}$ and C_{diesel} are the installed capacity of the generators, $p_{biomass}$ and p_{diesel} are the fuel prices of biomass and diesel, and $days^{biomass}_{operating}$ are the number of operating days of the biomass generator.

The cost of the backup diesel fuel will be,

$$x^{Solar}_{fuel,t} = \sum_{h=1}^{24} \eta_{diesel}(d_{h,t}, C_{diesel}) * p_{diesel} * d_{h,t} * (365 - days^{solar}_{operating}) \quad \text{(A4.2)}$$

Table 2-A4.1 and 2-A4.2 list all the cost inputs and assumptions for each of the alternatives.

Table 2-A4.1 Cost inputs and assumptions for the different alternatives

	Equipment	Capital Cost (in Rs.)	Annual O&M costs (fraction of capital costs)	Lifetime (years)	References
	LT line (per km)	190,000	0.03	20	(KERC,2010- Schedule of Costs)
Grid Extension	11 kV line (per km)	210,000	0.03	20	
	Transformers (in kVA) 25 63 100	 87,000 117,000 153,000	0.03	20	
Biomass Gasification	Gasifier (per kW) Engine (per kW) Civil works	25,000 30,000 72,000+ 9000*(Capacity)	0.05 0.05 0.02	10 20 20	Nouni et al. (2007) Banerjee(2006) (MNRE, 2008- VESP guidelines)
Solar PV	PV panel (per kW)	80,000	0.02	20	Aanesen et al. (2012) Nouni et al. (2006) Chaurey and Kandpal (2010) JNNSM guidelines (2010)
	Battery (per 12V-200 Ah battery)	22,000	0.02	10	
	Power conditioning unit (per kW)	40,000	0.02	20	
Diesel	Generator (per kW)	20,000	0.1	20	Nouni et al. (2007)

Table 2-A4.2 Summary of inputs for costs, efficiencies and other operational variables

	Length of the LT line	2 km	Assumption
	Local distribution loss	5%	Assumption
	Power Factor	0.95	Assumption
Grid Extension	Cost of power purchased (Rs./kWh)	2.5 (2-3)	Parameter
	Technical and commercial losses	20% (15-30%)	Parameter
Biomass Gasification	Cost of biomass fuel (Rs./kg)	1.5 (1-3)	Parameter
	Number of working days	300 (200-360)	Parameter
	Load Factor 0 50% 75% 100%	Fuel efficiency (kg/kWh) 0 1.68 1.54 1.40	Nouni et al. (2007)
Solar PV	Energy loss due to ambient temperature	0.1	Chaurey and Kandpal (2010)
	Energy loss due to dust	0.03	
	Energy loss due to mismatch among solar cells	0.02	
	Inverter efficiency	0.98	
	Battery efficiency	0.8	
	Charge controller efficiency	0.9	
	Effective hours of full sunshine (per day)	5.5 (4.5-6)	Parameter
	Number of working days	300 (250-320)	Parameter
	Terminal Voltage	120 V	Chaurey and Kandpal (2010)
	Maximum Depth of Discharge	0.7	Input
Diesel	Diesel fuel cost (Rs./l)	40	Ministry of Petroleum and Natural Gas (2013)
	Fuel efficiency (l/kWh)	0.3	Nouni et al. (2007)

[i] We assume that the cost of the solar lighting system is Rs. 12,000- purchased through a loan with a term of 5 years, at 12% interest rate, and 20% down-payment. Such a lighting system typically has 3-4 CFL lights. A system lifetime of 10 years is assumed, with a battery lifetime of 6-8 years (replacement costs of Rs.4000). A solar lantern costs Rs.1,600 and is assumed to be purchased with a one-time cash transaction. The lifetime of such a product is assumed 3-5 years, and the battery is replaced every year at a cost of Rs. 150. Based on these cost assumptions and discount rates at 30-60%, the amortized monthly costs of purchasing a solar lighting system is Rs. 275-370, and two solar lanterns is Rs. 130-265. Purchase of a solar product would imply high upfront costs, and the consumer will likely use a significantly higher discount rate than the social planner's 10%. Ekholm et al (2010) use discount rates of 62-74% for rural households and 53-70% for urban. Reddy and Reddy (1994) estimate an internal rate of return of 28% for a switch from kerosene lamps to electricity- which could be a lower bound on the discount rate.

Chapter 3: Do rural residential electricity consumers cross-subside their urban counterparts? Exploring the inequity in supply in the Indian power sector

Abstract

Given the low levels of electricity access in rural India, the poor quality of supply post electrification is an often neglected issue. Frequent supply outages have a significant impact on the quality of life of rural households and on the economic development of rural areas. Using a rich dataset from the Bangalore Electricity Supply Company (BESCOM), this paper analyzes supply rostering (alternatively, 'load shedding') in metropolitan, small town and rural feeders in and around Bangalore, the capital city of Karnataka in south India. The inequity in load shedding is analyzed through transfers due to differential tariffs between the urban and rural residential consumers, and the relief provided to BESCOM, through avoided procurement of additional supply from generators, because rural and small town feeders are load shed higher than Bangalore city. The values of the load shedding transfers are estimated to be in the range of Rs. 120-380/consumer-year from the rural consumers, and Rs. 220-370/consumer-year from the small town consumers (in aggregate, Rs. 200-640 million/year and Rs, 120-200 million/year, respectively). The metropolitan consumers are found to be net beneficiaries. Recognizing the revenue shortfalls of the utility (BESCOM) and lack of generation supply procurement options, we end with an examination of alternatives to the status quo and demonstrate the viability of current limited supply using smart meters as a solution.

1 Introduction

Electrification planning in India has been urban-centric, beginning with the provision of access. Rural electrification was largely neglected till the mid-80's, with the principal focus (if at all) being energizing irrigation pump-sets. A useful indicator of the importance given to village electrification is provided by how village electrification has been defined over time. Until 1997, a village was deemed to have been electrified if electricity was used for any reason whatsoever; this definition was revised to one where electricity was used in inhabited areas (Gokak report, 2002). Even today, the official definition for an electrified village only requires the existence of the distribution infrastructure, supply to public facilities and 10% of households being electrified (Ministry of Power, 2003). As per the 2011 Census, 45% of rural households (76 million) remain unelectrified, compared to 7%

of the urban households (6 million). The problem of rural electrification is particularly acute in the northern states of Bihar and Uttar Pradesh- with rural household electrification levels of 11% and 24% respectively (Census 2011).

This paper explores the more neglected issue of reliability of supply once a village has been electrified. The gains due to electrification are intimately associated with the reliability of grid supply- its availability, predictability and quality. Rao (2013) demonstrates that the availability of supply has a robust positive effect on the income of household enterprises, in addition to the effects due to access. Khandker et al. (2012) also show that supply availability has a significant effect on household electricity access and consumption levels. The poor availability of supply and the voltage fluctuations also impose significant costs on to the agricultural consumers, through days of lost income, the costs of backup source of power or through damage to equipment (World Bank, 2001).

Electricity has a fundamental technical characteristic of real-time dynamics. The modern electricity grid operates on Alternating Current (AC), which cannot easily be stored. Hence, the grid operates in a mode of real-time balancing, with supply and demand always in synch (net of losses along the wire). When the hourly demand exceeds the available supply, the utilities have to ration the available supply. While the institutional regulation of electricity supply varies across and even within countries, regardless of ownership or structure, one has assets for generation, transmission, and distribution. The latter is what is used for retail supply of electricity, whether in a competitive market set-up or (as is the norm in India) a regulated costs-plus geographic monopoly. Distributions companies such as BESCOM (Bangalore Electricity Supply COMpany) must purchase power from generators, and then deliver (and get paid for) power to end-users.

When faced with a shortfall in supply (through either low supply or higher than anticipated demand, or both), Indian utilities regularly resort to cutting off an entire feeder (11 kV voltage) of approximately a few thousand consumers – this is dubbed "load-shedding." This can be one or more 11 kV feeders in an area, and sometimes even the entire substation. Utilities develop rostering schedules on a monthly or seasonal basis and target achieving them. If deficits remain despite these "scheduled" outages, there are additional unscheduled outages. As Dreze and Sen (2013) described it bluntly, load shedding is the expression given to "managing the outages, instead of doing something about them".

Using a rich dataset (at a minute-level resolution for each feeder) for the Bangalore Electricity Supply Company (BESCOM), the study looks at the distribution of supply in metropolitan, small town and rural feeders. BESCOM serves eight districts in the state of Karnataka, including Bangalore city and the surrounding areas. The population of this region is 20.7 million (Census 2011), of whom 46% live in Bangalore city (hereafter, Bangalore will refer to the city unless specified otherwise). Besides being the capital city of Karnataka, Bangalore is also a major economic hub, known especially for the Information Technology industry.

The principal hypothesis tested in this study is that the rural residential consumers are load shed enough for the resultant relief to the utility to overcompensate for any tariff subsidy extended to these consumers relative to their counterparts in urban areas. We therefore quantify two kinds of transfers based on tariffs and load shedding. Both these transfers are framed in a somewhat narrow accounting sense, and do not consider factors such as the economic value of the unsupplied power or the consumer interruption costs. Section 3.1 will elaborate on the problem formulation.

Even a preliminary analysis of the data suggests that rural (R) feeders, and surprisingly non-Bangalore urban (NBU) feeders as well, receive supply that is worse than in Bangalore city (BU). However, there are high variances- and due to data constraints we cannot be sure whether some feeders receive especially poor or good supply all the time or whether some kind of rotation process is being used.

On monetizing, the load shedding transfer is estimated to be Rs. 240-510/ year/rural residential consumer. The net of load shed and tariff transfers is estimated to be Rs. 120-380/consumer-year from rural consumers and Rs. 220-370/consumer-year from non-Bangalore urban consumer; and Rs. 120-270 to the Bangalore urban consumers. In aggregate, these net transfers are estimated to be 400-850 million from the rural consumers. These results suggest that the direction of the transfers is robust.

Finally, we assess measures to reduce the load shedding in rural feeders. We demonstrate that providing uninterrupted but current limited supply, using smart metering technology, instead of outright blackouts is a feasible compromise solution. Compared to the installed costs of Rs.4000 per meter, the total willingness to pay among the stakeholders- through avoided interruption costs to the consumers, rerouted kerosene subsidies from the central government, and net transfers due to inequitable load shedding- is in the range of Rs. 2,900- 9,500.

In the next section, we present a broad overview of the power sector institutions, and the supply deficits that necessitate load shedding. Agricultural consumption plays an important role in the utility's finances and as a result, the electricity supply provided to villages. This is described in section 2.3. The rest of the background section directly sets the stage for the analytical framework used in this paper- the tariff setting process and the resultant subsidies, and load shedding. Section 3 covers the methods and data used for the analysis, and outlines three major research questions of interest here. Section 4 summarizes the results- providing estimates of load shedding for the three consumer categories, and the net transfers. We conclude the results section with an engineering economic analysis of the viability of using smart meters as one solution to blackouts. Section 5 discusses the policy implications of the study.

2 Background

2.1 Institutions

Up until the nineties, most of India's states had vertically integrated State Electricity Boards (SEBs) that looked after transmission, distribution, and much of the generation. These boards were for all practical purposes an arm of the state government. The SEB's finances were thus treated as secondary to the state's social and political goals. At the same time, the accounting methods were weak, and the utilities' operations were kept afloat by 'soft' transfers from the government (Tongia, 2007). Even by the end of the 80s, the Indian power sector was in crisis. Power shortages were constantly increasing and had become chronic. Theft ("commercial losses") was growing, as were technical losses because the infrastructure was in urgent need of an overhaul. In parallel with the onset of liberalization in 1991, a range of measures was introduced– that included private sector participation (especially with an eye on foreign investments) in power generation, corporatization and unbundling of the utilities, and the establishment of independent regulatory commissions. For more on the reforms process and the 2003 Electricity Act, see Thakur et al. (2005), Singh (2006), Tongia (2007). We will briefly discuss the significance of the reforms and the Electricity Act of 2003 on rural electrification in the country. We then highlight salient features of the reforms process in Karnataka and BESCOM.

As implemented, village electrification comes with a set of challenges and disincentives for the utilities. The loads are typically remote and dispersed, increasing the capital costs which cannot be recovered completely through the consumers because of their low affordability. Subsequent to electrification, residential demand is low (compared to the urban consumers) and there are few non-agriculture productive loads. As elaborated below, agricultural loads represent a particularly problematic category. Given this context, utilities do not find electrifying village attractive, unless there are high government subsidies. Multiple central government programs have tried to push village electrification aggressively. The most recent and ambitious of these was the Rajiv Gandhi Grameen Vidyutikaran Yojana, launched in 2006, under which 90% of the capital costs are subsidized by the central government. Karnataka is among the better electrified states in India, and household and village electrification rates have been among the highest (87% of rural households, and almost 100% of villages).

BESCOM was unbundled from the former Karnataka Electricity Board (KEB) as an independent (government owned) distribution utility in 2002, to service eight districts including and around Bangalore city. In parallel, Mangalore, Hubli and Gulbarga ESCOMs were created. Unlike many of the other states, Karnataka has historically had separate entities for power generation (Karnataka Power Corporation Limited), and transmission and distribution (KEB). The restructuring of the electricity sector started with the Karnataka Electricity Regulatory Act in 1999, and the creation of the Karnataka Electricity Regulatory Commission (KERC). Besides setting up the regulatory body, one of the objectives of the Act was to encourage private sector investment in generation, transmission and distribution (KERC, 2000).

2.2 Supply deficits

India's gross generation capacity has increased from 1.4 GW in 1950 to about 230 GW (2013). Over the last decade, the capacity has almost doubled with an average addition of 12 GW per year (Central Statistics Office, 2013). Despite this substantial growth, per capita electricity consumption was 684 kWh/year in 2011 (for the sake of comparison, China was at 3300, Brazil 2440, and OECD 8160) (IEA database, 2011). Demand has consistently outstripped supply and deficits remain a concern. For the year 2012-13, the Central Electricity Authority (CEA) estimated a peak deficit (in GW) of 9% and an energy deficit (in billion kWh) of 8.7% (CEA, 2013). Due to methodological and data reasons, the actual shortfall is likely to be substantially higher

The distinction between generation capacity and energy produced is important and it is worthwhile to discuss this briefly. Electricity demand at any moment will be in the units of power (watts, or W). When aggregated over time, the demand is expressed in Wh. In the power system network, supply should meet demand exactly at any instant. Typically, the demand at a particular time of day is usually well known, and power from the generating plants is dispatched accordingly. The deficit in supply is ideally met using reserves or peaking power plants. These plants, usually hydropower or natural gas fired thermal generators, should be able to ramp up quickly. Coal fired thermal plants, which account for almost 58% of the generating capacity, cannot ramp quickly and so cannot serve as peaking plants. They are used to meet the base load.

Of the approximately 120 GW added over the last 10 years, 70% has been through coal plants (Central Statistics Office, 2013). While India does have large reserves, the domestic coal has high ash content. Another major constraint has been access to coal mines due to environmental, and relocation concerns. Similar concerns have also affected capacity addition through large hydropower and nuclear plants. With natural gas, fuel availability has been a concern. As a result, the problem of deficits is not likely to be resolved quickly. While it is only a partial solution, there is considerable potential in India for improved energy efficiency and demand side management. Although, there have been programs like Bachat Lamp Yojana to encourage the uptake of Compact Fluorescent Lamps, there remains significant potential for progress through near interventions.

The state owned power generation in Karnataka was primarily based on hydropower until 1985 when the Raichur thermal plants became operational. The state has long term Power Purchase agreements for a capacity of about 13 GW– this includes shares of Central Generating Stations (about 1.8 GW) that are allocated to the state, as well as power purchased from Independent Power Producers (1.1 GW) and captive generation plants (0.4 GW) (CSTEP, 2013). In addition, the utilities in the state have been depending increasingly on expensive short term power purchase to make up for deficits in supply– in 2012-13, this was about 11 Billion kWh of the total 57.2 Billion kWh purchased (about 19%) (CSTEP, 2013). Much, if not all, of this power obtained with short term contracts is purchased during the hours of peak demand. Despite this, Karnataka's energy deficit for 2012-13 was approximately 14% and the "peak" deficit was about 14% as well (CEA, 2013).

2.3 Agriculture

Power for irrigation pump-sets is an important factor affecting the operations and finances of Indian utilities and is intimately connected to the availability and quality of electricity supply in rural areas, as we shall describe shortly.

With the advent of the Green Revolution, irrigation pump-set use was encouraged in many states of the country, especially those where agriculture had previously been mostly rain-fed. While before, the pump-sets and wells were public-owned, individually owned pump-sets started becoming popular during the 1980s (Dubash and Rajan, 2002). Their use mushroomed over the next two decades. With little oversight or groundwater planning, and negligible (if not zero) tariffs being charged for the electricity consumed by these pump-sets, the water tables in many states of the country have dropped dramatically, necessitating ever deeper wells and increasing the risk of well failure. The farmer lobby has been resisting tariff rationalization motivated in part by the high costs and risks of operating pumpsets (Narendranath et al, 2005). Another complaint is about the poor quality of supply which leads to motor burnouts due to low voltage and fluctuations (World Bank report, 2001).

Starting in the early eighties, the KEB, or perhaps more accurately, the state government, consciously prioritized agriculture over industry. Agricultural use was "aggressively" encouraged with de-metering of all pump-sets less than 10 HP and the introduction of capacity (in horsepower) based flat tariffs in 1981 (KERC, 2000). In parallel, in 1983-84, the KEB introduced a cap on sales to large, energy intensive industrial consumers, necessitating some of their demand to be borne by captive generation (Reddy and Sumithra, 1997). The power supply to agricultural consumers was heavily subsidized, eventually becoming free. The costs of the subsidies were borne by the larger consumers, most notably the industrial and commercial consumers, who began increasingly relying on captive generation. The power sector in Karnataka thus got locked in to an unsustainable cross-subsidy mechanism. It is important to note that the subsidies to agriculture were not borne by the state for many years. The state government only partly meets the costs of the subsidies.[2]

Since the de-metering of small pump-sets that began in the 1980s, even metering the consumption has been stoutly opposed by the farmers. One fear could be that the metering may be followed by tariffs. As a result, agricultural consumption is not reliably monitored by the utilities. In fact, the utilities tended to overstate the agricultural consumption to cover for the very high technical losses and theft (Ranganthan, 2005). Given this context, the only way for the utilities to limit consumption by the agricultural consumers is to provide restricted hours of supply. One common practice in many utilities is to provide a target number of hours of three phase supply in the mornings or late in the night, and provide single phase supply for households in the evenings. Most pump-sets cannot be run with single phase supply, unless phase converters (capacitors) are used. These are common, although the extent of their use is unknown. However, because of this, there is a disincentive to provide single phase supply to rural areas as well.

Recognizing this problem, the Andhra Pradesh state government introduced a physical segregation of rural feeders into agriculture and non-agriculture (primarily, residential) feeders in the early 2000s (ESMAP, 2013). A similar program in Gujarat has been especially acclaimed. While the agriculture feeders continued to receive restricted (but predictable) hours of supply, the non-agriculture feeders were to receive uninterrupted 3 phase supply (Shah and Verma, 2008). Based on the success of this program, other states including Karnataka have since sought to replicate it, and the segregation process is still underway.

2.4 Utility finances and tariffs

One of the principal difficulties in discussing "true" costs of supply in the Indian context is that accounting in the power sector has been generally weak or opaque. Ideally, the tariff design must balance multiple objectives: efficiently allocate the finite resources among the consumers, be sustainable for the utilities and other 'producers', and be equitable- a very subjective notion. In practice, electricity prices could, and, is the case here,

[2] The state government pays Commission Determined Tariffs on behalf of the subsidized agriculture consumers. These tariffs seem to be back-calculated from the total quantum of subsidy that the state government is willing to allocate, the gap in revenues for the utility, and the total estimated consumption by the agricultural consumers. For the year 2012-13, the CDTs were Rs. 1.3/kWh; in comparison, the average cost of supply was Rs.5/kWh

do become politicized. The role of the regulatory body would then be, among other things, to balance these objectives and limit the influence of the government in setting tariffs. With the setting up of independent regulatory commissions to regulate state-owned entities, the Indian power sector entered “unchartered territory” (Dubash and Rao, 2008). In its early days, KERC had to contend for authority with the state government that was “regulating in parallel” and continuing to impose its own political agenda on the tariffs (Dubash and Rao, 2008).

