Enabling Mini-grid Development in Rural India

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Abstract

Rural electrification rates in India lag behind government goals, in part due to the inability of distribution companies (discoms) to fund central grid expansion. In the absence of central grid electrification, generation systems that serve only a small number of customers offer an immediate pathway towards rural electrification, in particular mini-grids. Yet private investment in mini-grids in India has been virtually absent. Using a comprehensive life-cycle cost analysis, we find that mini-grids are more economical than incumbent energy services available to households without central grid connection. Through a qualitative analysis, we identify the threat of central grid extension as the gateway barrier preventing mini-grid development in India. The issues associated with the gateway barrier have common elements with the so-called holdup problem as identified in the economics of organizations. We suggest several modifications to a proposal by the Indian Forum of Regulators that would regulate the terms on which entrepreneurs could develop mini-grids and then receive contractual protections on these infrastructure investments.

Keywords

Mini-grids

Cost competitiveness

Regulatory barrier

Holdup problem

1 Introduction

Numerous studies have documented that electrification is a major step in the development of emerging economies, conveying significant benefits both in terms of consumer surplus and productivity; see, for instance, Khandker et al. (2012); Pachauri et al. (2004); Banerjee et al. (2015). Despite these benefits, 360 million to 460 million Indians, or 29% to 37% of India's population, have either no access to or only access to unacceptably unreliable electricity (Manglik, 2015).[1] India therefore has the highest absolute number