The Karnataka Electricity Regulatory Act requires KERC to lay out the methodology in setting tariffs. In the 2000-01 tariff order, the regulators stated that one of the objectives was to progressively phase out subsidies, and base the tariffs on the costs to serve a given category of consumers. Ideally, from an economic standpoint, the tariffs should be equal to the long run marginal costs of supply. The KERC opted to use the more conventional Rate of Return (or “cost-plus”) accounting approach instead, citing lack of sufficient data to compute the marginal costs. Even with such an approach, assets and expenditures must be separated between generation, transmission and distribution, and then used to compute demand (i.e. capacity) related, energy related and customer related charges for each consumer group. The fixed tariffs, that are capacity (kW) driven and unrelated to energy consumption (kWh), should ideally reflect the customer service *and* demand related charges. The demand related charges would account for the burden placed on “the system” by a given consumer especially at times of peak demand when the marginal costs of power are likely to be significantly higher than on average, due to the need for peaking power. Currently, fixed charges in the tariffs are limited to service costs like employee salaries, administrative costs, and costs of maintenance and repair, and are normalized using the consumers’ connected load. Demand related charges have not been included due to insufficient data- this is an important omission and is especially relevant in the context of this study.

KERC also discusses its approach in balancing the paying capacity of the consumers (and hence, the need for subsidies) with efficient pricing, and the significance of quality of supply. The regulators clarify that the constraints in paying capacity must be considered only for “lifeline” consumption (a basic minimum usage in households) and that the tariffs in general should be at least at average costs of supply. In 2002, the KERC approved a rural rebate of 25% in the *fixed charges* for residential and industrial consumers in rural feeders owing to the poorer quality of supply[3]. In 2005, stakeholder consultations instead resulted in a three tier pricing mechanism for metropolitan, small town and rural consumers to account for the difference in quality of supply. The measure was also designed to increase revenues from urban centers (especially Bangalore) that could then be reinvested to improve supply in rural areas. In 2010, the three tier pricing was changed to two tier (rural and urban).

The tariff setting process and tracing the changes in the pricing structure are important because many got locked in. In years that followed, the tariffs have been largely changed on an incremental basis and been set by the utilities while negotiating with KERC. The distribution utility estimates the likely demand and the costs of supply and operations for the upcoming year, and the revenue shortfalls with the existing tariffs in order to earn a particular level of profits. New tariffs are proposed for each of the consumer categories in order to meet these shortfalls. KERC decides, based partly on stakeholder inputs, whether these proposed increases in tariffs are reasonable.

For the year 2012-13, the consumption and average revenues received from different consumer categories are summarized in Table 3-1. The average revenues received per unit consumed- KERC's estimate of 'actual cost of supply'- was Rs.5/kWh. The magnitude of the cross-subsidization is clear from the weighted average tariffs from the low voltage (residential, agriculture, and some commercial consumers among others) and high voltage (predominantly industrial and commercial) consumers- Rs.3.9/kWh and Rs. 6.6/kWh, respectively. Note that for many of these consumer categories, there is an increasingly block tariff structure. The details for residential consumers are elaborated in Section 4.2.

[3] Quoting from KERC 2005: "Many rural consumers have strongly represented that there should not be any discrimination between rural and urban consumers in the quality of supply and it should be the same across the state and as such, grant of rural rebate would defeat its purpose of giving scope for the ESCOMs to further neglect the rural areas. A few consumers have also stated that the rural rebate should be so fixed that it would act as a disincentive so that better supply is provided to the rural areas".

Table 3-1: Consumption and revenues from important consumer categories in BESCOM for 2012-13 (BESCOM average revenue is Rs. 5/kWh)

Consumer category	Number of consumers	Total cons. (MU)	Average monthly cons. (kWh)	Revenue/ month/ consumer (Rs.)	Revenue per unit (Rs./kWh)
Rural- poorest *Bhagyajyothi*	0.7 million	110	13#	65*	5*
Irrigation pump-sets (<10HP)	0.7 million	4300	530#	700*	1.3 *
Rural residential	1.6 million	550	28	92	3.4
Urban residential	4.2 million	5600	110	470	4.3
LT Commercial	0.8 million	1800 (urban) 100 (rural)	210 (urban) 90 (rural)	1,600 (urban) 660 (rural)	7.6 (urban) 7.3 (rural)
HT Industrial	4866	5800	100 ,000	600 ,000	6
HT Commercial	4777	3900	68 ,000	540 ,000	8

#- Not always metered, and hence presumptive
*- Subsidized by Government of Karnataka
Data source: Estimated consumption and tariff levels from 2012-13 Tariff order, and number of consumers from 2013-14 Tariff order

Table 3-1 demonstrates that both urban and rural residential consumers (as aggregate categories) are cross-subsidized by the larger consumers. The poorest of poor consumers are completely subsidized by the state. The agricultural consumers have an interesting arrangement: although the state does pay the commission-determined tariff of Rs. 1.3/kWh on their behalf, this tariff is, even without specific calculations, noticeably lower than the cost of supply. The remaining costs are once again recovered through the cross-subsidies from the larger consumers.

To be clear, the tariff based transfers being studied here are based on the differential tariffs for the rural and urban consumers only.

2.5 Load shedding

Outages due to supply shortfalls come in different forms- scheduled and unscheduled outages, beyond unanticipated faults and burnouts. While the scheduled supply availability targets (or conversely, the scheduled load shedding arrangement) are decided in advance, the methods and often even the precise timing of the outages are not always transparent. Unscheduled outages are any that occur above and beyond the schedule, and are done if there is a deficit between available supply and the restricted demand. The smallest area that can be load shed simultaneously is that served by a single 11kV feeder. In addition to load-shedding, the first level of load management is rostered supply to agriculture, by switching off 1 or 2 phases out of 3 phases. This leaves supply to rural homes and other smaller users.

Maharashtra has a systematic load shedding arrangement. Feeders are classified into different categories based on losses and collection efficiency. The list of feeders in each category is updated every month, but this list is not explicitly declared. The load shedding arrangement is managed by the state load dispatch centre (SLDC), essentially working backwards from the worst feeders upwards until the supply and demand are balanced. Load shedding in Karnataka is not as transparent. In the event of a deficit, the Karnataka SLDC rations the load to be shed between the five ESCOMs based on extent to which they are overdrawing compared to the allotted supply for that hour. Within the ESCOM's the load shedding seems to be rationed among the 220 kV substations. Beyond that stage, there does not seem to be a consistent process in place. The actual load shed amounts are not published in Karnataka or most states.

The load duration curve for Karnataka (not just BESCOM, which is almost half the state load) in May 2012- April 2013 is shown in Figure 3-1. Load duration curves show the fraction of hours in the year corresponding to a given load level or higher. Considering the restricted supply, we distinguish between the estimated "unrestricted" demand (given the present tariff structure) and the loads served. The peak deficit estimates mentioned previously are computed as the difference between peak demand and peak load served. More et al (2007) argue that given the uncertainties in estimating load shedding, a more reasonable estimate could be derived from the load duration curves corresponding to demand and load at 15% of the year level. Based on this method, the peak deficit is computed to be 744 MW (or 9 %), which is more conservative compared to the official peak deficit estimates of 1295 MW (or 13%).

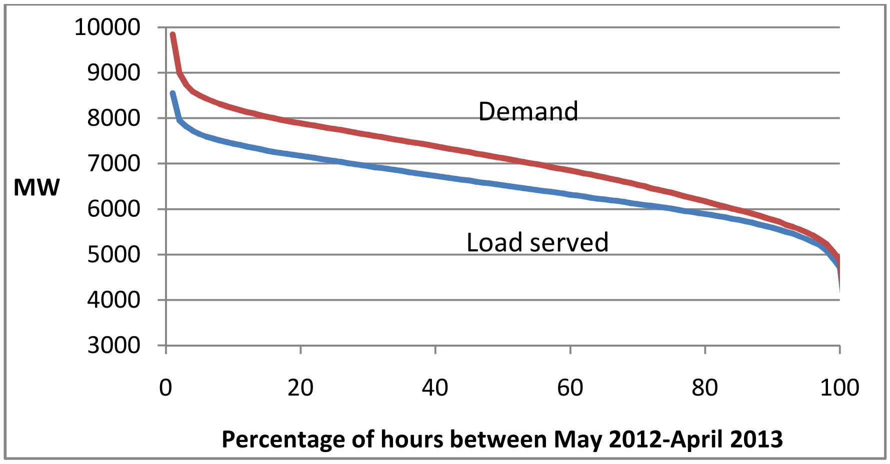

Figure 3-1: Load duration curve for May 2012- April 2013 for Karnataka. Compiled using state load profiles from KPTCL website

While making an allowance for the imperfect demand estimates, it is worth considering the hourly demands and loads as well. The load duration curves are a little misleading as they may suggest a time coincidence along the vertical. On the contrary, for the same level of demand, the load shedding varies by time of day, month, and season. Similarly, the peak deficit estimates present a partial picture, as shown by Table 3-2 that compares the hourly deficits (also computed by the KPTCL) with the official peak deficit estimate for the year. The deficit percentage was higher than "peak" about 12% of the time! Besides raising questions about the metrics used in reporting reliability, this also has implications on electricity planning and energy dispatch.

Table 3-2: Hourly deficits compared to peak deficit estimates and the timing of these instances for May '12- April '13 (Analysis based on state load profiles from KPTCL website)

		No load shedding	Hourly deficit % is greater than "peak deficit" of 13%	Hourly deficit is greater than "peak deficit" of 1300 MW
Number of hours in the year* (% of total)		2720 (31%)	1012 (12%)	468 (5%)
Time of day	6am-6pm	1%	19%	8%
	6- 9pm	4%	11%	8%
	9pm- 6am	80%	2%	0%
Months	August-September	25%	31%	16%
	March-April	30%	14%	7%
	Rest of the year	33%	6%	2%

*- Out of 8688 hours (363 days)- data for two days were missing on the KPTCL website

3 Methods

3.1 Framing the problem

Table 3-1 and the subsequent discussion highlight the many kinds of subsidy transfers among BESCOM's consumers. This paper will restrict the analysis to rural and urban residential consumers. The industrial and commercial consumers not only pay much higher tariffs, they also form a very distinct group compared to the residential users in terms of the the nature and times of electricity use and its economic value. Given the data constraints, much of the analysis is restricted to the consumer groups at the aggregate level. We do, however, distinguish between Bangalore urban (or metropolitan) and non-Bangalore urban (or small town) residential consumers, although there are no longer differential tariffs between these two groups.

The hypothesis in this analysis is that because the rural consumers are load shed "more than they ought to be", at a time of day the cost of procuring additional power is more expensive than on average, they provide a net "relief" to the utility. In parallel, because urban consumers are better off than what they "should have been", they are beneficiaries of this arrangement. In addition, the higher costs of peak procurement may have been passed down to all consumers, including the urban residential. Put another way, we are exploring how much more reliable supply the urban consumers are entitled to because of the higher tariffs that they pay.

There are two aspects to the problem- the tariff based transfer and the load shedding based transfer. The tariff based transfer will be related to the difference between the average actual tariffs and "uniform" tariffs, defined in some manner. The load shedding based transfer will be related to the difference between "equitable" and actual levels of load shedding. There are several ways one could define these "uniform" tariffs and "equitable" levels of load shedding.

As shown in Table 3-1, the urban tariffs are slightly higher than rural tariffs for all the consumption slabs. Typically, the average costs of supply are higher in the rural areas than urban. On a per consumer basis, the fixed costs of setting up the infrastructure will very likely be higher in the rural areas, especially as the villages get more remote and sparse; but as already discussed, there is no differentiation made between actual costs to serve consumers during the calculation of fixed charges. The difference in fixed charges (the rural rebate) was instituted to reflect the poorer quality in rural areas. The technical losses may be higher because of the longer feeder lines required (again, normalized per consumer or per unit delivered)[4]. Similarly, with not all consumers metered, commercial losses may be higher. This is especially the concern with agricultural consumers as described in the background section. Assuming that the technical losses are higher, the "uniform" tariffs must be such that rural consumers pay slightly more than the urban consumers should, reflecting the slightly higher costs of supplying each kWh to the consumer. The calculations are based on BESCOM's filings (called D-21) to the KERC while proposing tariffs.

To estimate the tariff based transfers, we consider the loads served in the urban and rural residential feeders, and remove the fraction of loads from non-residential sources. For the urban feeders, these are principally the commercial consumers. For the rural feeders, non-residential consumption with single-phase supply includes irrigation pump-sets running on phase converters and poorest of poor consumers who receive subsidized supply. Commercial sales from rural areas are small enough to be neglected for the analysis. Using the National Sample Survey (NSS) data, we can estimate the fraction of rural and urban consumers fall in different slabs. This is used to calculate the weighted average actual and "uniform" tariff for each of the feeder types. For the purposes of this analysis, only the energy charges are considered. These can be used to obtain the normalized tariff based transfers on a Rs./consumer-day basis as shown in Equation 1.

$$Tariff\ transfers = \frac{Load_{served}\left(tariff_{uniform}^{avg} - tariff_{actual}^{avg}\right)(1 - loss_{dist}) \prod (1 - frac_{non-residential})}{Number\ of\ consumers\ in\ the\ category}$$

- Eq.1

[4] The higher distribution losses and the subsequent higher marginal costs of supply merit additional discussion. The technical (or I^2R) losses depend on the power consumption in these feeders, which in turn depends on time of day. When irrigation pump-sets are used, the average active power consumption in rural feeders is very similar to that in the urban feeders around the same time (2-3 MW). In the evenings, with single phase supply, the predominantly domestic consumption in the rural feeders is about a third of that in the urban feeders, and hence, for equivalent technical losses, the feeder lines could be a factor of 3 longer. It appears that the conventional wisdom of higher technical losses I rural areas might be true on average, but during the evening peak, when supply is meant for households and not pump-sets, this may not be entirely true.

To estimate the load shedding based transfers, we need to compare the actual load shedding levels with an equitable level. The most straightforward choice of such an equitable level is one where all feeders get load shed to the same extent, say, by cutting supply for the same fraction of time. The relief could then be estimated based on the avoided unrecovered costs. However, the transfers obtained from this calculation do not have a very intuitive interpretation, and furthermore, don't sum to zero because the costs of supply and the marginal tariffs differ across consumer categories. Hence, we use an alternative method wherein we estimate the unrecovered costs of power supply if the rural and non-Bangalore urban residential consumers (the "contributors") are load shed at the Bangalore urban level (the "beneficiaries").

To estimate these load shed transfers, we use weighted average marginal tariffs, calculated in a manner similar to the weighted average tariffs- using the NSS data on household consumption. To avoid double counting we use the greater among the uniform and actual tariffs to compute the avoided unrecovered costs. Only residential loads and demands are considered, by deflating for the fraction of non-residential loads. When normalized by the number of consumers in the rural and non-Bangalore urban categories, we have the load shedding transfers in Rs./ consumer-day. The load shedding transfer *to* the Bangalore urban consumers is calculated by normalizing the aggregate rural and non-Bangalore urban load shedding transfers by the number of Bangalore urban residential consumers.

For rural and non-Bangalore urban consumers:

$$Load\ shed\ transfers = \frac{(Load_{at\ BU\ level} - Load_{served})(1 - loss_{dist})\{Cost_{peak}^{supply} - tariff_{marg}\} frac_{residential}}{Number\ of\ consumers}$$

-Eq.2

For rural consumers, the unsubsidized $tariff_{marg}$ should be used (to avoid double counting), and for non-Bangalore urban, the actual marginal tariffs are used. For Bangalore urban consumers,

$$Load\ shed\ transfers\ to\ BU\ consumers = \frac{Load\ shed\ transfers_{R}^{agg} + Load\ shed\ transfers_{NBU}^{agg}}{Number\ of\ BU\ consumers}$$ - Eq.3

Instead of this juxtaposition of tariff and load shed based transfers, other approaches could be considered too. One option is to consider the economic value of electricity in different parts of the grid. If load shedding is inevitable, it should be done in such a way that the economic loss is minimized. Alternatively, if different consumers have different interruption costs, load shedding should be done such that the aggregate interruption costs are minimized. The difficulty with either way of framing the problem is that there are likely to be significant income effects- consumers with higher incomes will have higher interruption costs- or there is a strong causal link between the reliability and economic output. One reason for the poor development of industry in rural areas is the poor infrastructure, including electricity access and reliability. And hence, arguing for a preferential treatment towards the urban areas due to the higher economic output becomes circular.

3.2 Data

Karnataka is the only state in the country which has implemented Supervisory Control and Data Acquisition (SCADA) systems for all the substations. The SCADA allows for real time centralized monitoring of the power supply and consumption in all the 11kV feeders at the substation level. Very briefly, the transmission infrastructure consists of 66kV or 110kV lines that are stepped down to 11kV by the substation transformers. The 11kV feeders are then stepped down to the Low Voltage level where the power can be used by regular appliances (at the notional 220 V supply). While faults can occur at the 400V level, all the load shedding decisions are implemented for entire 11kV feeders. The SCADA dataset provides information on the supply and the consumption on a minute-by-minute basis. Hence, we can estimate the demand and the load shed at a very granular level, for the first time in India.

The dataset used in this study has been obtained from Karnataka Power Transmission Corporation Ltd. (KPTCL) for some or all of BESCOM region for the dates listed in Table 3-3. The dates were chosen by KPTCL as representative of the three seasons. As KPTCL is responsible for transmission and not distribution, we do not expect there to be biases. Later, we use other estimates on loads served and shed at the state level, to weight the results from each of these nine days based on how representative they are.

Table 3-3: Dates and feeder types of SCADA data obtained from KPTCL

Zone	Dates	Number of feeders
Chitradurga Tumkur	Sep 25-27, 2012 Dec 25-27, 2012 Apr 13-15, 2013	Rural feeders: 600-637 Urban feeders: 46
Bangalore Rural	Sep 25 and 26, 2012 Dec 26, 2012 April 15, 2013	Rural feeders: 405-481 Urban feeders: 49-54
Bangalore urban	Sep 25 and 26, 2012 Dec 26, 2012 April 15, 2013 (NRS Substation- all 9 days)	Rural feeders: 82-92 Urban feeders: 955-966

Besides rural and urban feeders (that is, those which primarily serve residential consumers), the dataset includes commercial, industrial, waterworks and auxiliary feeders. High Voltage industrial and commercial consumers are not part of this dataset. BESCOM's feeder list was used to classify the feeders in the dataset into their types[5]. We do not have the consumer make-up of each of these feeders, and hence restrict ourselves to the aggregate analysis. Both the rural and urban feeders likely include commercial consumers. While the commercial consumption in rural areas is low enough to be neglected (about 100 million kWh in 2012-13), the urban commercial consumption is high (about 1800 million kWh). We do not know how much of this is through the commercial feeders alone and how much through the regular feeders.

Examples of a rural and an urban feeder from the SCADA dataset have been provided in Figures 3-2 and 3-3. The figures show the loads served in these feeders as a function of time of day. The rural supply consists of times of single (in green) and three (in red) phase supply, as already discussed. Three phase supply is typically limited to 4-6 hours

[5] If the feeders in the dataset were not part of the list, they were classified into one of the types using the following criteria: 1) based on keywords within the feeder names like "town", "waterworks", etc. and 2) based on whether periods of single phase and three phase supply were provided, this happens only for rural feeders

at not necessarily specified times during the day. Evening supply is usually restricted to single-phase[6]. The blank spaces within the figures correspond to times of no supply.

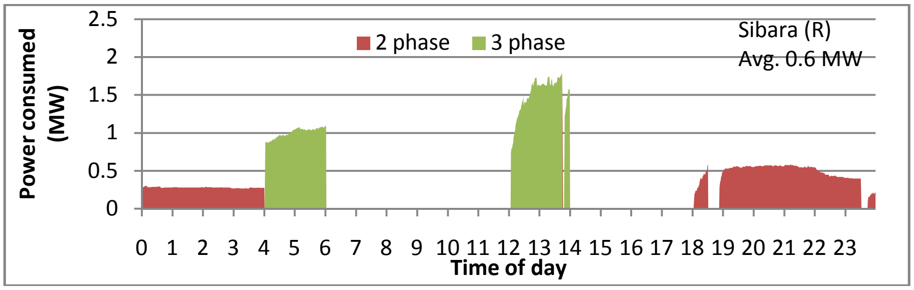

Figure 3-2: Loads with single and three phase supply for an example rural feeder in Chitradurga substation from September 26 2012

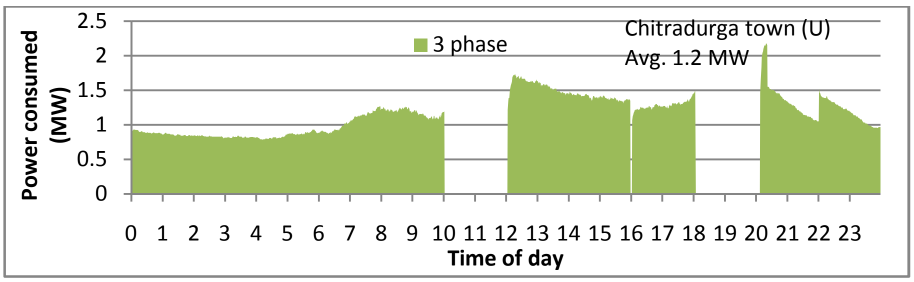

Figure 3-3: Loads with single and three phase supply for an example urban feeder in Chitradurga substation from September 26 2012

The distribution of hours of supply availability for three days from each of rural, non-Bangalore urban and Bangalore urban zones are shown in Table 3-4. From this table and Table 3-5, the motivation for this study is clear. The rural areas received significantly poorer supply than Bangalore urban; and among the urban feeders, non-Bangalore consumers receive worse supply. Rather surprisingly, the non-Bangalore urban consumers receive supply that is not significantly different from the rural feeders in the evenings.

[6] More correctly, evening supply to the feeder could be one phase, or two phases (for load balancing purposes) with an individual consumer receiving only one phase. Hence, this is still termed as single phase.

Table 3-4: Summary statistics on supply in the three types of feeders

	26 September '12 Mean (St.Dev.)	Median	26 December '12 Mean (St.Dev.)	Median	15 April '13 Mean (St.Dev.)	Median
Rural						
24 hours	10.9 (3.9)	11.2	13.2 (3.9)	12.0	13.6 (4.3)	13.8
3 phase all day	5.3 (3.8)	4.4	5.0 (4.0)	4.0	7.3 (5.5)	5.6
6pm-10pm	2.3 (1.1)	2.4	3.7 (0.7)	4.0	3.2 (1.1)	3.6
Non-Bangalore urban						
24 hours	15.8 (3.7)	15.8	20.8 (3.1)	21.0	19.3 (6.3)	21.9
6pm-10pm	2.6 (0.9)	2.4	3.7 (0.7)	3.9	3.2 (1.2)	3.7
Bangalore urban						
24 hours	22.3 (3.8)	23.9	22.6 (3.5)	24.0	22.1 (1.2)	3.7
6pm-10pm	3.8 (0.7)	4.0	3.8 (0.6)	4.0	3.4 (1.0)	4.0

Table 3-5: Results of two sample t-tests (with unknown variance) for evening supply in the three categories of feeders- absolute value of t statistics with null hypothesis as equal means (- p<0.01, *- p<0.05)**

	Sep 26 '12	**Dec 26 '12**	**Apr 15 '13**
Rural and Non-Bangalore Urban	2.9**	0.4	0.5
Rural and Bangalore Urban	38.3**	4.5**	4.1**
Non-Bangalore and Bangalore Urban	15.7**	2.6*	1.4

With the rural areas, one factor affecting the availability statistics is the restricted hours of 3 phase supply in the mornings. One difficulty with discussing load shedding for pump-set use is that the schedule itself is not hour-specific. The utility targets a certain number of hours spread over the day. Hence, the load shedding estimates are also not hour specific. Given the research questions in this study, the analysis is restricted to evening hours alone and all demand and load shedding estimates in rural areas are restricted to consumption with single phase alone, in order to avoid pump-set consumption.

3.3 Research questions

How does the load shedding compare?

The first piece of the analysis is to prepare a thorough set of estimates for the load shedding. Within the bounds of our problem framing (chiefly, non-commercial feeders, evening demand, non-agricultural rural consumption), we estimate the absolute and percentage load shedding in each of the feeders. The first set of comparisons in our analysis will be based on the load shedding levels.

Load shedding estimates are made by interpolating across times with no supply. The interpolations are made within 15 minute blocks for each feeder, if possible. If there was no supply over a given 15 minute block, the average demand (in MW) between 6-10PM for a given month is used to interpolate. To avoid 3 phase pump-set usage, we use a multiplier if the supply provided in the feeders is of 3 phase. The multipliers are feeder and season specific if there is any information available for loads served with single and three phase supply in the evenings. Otherwise, generic multipliers are used. On average, single-phase consumption was 20-30% of the consumption with three-phase. In other words, the three-phase specific loads, primarily due to pump-sets, were 3-4 times that of the single phase loads.

Is the tariff subsidy an adequate explanation for the load shedding disparity?

The next question is about the equity in such a load shedding arrangement. We compare tariff based transfers with load shedding transfers, from or to each of the three residential categories. The directions of the net transfers are of primary interest. The magnitudes of the net transfers could have additional policy implications in terms of tariff setting, and in assessing the economic argument for solutions to reduce such an inequity in load shedding.

Using the uniform tariffs, the tariff based transfers are computed for each of the consumer categories for the evenings of the nine days. Similarly, based on the load shedding estimates and benchmarking to the Bangalore-urban load shedding level, the load shedding based transfers are estimated for the nine days. The net transfers are just the sum of these two, and are computed for the three consumer categories for the nine days. We then use KPTCL estimates for demand and load shedding for the months May 2012- April 2013 to determine how representative each of these nine days is and use the resulting multipliers to make annual estimates via extrapolations.

How viable are the solutions?

Finally, we explore the alternatives available to reduce load shedding. There are two straightforward interventions: uniform percentage load shedding for all feeders, and additional procurement of peak power (through short term purchases, for instance) to avoid load shedding entirely. Several intermediate approaches exist in the continuum between these two extremes.

One way of facilitating such an intermediate approach is providing current limited supply as opposed to outright blackouts. Using certain kinds of smart meters, the utility could restrict the current drawn and hence, restrict the usage by the consumer. The smart meters would hence allow for uninterrupted (but occasionally limited) supply, which would remove the need for backup energy or battery storage. The installed costs are higher than for conventional static meters, but if these costs are picked up by a range of stakeholders besides the users installing these, the cumulative willingness to pay for it may make it a viable option. The stakeholders include consumer categories that benefit from the load shedding arrangement (making the quantities of the net transfers relevant), and the central government's ministry of petroleum and natural gas that could find an alternative channel for the very large kerosene subsidies.

3.4 Limitations

The analysis is in aggregate for entire consumer categories, and hence multiple points of heterogeneity at the feeder level are ignored. For instance, among both rural and urban feeders, some feeders will likely be load shed much more than others systematically. We are unable to differentiate between these due to the limited number of days of data. We also do not have the consumer mix at the feeder level. With the consumer data, we could have investigated whether feeders with consumers with low demand levels were load shed more (the utility maximizing revenues) or less (the utility minimizing number of consumers impacted) than those with high demand consumers.

On a related note, this analysis creates a dichotomy between urban and rural consumers. At the aggregate level, and even in terms of BESCOM's load shedding schedules which make a similar distinction, these are reasonable. However, it is likely that there is a continuum and that there will be pockets in urban areas (possibly, low income) that are load shed much more than others, and pockets in rural areas (with administrative capitals of local governments or with powerful local industrial or political lobbies) that receive good supply.

When we monetize the transfers, non residential loads are ignored because of the framing of the problem in this analysis. However, the supply to commercial or agricultural consumers will certainly impact the utility's finances, and this dimension is not included.

While we do attempt to understand the representativeness of the nine days of data, the discrepancies in the load shedding numbers demonstrate the difficulty in this exercise. To some extent, the direction of net transfers is of principal interest and the robustness of our results along that dimension can be verified more easily than the magnitudes themselves.

Another concern is about the representative of the BESCOM region itself. It is possible that the load shedding patterns will be very different in regions lacking a large metropolitan city like Bangalore. To help answer this question, we investigate supply availability for another part of Karnataka served by the Hubli ESCOM, with somewhat more limited data. The results are expounded in Appendix 3-1, but the differentiation remains between cities (now much smaller) and rural areas.

Finally, while computing the load shed transfers, we are implicitly assuming that there is power supply that is available which must only be procured at a certain higher than average cost. This is not always true.

4 Results

4.1 Load shedding estimates

Based on the steps outlined already in Section 3, the load shedding estimates for the three categories of feeders are summarized in Table 3-6. Briefly, the true demand is estimated using interpolations within 15 minute blocks between 6-10 pm. In the rural feeders, the demand is restricted to what it would be with single phase supply, that is after removing (most of) the agricultural load. The estimates are in terms of energy consumption (in MWh).

Table 3-6 Estimated aggregate demand and load shed in rural, small town and metro feeders from the 9 days

		25 Sep '12	26 Sep '12	27 Sep '12	25 Dec '12	26 Dec '12	27 Dec '12	14 Apr '13	15 Apr '13	16 Apr '13
Karnataka evening load shed % (KPTCL estimate)		16%	18%	17%	6%	7%	9%	5%	5%	5%
Rural	Demand (MWh)	3500	3600	2900	3200	3200	3300	2200	2000	2100
	Load shed (MWh)	1640	1540	1090	240	270	270	290	440	390
	Load shed %	46%	42%	38%	7%	8%	8%	13%	21%	18%
Non-Bangalore urban	Demand (MWh)	900	900	900	800	800	800	700	800	800
	Load shed (MWh)	340	330	190	60	100	90	120	160	150
	Load shed %	38%	36%	21%	8%	13%	11%	16%	21%	19%
Bangalore urban	Demand (MWh)	4300	4400	4200	3700	3700	3700	4000	4200	4300
	Load shed (MWh)	200	200	110	30	60	50	390	550	510
	Load shed %	5%	5%	3%	1%	1%	1%	10%	13%	12%
Estimated BESCOM Load Shed % (rural and urban feeders only)		25%	23%	17%	4%	6%	5%	11%	16%	14%

In general, rural feeders face a higher percentage of load shedding than the urban feeders. Non-Bangalore urban feeders, however, are significantly worse off than Bangalore urban, and surprisingly, are load shed more than even rural feeders in the evenings. Also worth noting is how the absolute load shed amounts from the rural feeders exceeded that from Bangalore urban on six of the nine days. In terms of load shed per consumer (in kWh), the rural areas are higher on all 9 days.

The differences day to day are low, while season variations are much higher. This is partly due to not just seasonal demand, but also seasonal supply variations. Importantly, April 2013 was just before an election, and it's possible that there was a directive to reduce the load shedding in rural areas, and hence the higher load shed from Bangalore.

Interestingly, the estimates do not seem to be highly correlated (correlation coefficient of about 0.68) with the reported state-level load shedding in the evening of the nine days. A clear one-to-one correlation is not necessary because the load shedding in BESCOM depends on whether it was over-drawing or under-drawing relative to its allocated shares of the state supply. Also, the entire demand for the state includes high voltage (especially industrial) feeders, which are not part of the data set. It is unknown how these are shed vis-à-vis residential feeders.

4.2 Fair tariffs

The first objective for this analysis is to estimate the uniform or fair tariff structure. Assuming for now, that the technical losses are higher, the uniform tariff structure (and thence, the tariff based transfers) can be derived using the following steps. First, we assume that the rural consumers are charged identically to their urban counterparts. This would imply higher revenues to the utility and hence, the next step would be to deflate the tariffs to ensure that the aggregate revenues to BESCOM remain unaffected. We ensure that the aggregate revenues from each of the fixed and the variable components remain unaffected. This additional precaution will be self explanatory shortly. Next, we account for the higher marginal costs of supply in rural areas due to the higher *technical* losses using a cost-plus approach. Hence, the "uniform" tariffs obtained in this manner will be such that the urban consumers actually pay lower than their rural counterparts do in any given consumption slab (tier). This is the only difference needed between rural and urban consumers since our calculations for load-shedding will be at the margin, and higher fixed costs of rural supply are treated as sunk costs.

Table 3-7 outlines the steps and the results of the calculation. KERC approved tariffs for 2012-13 are used along with slab-wise consumption data from the following year (2013-14) from BESCOM's tariff order filing to KERC (BESCOM's D21 filing in 2013 to KERC).

Table 3-7 Calculating 'uniform' tariffs

		Tariffs charged 2012-13		Step 1: If rural consumers paid urban tariffs	Step 2: Keeping aggregate fixed and variable charge revenues unchanged*		Step 3: Adjusting for higher marginal costs of supply in rural feeders (but keeping aggregate variable) **	
		Rural	Urban	Rural	Rural	Urban	Rural	Urban
Fixed charges	1st kW	15	25	25	23	23	23	23
	Additional kW	25	35	35	33	33	33	33
Energy charges	0-30	2.2	2.3	2.3	2.3	2.3	2.4	2.3
	30-100	3.2	3.5	3.5	3.5	3.5	3.6	3.4
	100-200	4.3	4.6	4.6	4.5	4.5	4.7	4.5
	>200	5.1	5.6	5.6	5.5	5.5	5.7	5.5
Average revenue per unit from fixed charges (Rs./kWh)		0.5	0.4	0.9	0.8	0.4	0.8	0.4
Average revenue per unit from variable charges (Rs./kWh)		3.0	3.8	3.2	3.2	3.7	3.4	3.7

Assumptions:
Data on consumptions within each slab are from the D21 filings by BESCOM for 2013
*- The deflating factor to keep the revenues unchanged is applied uniformly to all the slabs
** Inputs- Average cost of power purchase: Rs. 2.5/kWh, Transmission loss- 5%, Distribution loss- 10% (Urban), 15% (Rural)

The subsidies are computed as the difference between the actual tariffs and the fair tariffs. Based on this approach, the rural consumers are estimated to receive subsidies of Rs.0.3/kWh through fixed charges, and Rs.0.4/kWh through energy charges. In comparison, the urban consumers (no distinction made between metro and small town) provide negligible subsidies on fixed charges and less than Rs.0.1/kWh on energy charges per kWh. Factoring in the average consumption in urban areas being more than a factor of 4 than in rural areas, the average rural consumer receives a subsidy of about Rs.18/month, and the average urban consumer provides a subsidy of about Rs.7/month. (These net to zero because there are about 2.5 times more urban consumers than rural)

4.3 Net transfers- tariff and load shedding based

Our estimates of both kinds of transfers are summarized in Table 3-8. For all nine days, non-Bangalore urban consumers are net contributors, and Bangalore urban consumers are net beneficiaries. For the rural consumers, the direction of the net transfer depends on the load shedding level- as the outages become worse, the load shedding transfers increasingly dominate the tariff based transfers.

Table 3-8 Tariff and load shedding based transfers (Negative sign indicates that the transfer is to the category, and positive sign implies the transfer is from the category. Color coding of green indicates the net transfer is from the category, and red that the net transfer is to the category.)

	25 Sep '12	26 Sep '12	27 Sep '12	25 Dec '12	26 Dec '12	27 Dec '12	14 Apr '13	15 Apr '13	16 Apr '13
Rural									
Subsidies on variable charges (Rs./day/consumer)	-0.3	-0.3	-0.2	-0.4	-0.4	-0.4	-0.3	-0.2	-0.2
Subsidies due to avoided costs (Rs./day/consumer)	3.8	3.5	2.6	0.5	0.6	0.6	0.2	0.4	0.4
Non-Bangalore urban									
Subsidies on variable charges (Rs./day/consumer)	0.05	0.05	0.06	0.06	0.06	0.06	0.05	0.05	0.05
Subsidies due to avoided costs (Rs./day/consumer)	2.30	2.23	1.23	0.43	0.72	0.59	0.33	0.47	0.43
Bangalore urban									
Subsidies on variable charges (Rs./day/consumer)	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.05
Subsidies due to avoided costs (Rs./day/consumer)	-2.06	-1.93	-1.37	-0.31	-0.37	-0.36	-0.13	-0.27	-0.23

These results will be sensitive to some of the inputs and assumptions, and we will elaborate in the next section.

KPTCL publishes its estimates on the aggregate state level load served and scheduled and unscheduled load shed. These are available online as daily datasets, which were extracted and compiled for the months of May 2012- April 2013. Figures 3-4 and 3-5 summarize KPTCL's estimates of demand and load shedding. The 9 days from our data set have been highlighted in the two graphs. The last week of September 2012 seems to have been atypical[7] in terms of load shedding, but the December and April data seem to be broadly representative.

[7] Newspaper reports from the last week of September 2012 cite multiple reasons for the power shortages including coal shortages, maintenance shutdowns of the Raichur thermal power plant, and unanticipated low win power generation (Indian Express, Sep 27 2012; Deccan Herald Sep 29 2012; Times of India Sep 30 2012)

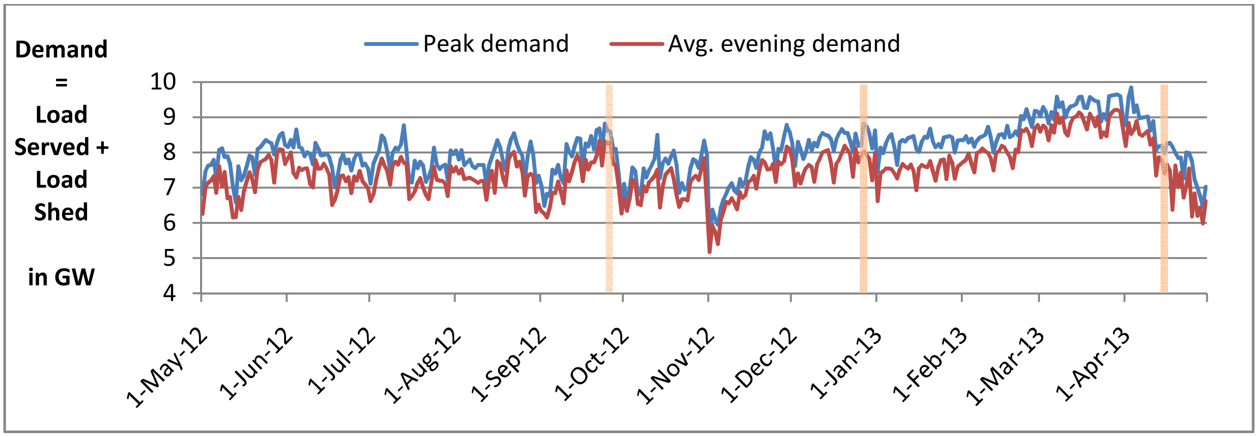

Figure 3-4: Variation of Karnataka state demand over the course of the year (Evening defined as 6-10PM)

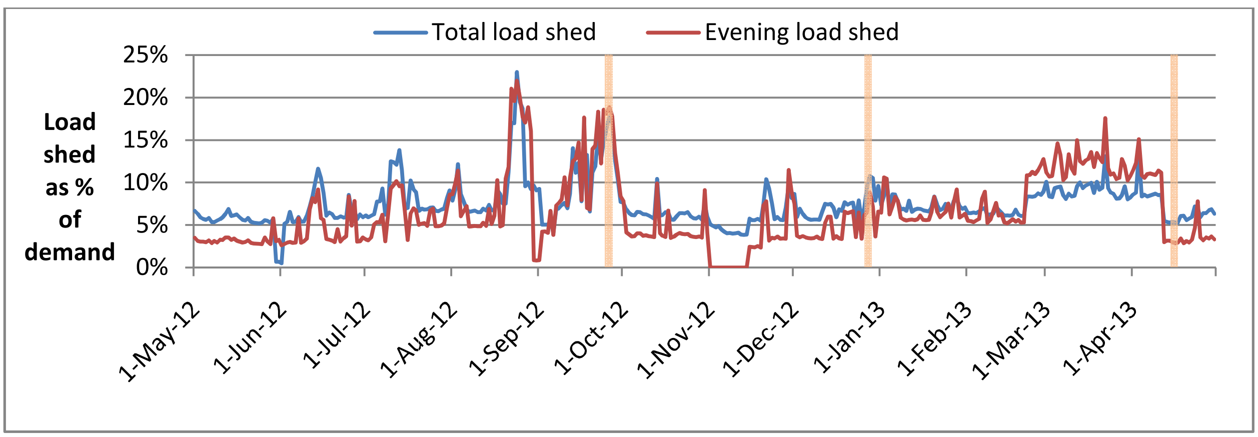

Figure 3-5: Variation in load shedding over the course of the year (Evening defined as 6-10PM)

In order to weight our estimates, each of the 365 days are classified into one of the 9 day- types, based on which of these 9 days is the most similar in terms of factors that could affect the load shedding schedule. The aggregate load shedding levels are likely to be highly correlated with the overall levels of load shedding in the BESCOM area, as well as the skew towards R and NBU feeders. Also, we may want to distinguish between scheduled and unscheduled load shedding (although we have been unable from doing so in the analysis of the SCADA dataset). Another factor that could affect the load shedding pattern is the evening or peak demand. The classification method should be able to combine multiple factors. We use a method wherein the day that has the smallest normalized squared distance in the n-dimensional space is found. That is, if the classification criteria belong to the set C, for each day *i* in the year, we find the day *j* from our dataset that minimizes

$$\sum_{c\in C} \frac{(x_{i,c} - x_{j,c})^2}{(x_{i,c} - X_c)^2}$$

where, X_C is the mean of $x_{j,C}$.

The results will depend on the classification criteria used. Table 3-9 summarizes the results from this classification procedure.

Table 3-9: Results of the classification process

Classification criteria	Number of similar days 25 Sep ‘12	26 Sep ‘12	27 Sep ‘12	25 Dec ‘12	26 Dec ‘12	27 Dec ‘12	14 Apr ‘13	15 Apr ‘13	16 Apr ‘13
A. Unscheduled and scheduled load shed in the evening	4	10	14	134	41	24	36	21	78
B. Unscheduled and scheduled load shed, and demand in the evening	9	2	11	98	43	18	14	143	24
C. Unscheduled and scheduled load shed in 24 hours	36	3	5	140	61	73	30	11	3
D. Total load shed and demand in the evening	36	17	67	14	60	165	3	0	0

Based on multipliers derived from the results in Table 3-9, the annual load shedding and net transfers are provided in Tables 3-10 (normalized to consumer-year) and 3-11 (aggregate). These four criteria provide a range for likely annual reality, and we do not aim to average these numbers.

Table 3-10 Normalized estimates for load shed and net transfers

Classification criteria	Annual load shed transfer (Rs. per consumer-year)			Annual net (load shed + tariff) transfer (Rs. per consumer-year)		
	R	NBU	BU	R	NBU	BU
A. Unscheduled and scheduled load shed in the evening	240	200	-140	120	220	-120
B. Unscheduled and scheduled load shed, and demand in the evening	230	200	-140	120	220	-120
C. Unscheduled and scheduled load shed in 24 hours	320	260	-190	190	280	-170
D. Total evening load shed and demand	510	350	-290	380	370	-270

Table 3-11 Aggregate estimates for load shed and net transfers

Classification criteria	Annual load shed transfer Aggregate (in Rs. Crores[#]) R	NBU	BU	Annual net transfers Aggregate (in Rs. Crores) R	NBU	BU
A. Unscheduled and scheduled load shed in the evening	40	11	-51	20	12	-45
B. Unscheduled and scheduled load shed, and demand	38	11	-49	20	12	-44
C. Unscheduled and scheduled load shed in 24 hours	54	14	-68	32	15	-62
D. Total evening load shed and demand	85	19	-104	64	21	-98

[#] 1 crore = 10 million

Irrespective of the classification criteria used, the rural consumers are consistently found to be net contributors to the system. Not surprisingly, the non-Bangalore urban consumers are net contributors too, and Bangalore urban net beneficiaries. Since there are positive transfers from the non-Bangalore urban consumers based on both tariffs and load shedding, the net transfers from them are higher than from the rural consumers. The magnitude of the net transfers will be sensitive to some of the inputs as shown in Figure 3-6. The results are reasonably consistent with distribution losses. As would be expected, the (avoided) procurement costs at peak demand are a sensitive input. The net transfers are positive from rural consumers, only if the peak procurement costs are greater than Rs.5/kWh. The results are not sensitive to the distribution losses in rural areas.

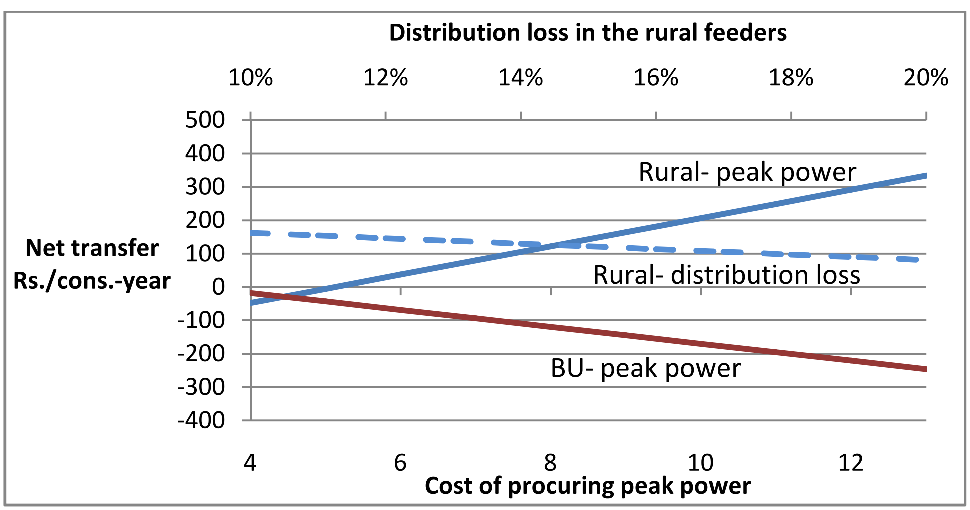

Figure 3-6: Sensitivity analysis of normalized net transfers (using scheduled and unscheduled load shedding, and demand in the evening)

Using state peak deficits, total rural residential consumption, and the rural residential demand as a fraction of peak demand, we can make rough estimates of state level and national multipliers to extrapolate the transfers from BESCOM level. Appendix 2 elaborates on the assumptions and the estimates. Based on these methods, the national multipliers are found to be in the range of 30x- 50x. Using the results with classification criteria B in Table 3-11, the national load shed transfers from rural residential consumers are in the range Rs. 1,200- 2,000 crores/year, and the net transfers are estimated to be between Rs. 600-1,000 crores/ year.

How significant are these numbers? The annual expenditure on electricity for rural consumers in the BESCOM range is on average Rs. 1150. The total cross-subsidy that the rural consumers receive from industrial consumers in comparison to the average cost of supply (as assumed by the KERC in the absence of better data) is about Rs. 450/ year. A load shed transfer of Rs. 240-510/ rural consumer-year is a non trivial amount, especially when we note that this transfer does not include the inconvenience costs due to outages and the costs of very inefficient backup lighting (through kerosene lamps typically) for the consumer. We will take this up further in the next section when discussing the economics of solutions.

5. One possible solution- Current limited supply

The analysis in the preceding sections demonstrates that the supply in the rural feeders is not only poorer than in the city feeders, but is inequitable even within a restricted economic profitability sense. The question then is about how the supply could be improved, while keeping the utility's finances in mind. This section is written with a focus on rural feeders. However, as we have seen, the non-Bangalore urban feeders perhaps have a stronger case in their favor for better supply. It is expected that any policy approaches that are viable for rural feeders will be even more applicable in the non-Bangalore urban feeders.

Two extreme approaches that are available are to load shed all feeders uniformly or to eliminate load shedding altogether by procuring additional power. There is, of course, a continuum between these. For instance, the load shedding could be lower and predictable. Instead of days with 2-3 hour outages during the evening followed by days with close to uninterrupted supply, schedules that are consistent through the week, well advertised, and at predictable times, would be preferable. Here, we explore the economics of the relatively novel notion of current limited supply as opposed to outright blackouts. That is, provided uninterrupted supply but with occasional restrictions on power (that is, in kW) consumption. These can be facilitated by replacing the conventional single phase static meters with smart metering technology. Where the static meters cost about Rs.800-1100, smart meters in the market today cost about Rs. 2,000-3,000, or slightly more depending on features. Hence, we would need to work out the viability of not only the incremental power procurement, but the installed costs of smart meters themselves. These costs have to be compared with the cumulative willingness or obligation to pay from the multiple stakeholders.

For the rural residential consumer, the willingness to pay will be a combination of two factors: avoided interruption costs and savings in expenditure on backup. Backups including kerosene lighting are not only more expensive per unit service delivered (say, on a light output-time in klm-h), but are also more expensive even per unit time used. Hence, there are net savings with even limited electricity supply. Kerosene lighting is the default choice for backups during outages, and the kerosene is subsidized by the central government. A reduction in kerosene consumption would be welcome to the central government too. Over the short term, this could represent a more effective channeling of subsidies for lighting fuel. Table 3-12 gives a sense of the costs of using electricity vis-à-vis conventional backup sources.

Table 3-12: Costs of lighting with and without electricity

	Cost of 1 hour of usage (Rs.)	**Lamp output (lm)**	**Cost per unit service delivered (Rs./klm-h)**
60 W incandescent - with grid power	0.18	720	0.25
15 W CFL - with grid power	0.05	750	0.06
Two Kerosene lamps	0.4 (+0.6 subsidy)	20-200#	2-20
Candle	5	10-15	330-500

#- Light output from kerosene lamps can vary within a large range depending on quality of lamps and factors like the wetness of the wick, and soot accumulation (Apte et al., 2007; Mills, 2003)

The interruption costs present a trickier problem for the following reasons. One, it is difficult to monetize the inconvenience to the consumers. Two, an abstractly defined interruption cost may not get translated into willingness to pay for the smart meter. Three, there is the question of whether all these interruption costs should get reflected in the charges to the consumer, or whether there should be a smaller, more equitable amount.

The interruption costs are estimated as loss in consumer surplus using the approach developed in Harish et al. (2014). Briefly, the method involves estimating the monthly demand curve for an "average" rural household in the country, and makes a series of assumptions regarding the household's electricity usage patterns. The principal assumptions are that lighting is the only end use for which there is significant willingness to pay, that much of the value of the electricity is derived in a few hours of high demand, and that within these few hours there is a certain flexibility in rescheduling activities that require electricity (and more specifically, lighting) in the order of their priority. The interruption costs are derived from known willingness to pay based on price elasticity of electricity consumption and the amortized costs of solar lanterns and lighting systems. That this willingness to pay will get reflected in the smart meters is a non-trivial assumption.

How much of this willingness to pay for reliable electricity ought to get reflected as the consumer's share of the smart meter's installed costs? The load shedding that the consumer faces could be divided into two components- an equitable level up to which the consumer could be reasonably expected to pay, and an additional unfair amount for which the compensation must come from the beneficiaries of the current arrangement. The rural household's interruption costs for the load shedding level could be used as a benchmark for their willingness to pay for the smart meter. And the net transfer from this consumer could be recovered in some manner from the urban residential consumers.

With the help of smart meters, the utility could schedule current limited supply in multiple ways. The approach we consider is to keep the schedule identical to what it is currently, and procure incremental power to provide current limited supply instead of outright blackouts to the rural feeders in the evenings. The costs of procurement and supply will exceed the marginal tariffs from the rural residential consumers. Hence, this component will reduce the cumulative willingness to pay for the meters.

In sum, the cumulative willingness to pay for the meter is the sum of

1. The net savings due to substitution of kerosene (backup) lighting and a portion of the avoided interruption costs for the rural households,
2. The subsidies provided by the central government for kerosene lighting (i.e. an alternative routing of existing support)
3. The net transfers (tariff and load shedding) from the rural residential consumers, recompensed by the utility perhaps through incrementally higher tariffs for the Bangalore urban consumers
4. Less the unrecovered costs of incremental power procurement for the utility

Table 3-13 provides a range of estimates for the annual willingness to pay for the meter through these stakeholders. The total discounted willingness to pay for the meters are also estimated, if these are spread over 10 years at a discount rate of 10%. This calculation assumes for simplification that the load shedding schedules will remain unchanged over time, as will the real costs of procurement.

Table 3-13: Economics of the current limiter

	Low	Likely	High
Assumptions/ inputs			
Annual evening load shedding %	14%	16%	19%
Number of kerosene lamps used	2	3	3
Fuel consumption (in liter/h)	0.01	0.01	0.02
Cost of peak power (Rs./kWh)	12	8	6
Kerosene consumed for backup lighting (l/ year)	4	7	17
(R. Cons.) Savings in kerosene expenditure (Rs./year)	80	140	330
(Central Govt.) Savings in kerosene subsidies (Rs./year)	120	210	500
(U. Cons.) Net transfers (Rs./year)	120	120	390
(R. Cons.) Avoided interruption costs (Rs./year)	290	340	420
Current limited load- 100 W			
(BESCOM (Less) Unrecovered costs (Rs./year)	220	150	110
(R. Cons.) (Less) Increase in electricity expenditure (Rs./year)	60	70	80
Cumulative stakeholder willingness to pay/ year (Rs.)	330	590	1450
Willingness to pay for the smart meter (Rs.)	2,000	3,600	8,900
Current limited load- 50 W			
(BESCOM) (Less) Unrecovered costs (Rs./year)	110	75	60
(R.Cons.) (Less) Increase in electricity expenditure (Rs./year)	30	35	40
Cumulative stakeholder willingness to pay/ year (Rs.)	470	700	1,500
Willingness to pay for the smart meter (Rs.)	2,900	4,300	9,500

Given that smart meters in the range of Rs. 4,000 are already available in the market, the analysis suggests that we are already in the ballpark in terms of viability. It is to be noted that some of the estimates used here are very conservative. The kerosene consumption estimated bottom up here is in the range of 4 to 17 l/ year, while the subsidized amounts usually (based on NSS 2011-12) purchased is in the range of 24 to 36 l/year (10^{th} and 90^{th} percentiles). Also, this analysis is being done based on *average* levels of load shedding. A solution like current limited supply which goes to the consumer level is probably ideal for feeders that receive particularly poor supply. Here, the kerosene expenditure as well as the net transfers will be significantly higher than on average, as would probably the consumer's true willingness to pay for the solutions.

The current limited supply case also seems to be preferable to the other alternatives of uniformly load shedding to rural and urban feeders, or providing uninterrupted supply if we consider all three principal stakeholders- the rural and urban residential consumers, and the utility. Using the inputs for the likely case from table 3-13 and 50 W supply, the unrecovered costs for the utility if uninterrupted supply is to be provided to rural areas by procuring additional power are of the order of about Rs 400/ rural residential consumer-year in comparison to the about Rs. 70/ rural residential consumer-year with current limited supply. The rural residential consumers themselves are better off, but the very high unrecovered costs may leave all the consumers in the BESCOM areas ultimately worse off. With uniform load shedding, the unrecovered costs for the utility are very similar to the current limited case (Rs. 60/ rural residential consumer-year with uniform load shedding to the Rs. 70). However, urban residential consumers, whose welfare is unaffected with the current limited supply, are worse off. The inconvenience costs of rural consumers are equal by design with their share of the smart meter costs

6 Discussion

This study highlights firstly the importance of using the data we have at our disposal in making better estimates of load shedding, and in developing more appropriate metrics to monitor supply reliability. Due to constraints in data available to us, we are unable to determine whether some feeders are always load shed much more than others. However, we do know though that on any given day many feeders are load shed more than on average. This is almost certainly poor planning as the inconvenience to the consumer due to outages over the course of a week is not likely to be linearly additive.

The study chooses one possible framing of the problem where there is a tradeoff between the subsidies (or the viability of the utility) and supply reliability. This tradeoff is based on the rationale provided by KERC for charging differential tariffs to rural and urban consumers. Such a formulation may not entirely reflect the utility's planning though. Load shedding schedules, especially at the substation level, are largely ad hoc. Hence, systematization of the scheduling processes and the chain of command are essential prerequisites. While recognizing the problem of the supply deficits, load shedding needs to be better planned, communicated, monitored and recognized as a short term solution.

Any discussion about the inequity in electricity services to rural and urban households in India is incomplete without noting the very poor levels of access in rural India. It could be argued that the net transfers estimated here represent a very conservative lower bound, given that costs of providing access to unelectrified rural households has been omitted from the analysis. There is a massive transfer through fixed costs because the overall system today is artificially cheaper by not serving the (mostly rural) unelectrified consumers.

One of the important results from this study is the neglect of the smaller town and cities in this region. Unlike in the villages, the partial defense of having instituted tariff differentials does not exist either. The neglect of smaller towns represents a broader skew of the state's investment and policies towards the metropolitan areas, which has led to a lopsided and increasingly unsustainable urbanization. The scale of migration to large cities which offer better economic opportunities and public services has resulted in dangerous levels of air pollution, congested roads and living areas, deteriorating law and order, and unchecked exploitation of groundwater resources.

What are the policy implications of this analysis? One way of interpreting the results is that the tariff differentials as they exist do not sufficiently account for the load shedding arrangement and as such, the *tariffs* need to be revisited and that (all else equal), the Bangalore urban consumers must pay more to reflect the better quality of service they receive. In our opinion, this must not be the solution or the take-away. Outages of the order that exist in rural India are indefensible, and while the constraints in supply must be acknowledged, alternative routes to reduce the impact of these should be considered urgently. These include at the most basic level, higher predictability in the outages -

through more transparent, well advertised in advance schedules- such that the consumers can plan for them. These could also include incentivizing the use of backup lighting like solar lighting systems which use an alternative, consumer owned source of generation to charge the batteries for use when needed. And alternatively, as explored in some detail here, we could explore new technology like smart meters to facilitate uninterrupted, but occasionally current limited supply.

While exploring the economics of the smart meters, our analysis is at the average levels of load shedding. A policy intervention on the other hand could instead start by identifying feeders which are especially vulnerable to frequent outages. The threshold of 'vulnerability' could be identified in a manner similar to our approach here and factor in the consumer willingness to pay and the subsidies available from the central and state governments. Once again, we stress on the need to putting the SCADA data to good use in monitoring the feeders, developing better metrics for reliability and actively intervening in underserved regions.

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Appendix 1- Rural-urban differences with no metropolitan city

It is possible that BESCOM is a relatively special case due to the distorting effect of having a large metropolitan city like Bangalore. To verify that the general rural-urban trend is valid, we used data from the distribution utility serving 8 districts in northwestern Karnataka in the Hubli-Dharwad region. Hubli ESCOM (HESCOM) has about 1 million each of rural and urban residential consumers. Tariff structures are very similar to those in BESCOM. We have data for 167-184 urban and 625-700 rural feeders from the 172 substations (the files for another 137 substations had entry errors with no valid data). Supply availability statistics for rural and urban feeders in our sample are given in Table 3-A1.1.

Table 3-A1.1: Mean (St.Dev) for supply availability in the HESCOM region. Absolute value of t statistics from a two sample t-test with unknown variance with null hypothesis as equal means (- p<0.01)**

	25 Sep ‘12	26 Sep ‘12	27 Sep ‘12	26 Dec ‘12	27 Dec ‘12
Rural					
24 hours	9.7 (4.0)	9.6 (4.2)	10.2 (4.6)	12.3 (4.3)	12.7 (4.5)
3 phase all day	6.1 (4.4)	6.1 (4.5)	6.6 (4.9)	7.7 (5.5)	8.2 (5.6)
6pm-10pm	2.5 (0.9)	2.4 (1.0)	3.3 (1.0)	3.1 (0.7)	3.1 (1.0)
Urban					
24 hours	19.8 (3.2)	20.7 (3.7)	20.8 (3.7)	22.2 (4.2)	22.5 (3.7)
6pm-10pm	3.5 (0.7)	3.4 (0.8)	3.3 (1.0)	3.8 (0.5)	3.9 (0.4)
t-statistic	15.2**	14.3**	10.9**	13.6**	16.8**

Supply availability in the rural and urban feeders are significantly different during the evenings. The only catch is that the biases due to the substations with no data are unknown.

Appendix 2- National estimates

To make order of magnitude estimates of the transfers at the national level, we need to estimate multipliers that reflect the factors that lead to the inequity in load shedding.

$$\textit{Load shed transfer from rural households nationally (Rs. per day)}$$

$$= \sum_{States} \{\textit{Avoided costs of procurement by discriminatory load shedding}\}$$

$$= \sum_{States} \left\{ \begin{matrix} \textit{State rural} \\ \textit{residential demand} \end{matrix} \; \begin{matrix} X\,(\textit{Actual rural load shed\%} - \textit{Actual urban load shed\%}) \\ X(\textit{Cost of rural supply at peak} - \textit{Marginal tariff}) \end{matrix} \right\}$$

A simplifying assumption is that gap between 'true' marginal costs of supply at peak hours to rural areas and the marginal tariffs are broadly similar across the country. Hence, we need to consider only the effect of supply deficits on the differences between urban and rural load shedding in each state, and weight these by the size of the rural demand. The differences in urban and rural load shedding will probably be closely related to the overall load shedding percentages, and in turn, to the state peak deficits for which we have official estimates. Hence, we could assume,

$$(\textit{Actual rural load shed\%} - \textit{Actual urban load shed\%}) \propto \textit{Actual overall load shed\%}$$

$$\propto \textit{State peak deficit\%}$$

In addition, states where the rural residential demand makes up a higher fraction of the overall peak may have lower disparities (with fewer consumers to treat preferentially). We could use this to derive a lower bound of the national multipliers.

$$\textit{National multiplier}$$

$$= \sum_{States} \left(\begin{matrix} \dfrac{\textit{State rural residential demand}}{\textit{BESCOM rural residential demand}} X \dfrac{\textit{State peak deficit\%}}{\textit{Karnataka peak deficit\%}} \\ \left\{ X \dfrac{\textit{Fraction of BESCOM peak from rural}}{\textit{Fraction of state peak from rural}} \right\} \end{matrix} \right)$$

Based on this we obtain multipliers provided in Table 3-A2.1 giving a national multiplier of 30- 50.

Table 3-A2.1: Estimating multipliers for the transfers

State	Upper bound-peak deficits	Lower bound-peak deficits/ rural as fraction of state peak
Andhra Pradesh	13	5
Punjab	7	5
Tamil Nadu	6	3
Uttar Pradesh	4	4
Karnataka	3	3
Maharastra	3	2
Himachal Pradesh	3	1
Jammu & Kashmir	2	1
Kerala	2	1
Haryana	2	1
Orissa	1	1
Madhya Pradesh	1	1
Bihar	1	1
Rajasthan	1	1
Chattisgarh	1	0
All India	**50**	**30**

Chapter 4: Modeling household demand for electricity services with unreliable supply- extensions

Abstract

The consumer demand for electricity is derived from the demand for the services facilitated by it. Frequent and long blackouts, characteristic of the electricity grid in India and many parts of the developing world, lead to forced reduction in consumption of electricity. The welfare loss to the consumers depends on the timing of the outages and on the services affected. This paper develops a microeconomic framework that can be used to study consumer demand and adaptation with unreliable supply. While setting up the utility maximization problem, the definition of energy 'service' is expanded beyond end use to other aspects like its time of use, duration, and deferability. The theoretical framework helps us identify gaps in understanding of consumer behavior and provides an analytical tool while scheduling the timing of limited supply. We use primary data collected from the Indian state of Karnataka as illustrations and conceptual inputs in developing the framework. The data are also used to explore the multiple dimensions of supply reliability (mean and variance of availability in times of high demand, predictability, and contiguity of supply) and suggest new indices to monitor the supply.

1 Introduction

Chronic shortages have been a feature of the Indian power sector for decades, and frequent blackouts and brownouts are especially common in rural areas in most parts of the country. However, perhaps given the poor access situation (45% of the rural households, and 33% of all households were unelectrified as per 2011 Census), supply reliability has been treated as a second order problem. Even the literature addressing the problem has been limited.

In this paper, we develop a model for electricity demand that explicitly considers the end uses or services it facilitates. The model is focused on the Indian domestic consumer who must adapt to frequent unpredictable outages that can sometimes last for hours. While illustrated with data collected in India, we believe that the model can be generalized to a wider context. In addition to proposing a new model for electricity demand, we identify interesting research questions that could improve understanding of consumer valuation of outages and adaptation. As the problem of supply deficits will likely remain, we show it is important that the planning of outages be made in a more systematic, thoughtful manner so that foregone consumer surplus (i.e. inconvenience) is minimized. Understanding consumer valuation will also help in investigating the usefulness of subsidies and the structuring of incentives for technologies that can serve as augmenting sources of power.

The growing numbers of companies offering microgrids and home lighting systems in the developing world and the products they offer, highlight importance of the distinction between demand for electricity and its services it makes possible (Harish et al., 2013b). While the prices per kWh consumed in some of these systems is almost an order of magnitude higher than tariffs for grid-based supply, the total expenditures are on par with expenditures on typical sources of lighting in the absence of electricity access. Further, although these services are typically restricted to only 5-6 hours of modest lighting through low wattage CFL or LED lights, the quality of this lighting is still better than that provided by kerosene lamps, and its availability is predictable. The high willingness to pay is not for electricity itself, but for reliable, acceptable levels of modern lighting.

. For electricity supply in places like India, the demand model must be able to incorporate three additional dimensions of consumer behavior due to the low quality and unpredictable nature of supply. First, it must consider the use of imperfect backup sources as substitutes for grid electricity during outages. Second, it must accommodate the fact that consumers may adapt to outages by rescheduling their activities. Third, outages may have consequences on appliance ownership. If the consumer behavior can be captured to a reasonable approximation in such a model, the welfare loss due to frequent outages can be calculated as the loss in consumer surplus as computed with the case of uninterrupted supply case.

The paper has three parts- development of the theoretical framework, a discussion of real world complexities based on primary data, and an application of these principles in developing reliability indices. The basic framework is described in section 2.1, and sections 2.2 to 2.4 will progressively introduce nuances and extensions to this framework as outlined below.

- Section 2.1: Utility maximization to determine demand for energy services with and without uninterrupted supply, and an alternative energy source
- Section 2.2: Defining energy services and functional forms for the demand
- Section 2.3: Adaptation and loss of welfare with an idealized backup source
- Section 2.4: Modeling the impact of variability and unpredictability of supply on consumer welfare

Sections 3 and 4 provide a real world context to this model using primary data on backups collected during surveys in village in Karnataka, and sample survey data on appliance ownership in the country. Section 3 discusses imperfections in the market for backup energy sources, and difficulties in modeling these through the idealized backup or in using data on their adoption to infer willingness to pay. In section 4, we expand on the discussion about electricity services, their deferability and scope for backup. Although, further work is required to implement some of the finer details of the modeling, the overarching principles can be used in developing better indices for reliability, as explained in Section 5.

2 Theoretical framework

2.1 Basic framework

The principal premise of the services approach is that the consumers consume and value the services derived from the use of energy as opposed to the energy itself. While many scholars in the literature have argued for this premise, this approach has only recently received formal treatment by Hunt and Ryan (2012), and Chan and Gillingham (2014) in order to understand rebound effects with improvements in energy efficiencies. We introduce additional features and nuances to this general model in order to make it suitable to understand the demand behavior in the face of frequent outages and significant interruption costs. The results also provide a useful framework in modeling consumer demand when there are alternative sources of generation that could meet specific services to augment or substitute grid electricity, as well as consumer response to time of day pricing.

Let us consider a case where we have two services s_1 and s_2 (e.g., lighting and watching television) which can be provided by two energy sources, electricity (e) and an alternative (a) which could be a composite of multiple energy sources. Let f_e and f_a denote the demand for these energy sources by a consumer with budget (or equivalently, income or expenditure) B, and a non electricity related commodity x_0 with a composite price p_0. Let p_e and p_a denote the prices.

For now, let us assume that the services provided by the two energy sources are indistinguishable to the consumer in terms of end use or quality. However, the prices per unit of service (however defined) will differ, because of the price of unit energy (Wh) as well as the efficiency by which they are transformed into the end uses. s_{1e} and s_{2e}, the services provided through the consumption of electricity are related to the electricity demands f_{e1} and f_{e2} (the sum of which are f_e) through the efficiencies η_{e1} and η_{e2} as

$$s_{1e}=\eta_{e1} f_{e1} \text{ and } s_{2e}=\eta_{e2} f_{e2} \qquad \text{-(1)}$$

(Similarly, $s_{1a}=\eta_{a1} f_{a1}$ and $s_{2a}=\eta_{a2} f_{a2}$)

For now, we can ignore the units of s_1 and s_2. This will be dealt with in the next section. We only note that s_{1e} and s_{1a} are expressed in the same units. Anticipating the discussion in the next section, let us further distinguish between the times of use for a given service. For the sake of simplicity, consider two broad times of use- morning (m) and night (n).

Based on this services approach, the consumer faces a utility maximization problem of the form

$$\text{Max } U\,(x_0,\, s_{1m},\, s_{2m},\, s_{1n},\, s_{2n}) \qquad \text{-(2)}$$

subject to

$$p_e f_e + p_a f_a = B \qquad \text{-(3)}$$

$$f_e = f_{e1} + f_{e2} = (s_{1e,m} + s_{1e,n})/\ \eta_{e1} + (s_{2e,m} + s_{2e,n})/\ \eta_{e2} \qquad \text{-(4)}$$

$$f_a = f_{a1} + f_{a2} = (s_{1a,m} + s_{1a,n})/\ \eta_{e1} + (s_{2a,m} + s_{2a,n})/\ \eta_{a2} \qquad \text{-(5)}$$

Let the solutions be $x_0^*(p_0,\, p_e\,,\, p_a,\, \eta_{e1},\, \eta_{e2},\, \eta_{a1},\, \eta_{a1}, B)$, $s_{1m}^*(.)$, s_{2m}^* (.),$s_{1n}^*(.)$, s_{2n}^* (.). In other words, the solutions are functions of the prices, conversion efficiencies and the budget.

Strictly speaking, we would have needed to determine the services derived from each energy source by time of use. However, if the energy sources are indistinguishable in terms of the quality of service derived, the choice of energy source for a given service j will be the one with the lower price per unit service, $p_e/\ \eta_{ej}$ and $p_a/\ \eta_{aj}$. See Chan and Gillingham (2014) for a fuller discussion of this corner solution.

It is important to state explicitly three assumptions we have made so far

1. We assume that the stock of needed appliances exists and only compute the consumption of the services through the utility maximization (i.e. this is a short run utility maximization problem)
2. We assume that the quality of the services is indistinguishable between electricity and the alternative source- that is, 'one unit of service j' from either grid-supplied electricity or the alternative are valued identically. This is a strong assumption for a few reasons. One, the units of the services could be ambiguous. Two, in the case of much of rural India, the alternative lighting fuel is kerosene which provides a significantly inferior form of lighting than electricity. The alternative energy source

could in actuality be different end use-appropriate sources. This could be easily implemented through the price and efficiency parameters.

3. We treat the alternative source to have costs that are "flow-based" that is, either requiring negligible upfront capital and with a fuel that can be purchased in the required quantities, or with capital that could be amortizable. However, alternatives based on solar energy or back-up sources like batteries with inverters have high upfront costs and limited storage capacity.

The definition of services is dealt in section 3 and again, in section 7. For simplification, the theoretical framework works with an idealized backup- 'flow based' and with identical quality as electricity. Section 6 introduces the complexities of real-world alternative sources.

The model so far assumes no constraints in supply of the two energy sources. We can now extend this to the case where electricity supply is restricted. Analogous to the utility maximization with unrestricted supply (2-5), we have

$$\text{Max } \{U\,(x_0{}^r,\, s_{1m}{}^r,\, s_{2m}{}^r,\, s_{1n}{}^r,\, s_{2n}{}^r) - \phi\,(\Delta f_a)\} \qquad \text{-(6)}$$

subject to

$$p_e f_e{}^r + p_a f_a{}^r = B \qquad \text{-(7)}$$

$$f_e{}^r = f_{e1}{}^r + f_{e2}{}^r = (s_{1e,m}{}^r + s_{1e,n}{}^r)/\,\eta_{e1} + (s_{2e,m}{}^r + s_{2e,n}{}^r)/\,\eta_{e2} \qquad \text{-(8)}$$

$$f_a{}^r = f_{a1}{}^r + f_{a2}{}^r = (s_{1a,m}{}^r + s_{1a,n}{}^r)/\,\eta_{a1} + (s_{2a,m}{}^r + s_{2a,n}{}^r)/\,\eta_{a2} \qquad \text{-(9)}$$

$\phi\,(\Delta f_a)$ is a possible disutility in being forced to use an alternative (backup) energy source which could ave some negative consequences such as producing indoor pollution and have adverse health consequences. This will be the case with energy sources like kerosene or diesel. Ekholm et al (2010) use a similar disutility term for traditional energy sources for cooking.

Let r_m and r_n represent the reliability of electricity supply in the morning and at night. For simplicity, we could think of these as fractions of time during these hours when electricity supply is available. In this case, we may have additional constraints for each service j in time of use t

$$(1\text{-}r_t)s_{jt,e}{}^{*} \leq s_{jt,e}{}^{r} \leq s_{jt,e}{}^{*} \qquad \text{-(10)}$$

$$s_{jt,a}{}^{r} \geq s_{jt,a}{}^{*} \qquad \text{-(11)}$$

The solutions with the restricted supply could then be said to be functions of the demand with unrestricted electricity supply and reliability during the times of use, in addition to the other factors like prices and efficiencies. Let these solutions be $x_0{}^{r*}(p_0,p_e,p_a, \boldsymbol{\eta}, B, r_m,r_n,\{x_0{}^*,s_{1m}{}^*,s_{2m}{}^*,s_{1n}{}^*,s_{2n}{}^*\})$, $s_{1m}{}^{r*}(.)$, $s_{2m}{}^{r*}(.)$, $s_{1n}{}^{r*}(.)$, $s_{2n}{}^{r*}(.)$.

If electricity was not the preferred source for any of the services previously, the restriction in supply will not affect the results for that service. The consumer can adapt to the outages and some of the services may be deferrable partially. Inequality (10) allows for this adaptive behavior, and inequality (11) articulates the other side of this adaptation in that the demand levels for the alternative can only increase from the unrestricted case. However, the total service demanded, despite any adaptation, may still diminish. In other words,

$$(s_{jt,a}{}^{r*}-s_{jt,a}{}^{*}) \leq (s_{jt,e}{}^{*}-s_{jt,e}{}^{r*}) \qquad \text{-(12)}$$

This last inequality forms the context for the consumer interruption costs due to a forced reduction in service demand (separate from the disutility due to pollution). As the same or lower level of service is consumed with a higher expenditure in the restricted case, there is a reduction in consumer surplus. The results of the utility maximization will give us Marshallian demand curves, which could be used to calculate the reduction in consumer surplus.

In the next section, we discuss the nature of the electricity services and functional forms to articulate their likely interactions with each other, and with prices and incomes.

2.2 Services and budget allocation

The cost of an outage for a given consumer depend on the time of day of its occurrence, its duration, the predictability of the event, the services affected, and their time specificity (or conversely how deferrable they are). For this reason, it becomes necessary to make a distinction between end use and service, with services being defined by both the end use and the time of use. The reasoning is simple: value derived from an end use such as lighting is much greater early in the evening than at 3am or noon.

Appliance ownership is income dependent, and hence, so too will be the services derived from appliances. In addition, with a fixed appliance stock, the services derived from them may become more diverse- for example, getting used at other times of the day and for longer durations. With ambient services like lighting or space cooling (or heating), additional variables may include the intensity of use (that is, the brightness, the rotation speed of fans or the temperature differential), and the living spaces served. These dimensions are important in determining the units in which services are measured, and subsequently, in defining the demand curves (that is, the units of the 'good' being demanded). Taking the example of lighting, do the consumers value the time aggregated light output (in lm-h), or room-hours with lighting of some threshold brightness? Does the value derived also depend on the time of day and/or the living space served? In both cases, the answers are likely yes.

The functional form of the utility function should reflect the consumer's preferences in allocating the total budget, and should allow for empirical testing of the underlying assumptions. Two-stage budgeting is a popular approach in this regard. This principle involves grouping 'related' commodities together into clusters among which the budget is allocated at the first stage. Clustering allows the use of group price indices to determine the share of the overall budget allocated to the group, and this group expenditure is then allocated among the constituents based on their relative prices and utility derived from the consumption of each. Two-stage budgeting thus imposes a separability in the sense that changes in the price of a commodity in one group cannot affect the demand of a commodity from any other group except through an income effect (that is, there are no substitution effects). For example, Figure 4-1 is a utility tree that schematically describes the stages of budget allocation among the goods and services consumed. Here, a share of the total expenditure is allocated among broad categories like food, housing, cooking energy and electricity at the first stage, and the electricity budget is then distributed among the services. For instance, the price of potatoes will not directly affect the number of hours of TV watching except through an income effect.

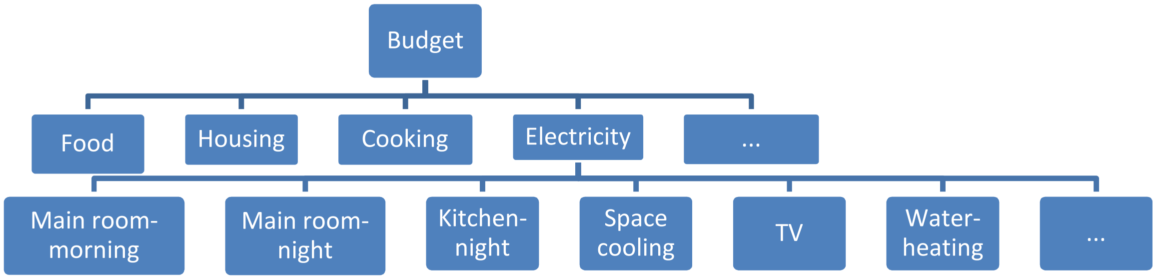

Figure 4-1: Two stage budgeting and separability of the utility function

The two stage budgeting model can be functionalized using the Almost Ideal Demand System (Deaton and Muellbrauer, 1980b). This has been also used in the electricity demand context in studies such as Hunt and Ryan (2012) and Gundimeda and Kohlin (2008). The expenditure share on electricity is found in the first stage of the budgeting process as

$$w_e = \alpha_e + \sum \gamma_{ij} \log p_j + \beta_e \log (I/P) \qquad \text{-(13)}$$

Here, the γ_{ij} are related to the price elasticities of the commodity groups in the first stage, I the income (or budget) and P is a price index of the commodity basket.

The expenditure on electricity B_e ($=w_e I$) is then allocated among N services (defined by end use, time of day, and for ambient applications the intensity of use and living space served, if necessary). Let the price of service k be π_k, and the service demanded be s_k (with a conversion efficiency of η_k). Note that we can restrict ourselves to only those services that are best met through electricity (because of the corner solution with multiple energy sources for the same service). Let the share of the electricity expenditure spent on service k be,

$$\begin{aligned} w_k &= \alpha_k + \sum \gamma_{kj} \log \pi_j + \beta_k \log (B_e/p_e) \\ &= \alpha_k + \log p_e \sum \gamma_{kj} - \sum \gamma_{kj} \log \eta_j + \beta_k \log (B_e/p_e) \qquad \text{-14} \end{aligned}$$

The price of electricity p_e can replace the price index P. Note that for the expenditure function to be linearly homogenous in prices for this to be a "valid representation of preferences" (Deaton and Muellbauer, 1980b), the parameters must meet a few additional conditions

$$\sum \alpha_k = 1,\ \sum \gamma_{kj} = 0 \text{ (when summed over k), and } \sum \beta_k = 0$$

$$\sum \gamma_{kj} = 0 \text{ (when summed over j)}$$

$$\gamma_{kj} = \gamma_{jk}$$

The Marshallian demand would then be

$$s_k^* = w_k B_e / \pi_k = w_k B_e \eta_k / p_e \qquad \text{-(16)}$$

With increase in income,

$$\partial s_k^* / \partial I = \partial s_k^* / \partial B_e \, . \, \partial B_e / \partial I = (\eta_k / p_e)(\beta_k + w_k)(\beta_e + w_e) \qquad \text{-(17)}$$

$\partial s_k^* / \partial I > 0$ for normal goods. Services (goods) for which income elasticity ($\partial s_k^* / s_k^* . I / \partial I$) is less than unity are conventionally defined as necessities, and otherwise, luxuries.

2.3 Reliability and adaptation with a 'perfect' backup

To model for unreliability of supply, we make an incremental extension in defining the *N* services that require electricity- a time of use t_j for each service *j* and a restriction that the service demanded, s_j, be expressed either in duration of use or in units that are linearly proportional to duration of use. To distinguish between the two, we denote the duration of use as d_j, where $d_j = s_j/k_j$, the intensity of use for ambient applications and $d_j = s_j$ for the rest. Let r_j denote the fraction of time during t_j that supply is available. The deferability of demand can then be defined in terms of d_j and t_j, as the attribute of service *j* that the cumulative duration of use can be distributed within t_j in any manner whatsoever to yield the same level of utility. Note, a special case is where $t_j = d_j$ and the services are not deferrable.

By definition, as long as $r_j t_j \geq d_j^*$, the consumption of service *j* is unaffected by outages, and without any inconvenience to the consumer. If $d_j^* > r_j t_j$, the duration of use of service *j* through electricity is restricted to $r_j t_j$ in the absence of a backup. With no backup, this reduces to a rationing problem, where we have to maximize the utility with the demand for service *j* restricted. We use the net income (by subtracting out the expenditure on the restricted service), and maximize the utility with this net income in the budget constraint. This is equivalent to using an artificially higher "shadow price" for the affected service *j* which yields the restricted demand level as part of the solution to the utility maximization problem. The welfare loss due to the outages (in the absence of a backup) is then conceptually identical to the price increasing to the shadow price level, and can be computed as the loss in consumer surplus.

If a backup or alternative source of energy exists, which is more expensive than electricity (as it must be for services that would ordinarily use electricity), we have a new utility maximization problem. If t_j is well defined and r_j is known, we have a non linear pricing scheme of the form:

$\pi_j = \pi_{je}$ if $d_j \leq r_j t_j$ and

$\pi_j = \pi_{ja}$ if $d_j > r_j t_j$ -(18)

Not only is the demand likely to be reduced for services directly affected by outages, the demand for the rest may be affected as well, as the electricity budget gets reallocated to meet the higher priority services. If a perfect backup exists (one that can meet any of the services affected by outages albeit at a higher price) the associated welfare loss is identical to the case where the price of electricity increases to some intermediate level between the real price of electricity and the backup. If the backup can meet only certain services, and the consumption of a few others are restricted, we need to consider reduction in demand with higher prices for the first group and the shadow prices for the latter, as shown in Figure 4-2. The figure shows the shift of the (electricity) budget line with unreliable electricity supply and the use of an expensive backup for the service affected by the outages. This optimal consumption bundle with unreliable supply is the point at which this new budget line is tangential to the indifference curve for some lower consumption utility level.

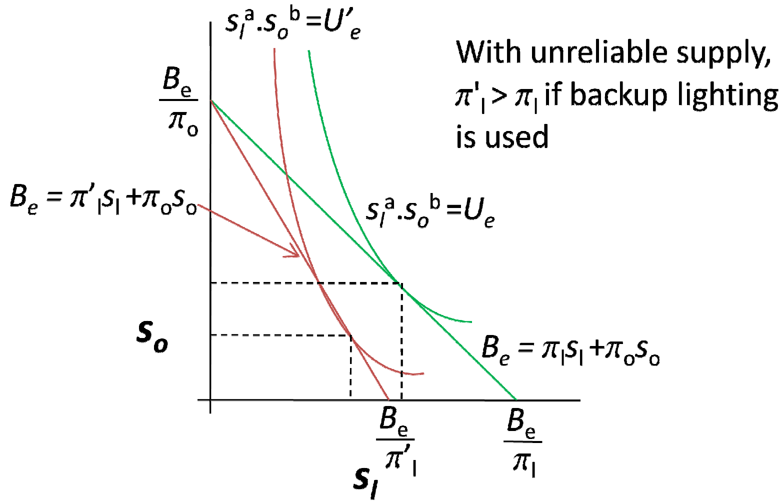

Figure 4-2: Shift of the optimal bundle of energy services due to outages, if only one service (lighting) has a backup. Even if outages affect only lighting, the use of a more expensive backup for lighting may reduce demand for both lighting and other (o) services

For services characterized by both duration (d_j) and intensity (k_j) of use, the demand served with the backup could involve a reduction in either or both. If the service is valued as the product of the two (s_j), the calculation of the loss in surplus is straightforward. Otherwise, we need to be able to understand the relative preferences and tradeoffs between these two aspects of the service.

We also need to consider one other aspect of temporal preferences while defining the time of use t_j. Empirical estimations of the demands will likely use monthly expenditure and consumption data, and hence, the demands for the services will be estimated at the monthly level. However, for each service *j* the time of use t_j is defined as the smallest interval of time over which the demand for *j* is independent of the consumption outside this interval. By independence, we mean the following:

3. Consumption of *j* in this interval is valued independently of consumption of *j* in any other period.
4. Demand in a subset of this interval is valued as a function of consumption in the rest of the interval.

For example, let t_l and d_l together define the time of use of lighting in the living room at night and its deferability, and the demand for this lighting is independent (but identical) from one day to the next in a month. While demand for this lighting service could be estimated over the course of a month, the interruption costs should be based on the demand curves for the individual days. A daylong outage that restricts the lighting consumption on that day cannot be compensated for by consumption on some other day.

2.4 Dimensions of reliability

In the description of the basic framework, reliability was incorporated as the fraction of time with electricity supply during each of the time periods of interest. Here, we explore the statistics that need to be considered with reliability. The answers to three questions are of interest:

1. Within a given time of day where services are required, how much supply is typically available (the mean or median)?
2. How do they vary from one day to the next in terms of durations, and how predictable is their timing?
3. How many days in a month or year are there with extreme events like no supply availability whatsoever over the course of a day?

Let us consider the case where one of the services (say, lighting in the main room in the evening hours) has much higher priority than others. Continuing the notation from the previous sections let the duration of demand be d_l* and the price π_{le} with electricity and π_{la} with the substitute (the' intensity' k_l is assumed constant here for simplicity). If the fraction of availability of supply in this period t_l on day i is r_i we can discount the deferability to get r_{li} as $(d^*_l - r_i t_l)/d^*_l$. Over the course of a month (or any other convenient set of contiguous days), let r_{li} have a known distribution with mean m_l and standard deviation σ_l. The constant intensity assumption ensures that the electricity consumption for this service is restricted to $s^{r*}_{le} = \sum r_{li}\, d_l^* k_l\, \eta_{le}$. With the assumption that this service is accorded a much higher priority than any other, the demand with the substitute will be $s^{r*}_{la} = \sum(1\text{-}r_{li}) d^*_{la}\, k_l \eta_{la}$ where d^*_{la} is the unrestricted demand with π_{la}. (This imposes an additional continuity condition…) The total 'restricted' demand would then be

$$s_l^{\,r*} = d^{r*}_{le} + d^{r*}_{la} = \sum(r_{li} d_l^* + (1\text{-}r_{li}) d^*_{la}) \qquad \text{-(19)}$$

If $D(\pi_l)$ is the demand at price π_l and the inverse demand curve is $\Pi(d^*)$ (that is, $D(\Pi(d^*)) = d^*$), the loss in consumer surplus is estimated as

$$\text{Interruption cost} = k_l \qquad \text{-(20)}$$

The interruption cost estimation (even if the simplifying assumptions are reasonable) will depend on the functional forms of the demand curve and the distribution of r_{lj}.

However, this is a static model for the consumer's adaptive behavior. Munasinghe (1988) discusses how the interruption costs depend on the difference between expected and actual reliability levels (his schematic is reproduced in Figure 4-3). The reasoning is that if the expected reliability level is high, but the actual reliability is low, the consumer is less prepared and hence, will have a higher outage cost than if the expected level was low to begin with. The author also notes that at any given actual reliability level, the outage cost is least when the actual level is equal to the expected level (in the figure, C<D and A<B). Munasinghe does not define what reliability level here refers to, but the intuition about expected and actual availability fits nicely with our subsequent discussion about predictability.

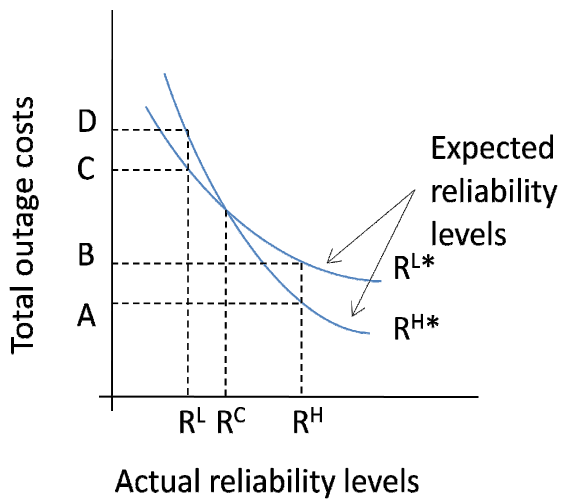

Figure 4-3: Expected and actual reliability levels, and their impact on outage costs (reproduced from Munasinghe (1988)) R^H and R^L are high and low actual reliability levels respectively, R^{H*} and R^{L*} are high and low expected reliability levels

Note that the "expected level" could refer to the utility announced level, or be based on the consumer's experiences. It is possible that recall biases limit the consumer's learning over time. This discussion suggests that unrealistic reliability levels promised by the utility would at best be inconsequential if the consumers do not trust them, or would otherwise hurt the consumers by false information. If the outages are predictable, (e.g. as advertised in advance or occur regularly at the same hour) consumers can presumably schedule their activities anticipating them. Backup sources or substitutes can be used more efficiently.

Let o_l be the fraction of time of d_l* during which the probability of an outage event is higher than some threshold, at least as per the consumer's experience. The consumer may then reschedule activities that require lighting such that the most important of these are unaffected by the expected outages. One way to model this would be to consider an adapted demand d_l' equal to $(1\text{-}o_l)d_l$. The adaptation could be through adjustment in the intensity of use k_l such that the value or surplus derived from the service remains unaffected.

Note that o_l and r_{lj} are very different parameters. o_l is based on the consumers' prior experience of outages during the hours of the day when lighting is required. r_{lj} is the actual fraction of these hours when supply is available on day *j*. The timing of the outages informs o_l. This relationship will become clear in section 8.1, where we propose predictability metrics and use primary supply data to demonstrate these.

A brief word about the long run effects of uncertain supply. Unpredictability of supply (either or both of day-on-day variability in durations during important times of day, or predictability) could lead to two consequences. One, with higher uncertainty, the consumers may be sub-optimally sized. Because larger backup sources carry high upfront costs, and allow for little scope for flexibility subsequent to purchase, this could result in welfare losses due to insufficient backup capacity or in opportunity costs due to over-sizing. Two, the risk of under-utilization of appliances could lead to non-adoption of new appliances and hence, foregone surplus.

3 Backup and alternative sources of energy in rural India

In most cases, the perfect backup assumed in section 2.3 does not exist, and each alternative falls short either in terms of not being an indistinguishable substitute for electricity or in terms of the lumpiness of its costs. As a result, the response to outages will carry additional costs to the consumers. Conversely, the adoption and usage of backups would ideally reflect the revealed preferences of the consumers and their valuation of the services. The discussion in this section will borrow from the primary data gathered from household surveys in villages in Karnataka. The surveys were conducted in April and May 2013, and the villages were the same as or near those where the electronic data loggers we developed and deployed had been set up.

Kerosene lamps are the most common source for lighting in households that are not electrified, and are the most common backup (especially in rural India). Per 2011 Census, 31% of the households in the country used kerosene lamps as primary lighting- this number increased to 43% in the villages. Use as backup is not as clear from the data, as kerosene fuel is often used for cooking as well.

In our surveys too, kerosene lanterns are by far the most common backup source of lighting. Only 44 of the 216 respondents reported not using kerosene for lighting at all. 32 of these 44 households were 'Above Poverty Line' houses and hence are not entitled to subsidized kerosene. For 142 surveyed houses, kerosene was the primary backup used. As shown in Table 4-1, kerosene lamps are common even as supplementary backup sources even if the households used sophisticated systems like battery inverters. The use of multiple backups could be a means of risk mitigation; or, each backup could have a specific end use (as a mobile lighting device for example). Most backups can only meet lighting requirements.

Table 4-1: Stacking of backup sources and high dependence on inefficient fuel based lighting

Primary backup	Other backups (if any)	Number of respondents	
Kerosene lamps (wick and chimney lanterns)	Kerosene lamps only	110	
	+ candles	13	
	+ rechargeable battery lamp	9	
	+ flashlight	6	
	+ candles, rechargeable battery lamp	2	
	+ candles, lamps with other fuels	1	
	+ solar lantern, flashlight	1	142
Battery inverter	Battery inverter only	13	
	+ kerosene lamps	3	
	+ rechargeable battery lamp, kerosene lamps	2	
	+ solar lantern, kerosene lamps	1	19
Rechargeable battery lamp	Rechargeable battery lamp only	11	
	+ kerosene lamps	5	
	+ candles	1	17
Candles	Candles and Kerosene lamps	9	
	Candles only	7	16
Lamps with other fuels (Pressurized kerosene, palm or vegetable oils)	Lamps with other fuels only	3	
	+ kerosene lamps	3	
	+ candles	1	7
Flashlight	Flashlights only	5	
	+ Lamps with other fuels	1	6
Solar lantern	Solar lantern only	1	2
Solar lighting system	Solar lighting system only	1	1

Subsidized kerosene in the public distribution system (PDS) outlets is rationed. Hence, even if electricity supply is never available in the evenings, these households are forced to spread out the usage of the kerosene over the entire month. As a result, it is difficult to back-calculate the willingness to pay for backup lighting based on kerosene expenditure. Keeping this caveat in mind, Figure 4-4 summarizes the expenditure on kerosene lighting as a fraction of electricity expenditure.

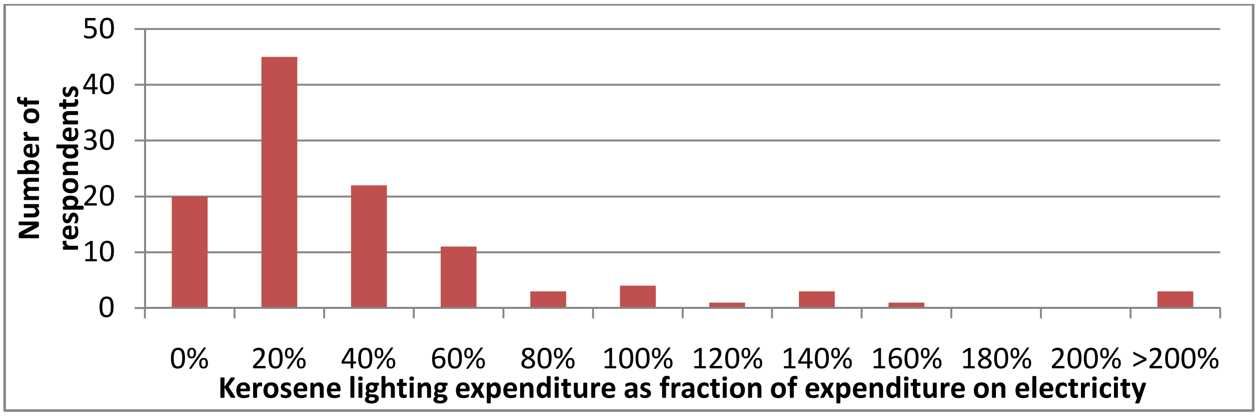

Figure 4-4: Cost of fuel based backup lighting as a percentage of electricity expenditure

Kerosene lamps are almost a factor of 50 dimmer than typical incandescent bulbs (40- 50W) or compact fluorescent lamps (10 W). Kerosene lamps not only cost more per klmh delivered, but more per unit time as well (this is already discussed in Chapter 2 of the thesis). And hence, we have three major difficulties in incorporating kerosene demand in Indian homes into our framework. One, the service delivered is very likely inferior to that provided by electricity. Two, the fuel is rationed. Three, the rationed quantity has a competing use as cooking fuel.

While kerosene lamps have negligible upfront costs (the common 'wick' lamps are often assembled at home), larger backups typically involve significant upfront costs. The costs of these products among the surveyed households are summarized in Figure 4-5. There is a continuum between flashlights and rechargeable battery lamps. Flashlights are cheaper, smaller and not as bright, and are more appropriate as mobile or temporary lighting than as ambient lighting. Battery inverters also seem to exist as a continuum-serving loads of 2 lights for 2-3 hours to larger sizes that can support 2-3 lights and fans for 7 hours. For the most part, battery inverters and solar lighting systems are an order of magnitude more expensive than single light rechargeable lamps. The market for these backups is relatively nascent and awareness of the range of products and prices remains low. This is especially the case with solar lighting systems. Although there are multiple product sizes available, and at prices that could be affordable to many households, often these are not well know and characteristics of purchased systems show local homogeneity (Harish et al, 2013b). The range of prices of battery inverters installed here is an encouraging sign.

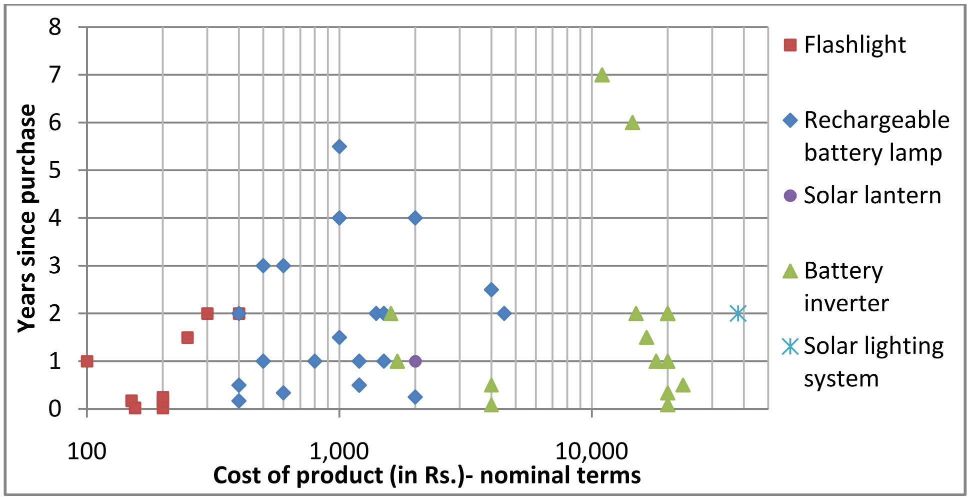

Figure 4-5: Cost of non-fuel based backups (logarithmic scale)

The most sophisticated backups commonly in use in India are (grid electricity charged) battery inverters, and diesel generators. Both are typically limited in terms of capacity and in most cases, will not be perfect substitutes of electricity. Battery inverters are the more common of the two as residential backup power. Diesel generators (DG sets) usually serve larger residential complexes in cities and commercial establishments. DG sets lend themselves more easily for modeling as the fuel costs are the principal driver of the costs of the backup. In contrast, battery inverters have high upfront costs, and the variable costs are the costs of grid power to charge the battery. Hence, not only will the presence of these devices influence electricity demand, their performance as backup will also depend on availability of sufficient grid supply.

As backup purchase and use directly represent the consumer's private response to unreliable supply, they provide a useful way to study their willingness to pay- how much and for which services. However, imperfections in the market limit the extent to which we can make inferences based on these alone. Evening lighting is clearly highly valued, and when kerosene lamps are employed, consumers are paying 2-8 times more per unit time used despite the significantly poorer quality. The low usage of backups that can provide other services does not necessarily mean they are not valued. The nascence of the market for solar lighting systems and battery inverters inhibits the scale of adoption. Another inhibiting factor is the lack of easy access to credit. Among agricultural families, a large fraction of the rural population, cash earnings are restricted to a few times in a year and most of these earnings are often reinvested quickly into the farm. As a result, there is not only the question of credit, but also the availability of appropriately structured loans. The role of rural banks is one of the principal reasons for the relatively high diffusion of solar lighting systems in Karnataka (Harish et al, 2013 b). In addition, substandard quality of the products and after sales services (for the larger backups) has also inhibited adoption.

4 Preferences among end uses

The hierarchy of value attached to electricity services may be inferred from usage patterns that increase with income levels. As income grows, we expect and observe that the rates of access increase. Also, as income grows, appliance ownership increases and electricity use becomes more sophisticated. From the National Sample Survey data, we find that this sophistication of use follows a very interesting overall trend as shown in Figures 4-6 and 4-7: electric lighting -> fans -> television -> refrigeration and then other appliances. Median rural households (from an electricity use perspective) in the first decile have no access; in the second and third, they are electrified but use only lighting; in the fourth and fifth, fans are added; and, in the seventh or higher there is TV. Urban households have a more sophisticated electricity demand in every decile. The median households in the first three deciles use electricity for lighting, fans and TV; in the next four, they add a refrigerator, and even more appliances are found in higher deciles.

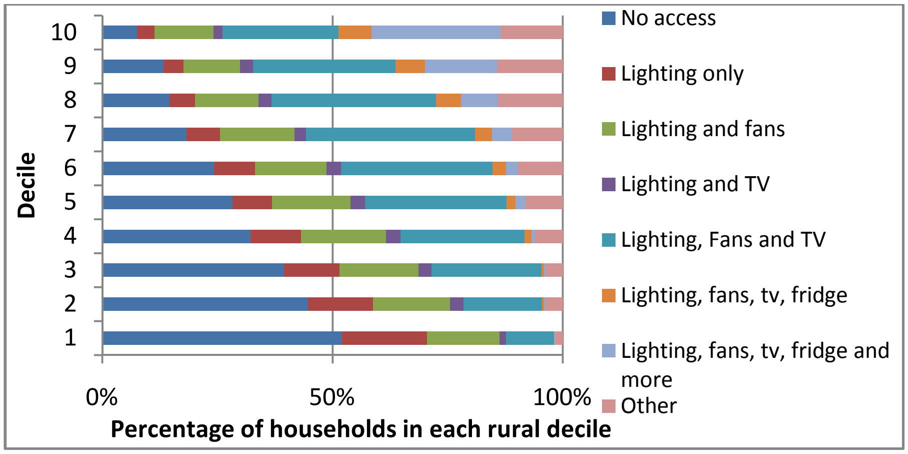

Figure 4-6: End uses among rural households in India 2011-12 (using NSS 68th round)

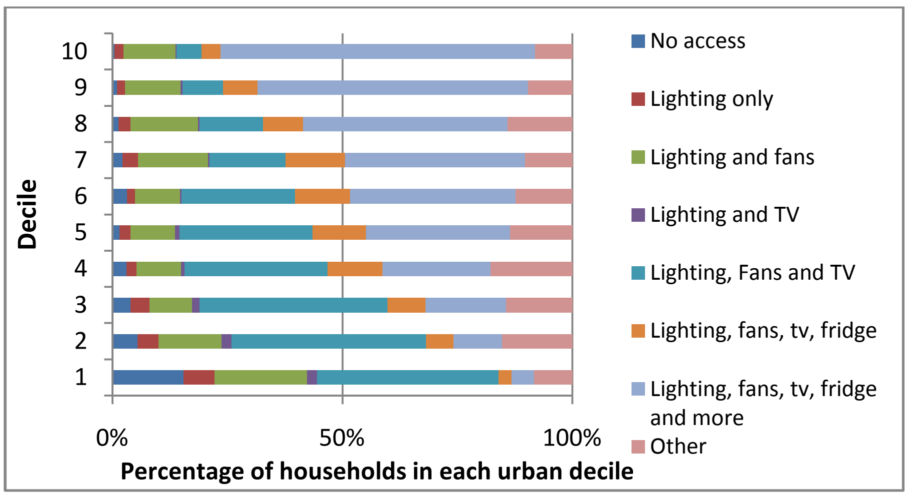

Figure 4-7: End uses among urban households in India 2011-12 (using NSS 68th round)

The hypothesis suggested by these two figures is that not only do the appliance ownership rates increase with income, but that the ownership broadly follows a surprisingly simple trajectory. To be clear, we need to consider other determinants like climate, region, and perhaps even factors like education, and use the absolute incomes instead of the percentiles, to test such a hypothesis. But, it is interesting that such a large fraction of the households nationally fall into one of these categories given the number of combinations under the umbrella of 'Others' (for example, this may include lighting, TV and fridge, but no fans).

Anecdotally, this 'order' is supported by the design of grid backups and substitutes. As we have already seen, the vast majority of these, including the ubiquitous kerosene lamps, support lighting alone. The most comprehensive of these alternatives to the grid are the solar lighting systems. Based on interviews with firms selling these systems in India, Harish et al (2013a) discuss how with a decrease in costs of photovoltaic panels and the use of energy efficient lamps, the products are now also being fitted with fans, presumably in response to the consumer demand.

Wilson et al. (2010) discuss methods to estimate benefits of electricity access and work with klm-h for lighting and kWh for all the other appliances. Table 4-2 lists some of the most common end uses, the units for defining the quantum of service and their scope for deferability or use of backup sources.

Table 4-2: End uses with electricity, their likely deferability and use of backup

End use	**Service defined as**	**Deferability**	**Backups**[8]
Lighting (ambient)	By room and time: Duration with lighting (or) Light output-hours	Low Activities facilitated by lighting may be deferrable	Kerosene lamps Flashlights Solar/ grid chargeable lamps Solar lighting systems Battery inverters Diesel generators
Cell phone charging	Duration	High (during a day)	Some solar lanterns and higher
Ceiling fans (ambient)	By room and time: Duration with cooling (or) Cooling degree hours	Low-medium	Solar lighting systems Battery inverters Diesel generators
Television	Entertainment-hours	Medium-high	Battery inverters Diesel generators
Refrigeration (continuous use)	Internal cooling degree hours	Low- Medium (Short outages may not affect much)	None (?)
Air conditioners (ambient)	Cooling degree hours	Medium (could be substituted by fans)	Large battery inverters Diesel generators
Electric heaters (ambient)	Cooling degree hours	Low- Medium	Substitute by burning fuel
Water heating	Volume heated	Low (time specific)	Substitute by burning fuel
Water pumping	Volume pumped	Low- high (depends on frequency of water supply)	None

[8] Larger appliances like refrigeration or air conditioners are typically on a parallel circuit from lights, fans or televisions, because they draw a higher current. Battery inverters are commonly connected to the 'lighting' circuit only, and these large appliances have limited scope for a backup source of power.

5 Applications

Supply deficits and load shedding are likely to remain persistent problems in the Indian power sector. The literature regarding consumer preferences and tradeoffs among energy services is limited. For instance, in the case of lighting we do not know enough about tradeoffs between contiguity, brightness levels and duration of use for lighting. Such tradeoffs are made by millions of households while adapting to frequent outages with rationed kerosene or even battery operated lanterns that are also only a fraction as bright as their regular grid operated lights. In this context, the energy services framework and loss of consumer surplus approach to interruption costs could offer useful tools to policy analysis. In Chapter 2, we use some of these methods to investigate the viability of local microgrids based on biomass, diesel or solar PV in unelectrified and under-electrified (due to frequent outages) villages in India. In Chapter 3, a similar approach is followed to determine the 'fair' share of current limiter's costs to be borne by the rural residential consumers.

The intuition and experiences that inform the approach outlined in this paper can be used to 'manage' the supply deficit problem better. This could be done by designing more appropriate reliability indices for monitoring supply and prioritizing regions that need attention the most, or in developing load shedding schedules that minimize consumer inconvenience.

5.1 Designing reliability indices for monitoring and targeted interventions

Reliability indices that reflect the factors determining consumer inconvenience are essential to identify areas that need the most attention. The design of the interventions- technology route, incentives (if any), and institutional delivery route- should ideally reflect the dimensions of the problem- electricity access, supply availability, predictability and quality, and household affordability.

Here, we illustrate methods to measure supply availability and predictability for a few villages in Karnataka in the months of March and April 2013. The supply availability data were logged using specially designed devices with a programmed PCB and a small memory chip. These devices[9] were assembled by a battery inverter company in Bangalore that also helped in setting these up in a few urban and rural locations across Karnataka state in south India. Summary statistics on hours of availability are provided in Table 4-3. Reflecting the discussion earlier in this paper, the availability is characterized with the mean and standard deviations of hours of supply in key time windows, and number of days with no supply all day.

Table 4-3: Summary statistics on supply availability

Region	Location type	Number of contiguous days of data	Number of days with no supply	Mean hours of availability (St.Dev.)		
				Over 24 hours	6am- 6pm	6pm- 10pm
Shimoga	Rural-1	54	1	16.3 (3.2)	5.4 (1.7)	3.6 (0.8)
Shimoga	Rural-2	68	0	22.1 (1.3)	10.9 (1.0)	3.6 (0.5)
Shimoga	Rural-3	58	8	18.0 (7.7)	8.5 (3.8)	3.0 (1.4)
Shimoga	Town	64	2	19.7 (4.9)	9.3 (2.7)	3.1 (0.9)
Mysore	Rural-1	122	0	10.5 (4.6)	4.0 (2.7)	2.6 (0.9)
Mysore	Rural-2	80	0	7.4 (2.5)	2.8 (1.3)	1.1 (0.8)
Mysore	City	81	3	21.6 (5.5)	10.7 (2.9)	3.6 (1.0)
Mysore	Rural-3	100	0	19.5 (2.8)	8.9 (2.0)	2.9 (0.9)
Raichur	Rural-1	56	0	11.9 (2.7)	3.6 (1.2)	2.9 (0.9)
Raichur	Rural-2	80	19	2.1 (1.7)	2.1 (1.7)	0.0 (0.0)
Raichur	Rural-3	79	0	18.6 (3.2)	8.1 (2.2)	3.0 (0.8)
Raichur	Rural-4	79	5	7.2 (6.2)	2.6 (2.9)	1.0 (1.2)
Mangalore	Semi-rural-1	51	0	22.8 (1.1)	11.3 (0.7)	3.6 (0.4)
Mangalore	Town	54	0	22.0 (1.7)	11.3 (0.9)	3.1 (0.7)
Mangalore	Semi-rural-2	28	0	21.8 (2.7)	10.5 (1.6)	3.6 (0.8)
Mangalore	City	55	0	22.5 (1.4)	10.8 (1.1)	3.7 (0.4)
Tumkur	Rural-1	121	0	20.5 (3.2)	9.5 (2.2)	3.8 (0.5)
Tumkur	Rural-2	82	0	18.9 (4.1)	8.4 (2.7)	3.5 (0.8)
Bangalore	Metropolitan	84	0	23.5 (0.9)	11.6 (0.8)	4.0 (0.1)

The standard deviations are high for many of the locations. The day-on-day variations in the availability in three of these locations are shown in Figures 4-7to 4-9. The evening hours (6-10 pm) are times of high demand for domestic consumers in both rural and urban areas, as well as the aggregate network and supply deficits necessitate blackouts. In the morning hours (6am-6pm), the primary load in rural areas is irrigation pump-sets and the supply is typically restricted to a few (usually, 6) hours.

[9] The device was designed so that it could be plugged into any power socket, and with a capacitance circuit serving as temporary (for a few seconds) energy storage. It can log the time of onset and end of each outage event, and the average voltage either once every two hours or between two outage events, whichever is shorter.

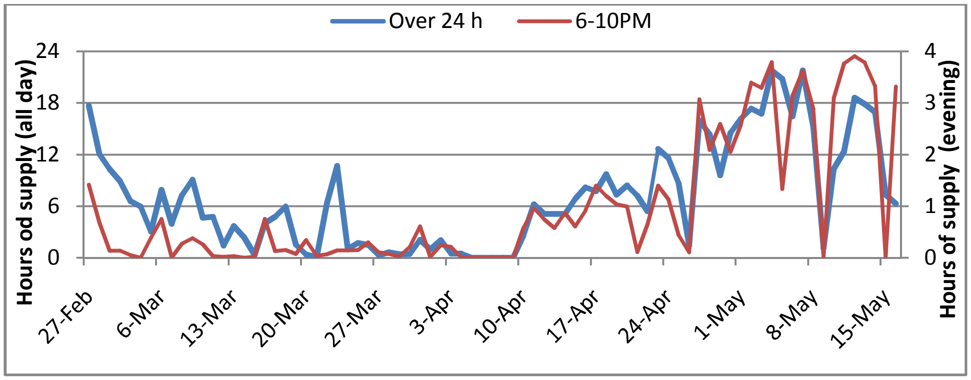

Figure 4-8: Supply availability over the logged period-Rural (4), Raichur (example of low mean, high variance)

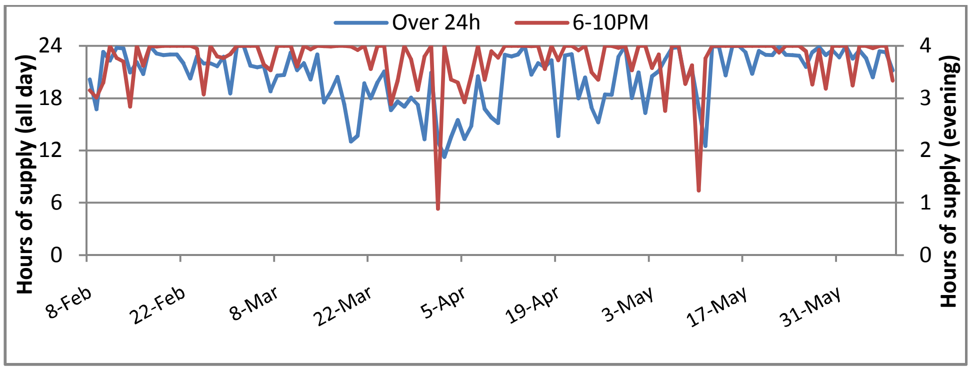

Figure 4-9: Supply availability over the logged period- Rural (1), Tumkur (example of high mean, high variance)

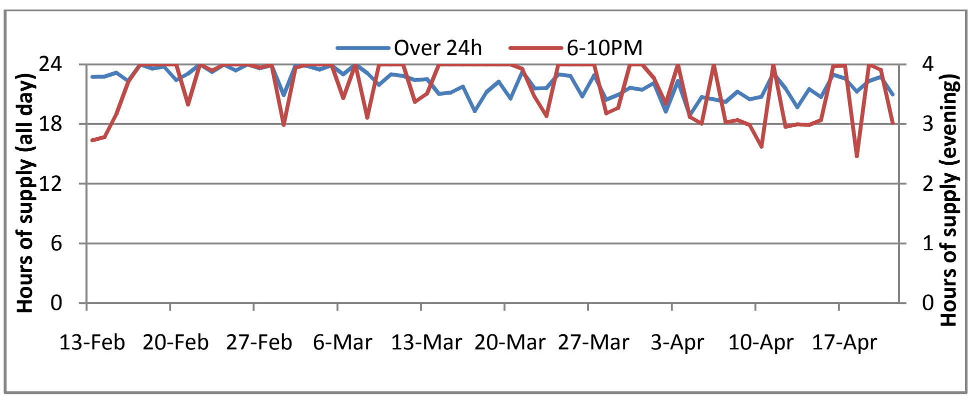

Figure 4-10: Supply availability over the logged period- Rural (2), Shimoga (example of high mean, low variance- most preferred)

While the standard deviations present a partial picture of the day-on-day variability in supply, we are also interested in the regularity of the timing and duration of outages. Figure 4-11 shows the times of the outages in the evenings for one of the rural locations in Raichur. It is evident that outages are relatively common between 7-8PM and in late April between 6-7 PM. The official scheduled supply during the period is not available and hence, we cannot be sure if some of these outages were known in advance.

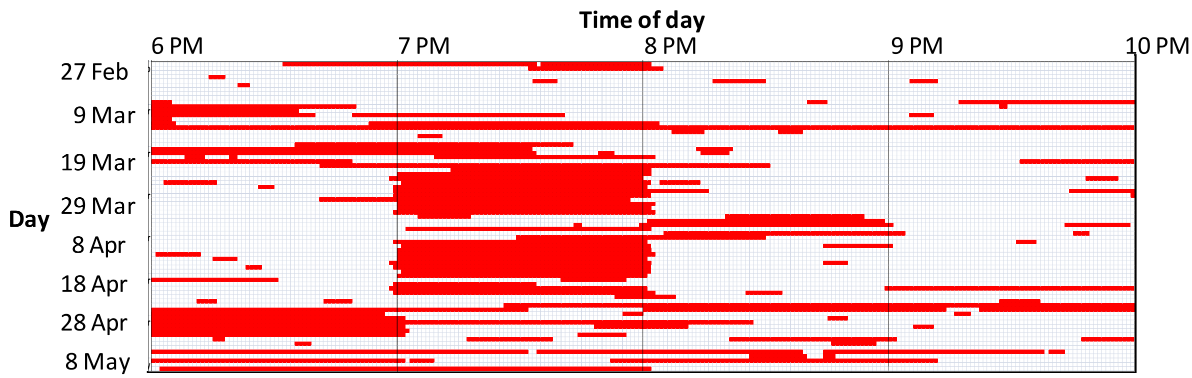

Figure 4-11: Power outages between 6-10 PM in Rural (3), Raichur during 27 Feb 2013- 5 May 2013 showing time coincidence of blackouts (shaded red)

Figure 4-11 suggests the design of predictability metrics that reflect the regularity of the outages. Based on a reasonable number of contiguous days, we can determine the fraction of days when there is an outage at a particular time of day (calculated minute-wise here). And then predictability can be calculated in terms of the fraction of these times during which supply outages follow a regular pattern.

Figure 4-12 shows histograms (or probability density functions) of the frequency of an outage at a given time in the evening for a few of the locations we monitored. Ideally, we would want the curve to be concentrated as much as possible at the low outage probability extreme. The next best would be few, but predictable outages. The unpredictability of the supply can be measured through the fraction of time when the chances of an outage are similar to that of grid availability- i.e. when an outage event tends towards an unbiased coin toss (A). Conversely, predictability can be measured either through the fraction of time during which both outages and supply are likely (B), or could be restricted to the time when outages are unlikely (C). Table 4-4 provides the estimates for area under the curves within each of the A, B and C regions for the 19 locations where the supply data were logged.

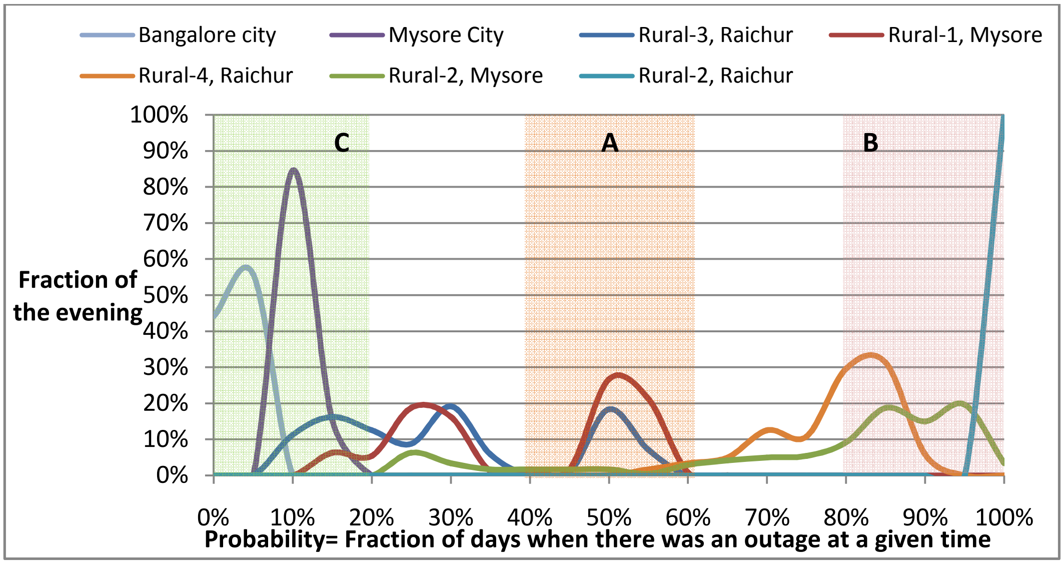

Figure 4-12: Histograms of probability of outage in the evening hours for a few exemplar locations. Areas under the curve within shaded areas A, B and C can be used to measure predictability

Table 4-4: Predictability of supply for 19 locations in Karnataka where supply was logged

Region	Location	Mean availability 6-10PM	Predictability of supply A. Fraction of time with high uncertainty[1]	B. Fraction of time with high probability of outages[2]	C. Fraction of time with high probability of supply[3]
Bangalore	Metropolitan	99%	0%	0%	100%
Tumkur	Rural-1	94%	0%	0%	100%
DK-Udupi	City	94%	0%	0%	100%
Mysore	City	91%	0%	0%	100%
Shimoga	Rural-1	90%	1%	0%	97%
Shimoga	Rural-2	90%	0%	0%	79%
Mangalore	Semi-rural-1	90%	0%	0%	74%
Mangalore	Semi-rural-2	90%	0%	0%	98%
Tumkur	Rural-2	87%	0%	0%	94%
Mangalore	Town	78%	1%	0%	54%
Shimoga	Town	76%	18%	0%	48%
Shimoga	Rural-3	76%	0%	0%	19%
Raichur	Rural-3	73%	26%	0%	40%
Raichur	Rural-1	72%	2%	0%	17%
Mysore	Rural-3	72%	18%	0%	35%
Mysore	Rural-1	63%	50%	0%	12%
Mysore	Rural-2	25%	6%	57%	0%
Raichur	Rural-4	24%	5%	37%	0%
Raichur	Rural-2	0%	0%	100%	0%

1. Fraction of times when probability of outage is between 40% and 60% (50% implies equal chance of supply or outage)
2. Fraction of times when probability of outage is more than 80% (high probability of outages)
3. Fraction of times when probability of outage is less than 20% (high probability of supply)

The predictability numbers should be read along with mean availability. Note that because both have been determined over the same span of time, a part of their correlation is trivial. For instance, if mean availability is very low (very high), predictability of outage (supply) has to be high. This is evident from top and bottom rows of Table 4. Hence, in these cases, the predictability metrics provide no new insight. Predictability metrics are most interesting at intermediate levels of availability. Table 4 demonstrates that in our sample, all locations with intermediate supply availability (between 60% and 90%) had negligible outage predictability (column B). One explanation could be that perhaps a two month period is a little too long to compute these metrics. For instance, for the location in Figure 10, one can see how although the timing of outages is clearly regular between 7-8 PM in distinct contiguous sets of about 10 days each, over the logging period, there is an outage during this time for only about half the days.

In principle, understanding the adaptation to uncertainty (standard deviation and predictability) in supply would help in designing a smaller set, if not a single number, to characterize consumer inconvenience.

5.2 Making spatial supply rostering schedules efficient

Given that continuous supply is not possible, a related problem is in designing the rostering schedules of supply. While systematically load shedding some feeders much more than others will certainly have equity implications, load shedding among the feeders such that some experience longer outages than others, but in rotation, may still be inefficient. If the assumptions of each day being valued independently and a downward sloping demand curve with the duration of use of the principal energy service are reasonable, then we expect that the sum of the surplus loss over the days will increase with increase in standard deviation. Conversely, after normalizing for income effects, the aggregate surplus loss over a region on a single day will increase with increase in variation among the feeders in this region.

Let us consider the simple case of a linear demand curve for lighting in the main room in the evening (the "principal" energy service), as shown in Figure 4-13. We can assume that demand is expressed in hours of lighting. If the demand with unrestricted supply is q^*, and the restricted demand is q^{r*} due to supply only for a fraction t of the evening. In the absence of a backup, q^{r*} is approximately tq^*. The loss in surplus will be the area of the triangle B'Q'Q. To normalize the difference in demands due to higher incomes or any other determinant, the relative loss could be estimated as the ratio of areas of BPQ and B'Q'Q and with our assumptions this is equal to $(1-t)^2$.

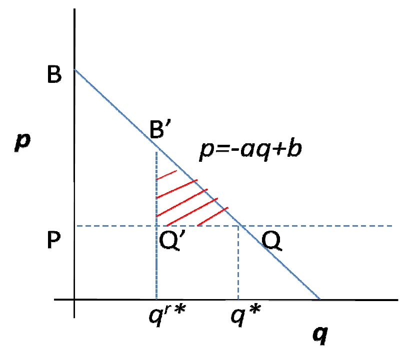

Figure 4-13: Deriving the relative loss of surplus with a linear demand curve

If t_i is the fraction of the evening with no supply in feeder i, we can calculate the square root of the weighted mean of $(1-t_i)^2$ with the number of consumers in each feeder as weights. The resultant single fraction $(1- T)$ is the aggregate load shedding level that would lead to the same aggregate inconvenience as the different load shedding levels over all the feeders. The use of the squares ensures that longer than average load shedding gets penalized. In other words, this root weighted mean sum of squares (RWMSS) of fractions with no supply is calculated using the number of consumers (c_i) and fraction of evening with supply (t_i) for the N feeders,

$$\text{RWMSS}= (1-T)= \left(\sum(c_i.\ (1-t_i)^2)/N\right)^{1/2} \qquad \text{-(21)}$$

As an illustration, the mean and median fractions of time with no supply in a region served by the Bangalore Electricity Supply Company (BESCOM) are compared with the RWMSS values in Table 4-5. The data on supply availability have been obtained from Karnataka Power Transmission Corporation Limited (KPTCL). While the mean values are closely correlated with the load shed for the utility, the RWMSS values provide information regarding the welfare loss to the consumers. Note that if all the feeders uniformly faced load shedding for (1-T) of the evening, the same aggregate level of load shedding could be accomplished with lower loss in consumer welfare.

Table 4-5 Comparing summary statistics for availability of supply in the evenings. All numbers are in %

		Sep '12	Dec '12	April '13
Rural	Mean	28-42	8	10-17
	Median	23-40	1-2	3-5
	RWMSS[1]	42-48	19-21	26-33
Urban	Median	20-36	2-7	10-17
	Median	20-40	0-1	0-3
	RWMSS [1]	27-43	9-14	27-32

1. Due to unavailability of data, instead of number of consumers, aggregate domestic demand is used as weight

If the same levels of aggregate load shedding need to be achieved daily and all the feeders contribute in an equitable way, the inter-day variation for any given feeder will also decrease significantly.

6 Discussion

The central argument of this study is that the inconvenience from different kWh of consumption restricted or each minute of load shedding is far from being equal. The inconvenience costs depend on the time of day, the length of the outage event, the extent to which it was expected, the services affected and the ability of the consumer to cope with it.

Consumers adopt backups as a means to cope with unreliability in supply. While the presence of subsidies introduces an element of complexity, supply unreliability is a failure of the state and the utilities as electricity is a public good. And while all consumers ought to be compensated for this inconvenience, poorer consumers are especially vulnerable because they may not be able to afford the means of coping. The high willingness to pay for the services at low levels of demand indicate the high marginal value of the consumption, and conversely the high costs of forced curtailment of services.

Summarizing the discussion in the study, the welfare losses due to outages will have the following components,

- Short run (with fixed appliance stock and backup)
  i. Loss of consumer surplus due to lower consumption and/or higher price of service with the use of backup, after allowing for deferability.

ii. Loss of consumer surplus due to services without a backup, that are directly affected by outages.
iii. Loss of consumer surplus due to services without a backup, not directly restricted by outages, but substituted with a higher valued service that is affected directly.
iv. Besides deferring, limited scope for adapting to variability in durations of supply and unpredictability
v. For appliances that are expensive, opportunity costs due to underutilization

- Long run and impact of uncertainty in supply

i. Foregone surplus due to non-adoption of expensive appliances due to the risk of underutilization
ii. Oversizing of backup and the resulting opportunity costs

Munasinghe and Gellerson (1979) recommend using productive losses due to unreliability instead of the consumer value or willingness to pay. Their objections are primarily due to the difficulty in empirical assessments of willingness to pay and the appropriateness of the available data in being used for interruption costs. Revenue losses or increased costs of backup due to outages certainly provide a useful way to monetize the inconvenience. However, productive losses could also be subtler. Reliable lighting may have a significant positive effect on children's education (Khandker et al., 2012; World Bank, 2008) Availability of lighting at night or the ability to refrigerate food could mean increased availability of time and hence greater earnings for women (Dinkelman, 2011; Samad et al.,2013; The Economist, 2014). Beyond the implications within the household, reliability of supply first and foremost affects the use of irrigation pump-sets and agricultural yields. Erratic voltage fluctuations also pose the risk of pump-set burnouts. Absence of reliable supply (along with other supporting infrastructure like transportation) will inhibit the growth of new industries in the region as well.

Even without monetizing these preferences in terms of willingness to pay, these principles could be used in informing interventions. For instance, as already discussed, we could design suitable reliability indices measuring availability, inter-day variations and predictability, focusing on times of day with highly valued demand. The guiding principles for load shedding would look something like below.

1. Outages should be as few and as short as possible
2. If load shedding cannot be avoided, the shedding time tables should be advertised in advance as widely as possible, and even if not strictly advertised, they should be predictable
3. For the same average duration of outages during an important time of day (say, 6-10 pm), outages of short durations daily are preferable to less frequent, but longer outages

While points 1 and 2 are straightforward, point 3 depends on the independent daily demand assumption being correct. The assumptions or additional research become necessary to compare the merits of dissimilar interventions, e.g. current limited supply using smart meters versus rooftop solar PV and battery storage. As described in Chapter 3, using smart meters, outright blackouts can be avoided to provide uninterrupted but occasionally current limited supply. Alternatively, incentives could be provided to purchase solar PV based systems to perform as a backup or substitute source of power. Current limiters will ensure uninterrupted supply to the priority services, whereas the solar-battery configuration has limited stored energy which is more versatile in terms of end uses but with limited duration. Consumer tradeoffs between continuous (and hence, uninterrupted lighting, say) and adequate (in kW) supply could provide a useful perspective, in addition to factors like costs and suitable institutional delivery routes.

In conclusion, the theoretical framework proposed in this paper could offer useful insights in designing interventions to minimize the welfare losses due to frequent outages. We have also identified some gaps in our understanding of consumer behavior in response to these outages and in general, in their relative preferences among competing services and complementary attributes defining these services.

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Chapter 5: Conclusions and Future Work

Rural electrification planning in India has focused far too much on the question of access— extending the wire to consumers—and far too little on the subsequent supply. As a result, although electricity services could play a substantial role in the development of Indian villages, this promise is not nearly met. As electricity is a public good, the low levels of access and reliability represent a failure of the state. For the consumers, this failure has direct costs- in terms of the use of expensive and often inferior backup energy, lost revenues, and costs of repair and replacement of damaged equipment (due to voltage fluctuations). This is in addition to longer-term costs through impact on children's education, drudgery and suboptimal time allocation for labor especially among women, and inhibited growth of local industries.

There is an urgent need for a revision of electricity planning goals— going beyond merely numbers of villages with a fraction of the houses having a wire to how the electricity is being used. Current targets like 1kWh/household/day or a minimum of 6-8 hours of supply/day are not nearly sufficient. The latter especially is unacceptable by any reasonable modern standard. While recognizing supply deficits and the entrenchment of institutional barriers in providing reliable supply to villages with business as usual practices, several interventions exist that are technically and economically feasible. Although these interventions do not necessarily serve as long-term solutions, they go a long way in reducing consumer inconvenience in the medium term (say, over a decade). Depending on the acuteness of the unreliability problem locally, one could consider entirely new sources of generation at the village level; or at the individual consumer level, options like solar lighting systems, current limited supply or a parallel DC wiring. Most importantly, the interventions have to be designed to suit local (at the district, if not village, level) needs— and this has not been possible with the design of large, central government driven programs like the Rajiv Gandhi GrameenVidyutikaranYojana.

Electricity planning and regulation in the presence of persistent supply deficits— which is the case in many developing countries— is an underexplored area of research and practice. Several important questions need to be answered in this context

- With percentage deficits at an order of magnitude higher than in the developed world, how can the limited available power be allocated to maximize macroeconomic development in the region?
- How can the needs of the industries and other commercial enterprises be balanced with the modest demands of the poor who are more expensive to serve?
- How can tariffs be designed, based not only on allocation efficiency, utility viability and consumer affordability, but reflecting service interruptions as well?
- When services are not expected to be near uninterrupted, how are best practices and service standards for the utilities to be defined?
- As conventional reliability indices provide information of limited value for planning, what metrics would be appropriate here?

Questions like these involve tradeoffs that need to be made involving values that do not always lend themselves to monetization. One of the principal contributions of this dissertation has been the articulation of two such tradeoffs in studying rural electricity supply. The first tradeoff considered is between the costs of improved supply through distributed generation as a standalone or backup plant, with the resulting increase in consumer surplus. The second involves a comparison of tariff-based transfers between rural and urban residential consumers, and the disparity in supply the two receive, which is either rationalized using or meant to be reflected in the subsidies to rural consumers.

Interventions for different levels of unreliability

The three chapters in this dissertation deal with three types of problems and interventions.

Chapter 2 investigated the viability of microgrids for villages that are unelectrified or receive extremely poor supply, by trading off costs of supply with the reduced consumer inconvenience through more reliable supply. Interestingly, despite accounting for interruption costs (within the limits of the modeling assumptions), grid electricity supply of fairly high levels of unreliability (up to 3 of 6 hours during peak demand with no supply) was found to be preferable to more reliable distributed generation based alternatives. Only those scenarios where the supply was especially unreliable were found to merit an intervention. This analysisis hence relevant in Indian states with especially poor infrastructure, like Uttar Pradesh and Bihar— which together account for 34 million unelectrified households (Census 2011).

The analysis in Chapter 3 was based in Karnataka, a state with significantly stronger infrastructure. We showed that contrary to the claim that rural consumers are heavily subsidized, the disparity in supply rostering in cities and villages when monetized makes rural consumers net contributors vis-à-vis their city counterparts. In such a context, current limited supply instead of outright blackouts in rural feeders is found to be an economically viable option, with the smart meters currently available in the market.

In Chapter 4, we develop a broader model for the household demand for electricity services in the presence of frequent outages, based on prior literature and primary data gathered through household surveys. The underlying principles are applied to propose reliability indices reflecting variability of supply. These could be used to plan and monitor load- shedding schedules that minimize consumer inconvenience.

Chapters 2 and 3 discuss consumer interruption costs, which are useful in including consumer welfare in engineering economic analyses of some of these interventions. Appropriate monetizing of inconvenience, would help in putting subsidies in perspective. Most importantly, interruption costs could be useful in comparing dissimilar policies. However, as laid out in Chapter 4, there is a need to study further how consumers adapt to different aspects defining unreliability of power— supply during different times of day, variability in durations and timing of outages. In order to minimize welfare losses, further investigation is needed to understand better consumer valuations of intermediate 'levels' of electricity services. This is essential because most interventions, that are technically, economically and institutionally viable at a large scale and with aggressive timelines, will fall short of the kind of standards of electricity supply expected in the developed world.

Institutions

Providing access to reliable electricity supply in rural India involves balancing often-contradictory objectives: ensuring equitable access with minimizing capital subsidies, equitable supply with utility viability and 'efficient' rationing, political patronage with objective pricing, providing comprehensive policies with expediency in claiming credit for these policies using targets that are easy to monitor and report. Part of the reason for these contradictions is the presence of multiple stakeholders.

- Chapter 2 discussed the roles of central energy ministries, state governments and utilities in the financing, planning and implementation of the national rural electrification program.

- Chapter 3 explored the interplay between the state government, an independent regulator, a state owned but independent distribution utility, and consumers (also, the electorate) in setting tariffs.

In Chapter 2, costs of providing reliable supply to villages are estimated in terms of subsidies required, while in Chapter 3, one of the principal results is that there is a net transfer from rural residential consumers to those in cities. This apparent tension between the two studies can be attributed to the way the costs of supply are accounted for by different stakeholders. Chapter 2 considers the capital and operating costs while electrifying a village with the financial support of the Central Government. On the other hand, Chapter 3 focused primarily on the distribution utility and the state electricity regulator approving the final tariffs. These tariffs are largely based on the operating costs of supply alone, and the fixed costs are assumed to be either sunk or distributed among all the consumers in the region. These differences in accounting among the concerned institutions must be incorporated while modeling interventions in order to reflect the objectives and constraints of the decision makers.

In the presence of these institutions, supply costs and revenues form only aspect in determining the design and success of interventions in the power sector. Separating rural feeders to service agricultural and non-agricultural loads has become popular with at least five states investing in these projects to provide uninterrupted supply in the village proper. This is a tacit recognition of the intractability of implementing agricultural tariff reforms in the near future.

Redesigning rural electrification policy

Several measures have to be taken in parallel to improve the quality of supply in rural areas— and many of these are being done. Tariffs need to be rationalized and reflect the costs to serve, new power plants with reliable fuel supply need to be built, demand side efficiency measures need to be aggressively pushed, technical losses need to be minimized with new investments in the infrastructure, theft needs to be cut down through better metering and collection and perhaps, the involvement of franchisees at the distribution level. However, in addition to these, we need to consider new alternatives for the short to medium term at the very least. This could be in the form of distributed generation at the consumer level (with solar rooftop systems), or limited supply instead of outright blackouts, either using a smart meter or a parallel DC wiring at the consumers' houses.

At the broader level, supply unreliability of this magnitude needs to be formally deemed as unacceptable by stakeholders across the board. This could be codified in terms of more stringent supply availability targets, especially at times of peak demand like in the evenings, and penalties imposed on utilities to ensure that these are met. The targets and planned outage times need to be advertised widely and monitored with performance data being made available publicly. The sum of these measures would make the utilities significantly more accountable to the consumer groups and the regulator.

For states where the utility's finances will not permit these targets to be feasible, an alternative set of norms for electricity *services* could be developed which allow the use of the short term measures mentioned earlier. For villages, these norms could be developed for irrigation pump-sets, industries, and public facilities like schools, health care centers, streetlights and drinking water infrastructure, in addition to residential consumption. The distribution utilities could remain as the nodes for delivering these services and routing the requisite subsidies (if any), but with the specific modes of delivery being flexible and worked out with the local government (Panchayats, in the case of villages). Hence, while the norms are national, the planning and implementation would be local and accountable to the consumers.

Such an approach could allow for the use of multiple energy sources, with the focus being on both the costs of these sources and the institutional ease in delivering services through them. There will often be tradeoffs between these factors. For example, while solar lighting systems are expensive (per kWh delivered) given that they use solar photovoltaics coupled with battery storage, India has well developed markets in many states and experience in terms of private companies with products and strategies for the rural market, and rural banks as intermediaries for market creation.

The problem reduces to defining and meeting implementable minimum standards of services to electricity consumers throughout the country, with ‘implementable’ and ‘services’ being the key operating words. Several parts of India have outages for many hours daily, and it is extremely unlikely to transition to these standards in the foreseeable future. We need to recognize our supply deficits and the financial health of our utilities, while also appreciating the unacceptability of the current state of supply. This necessarily requires a more effective use of existing available institutions and relatively novel technology routes, and the willingness to work with local governments and citizens’ groups in collecting feedback and making necessary course corrections. As Homi Bhabha memorably put it[10], “no power is as expensive as no power”.

[10] Bhabha said this in 1964 while justifying the use of expensive nuclear power in a developing economy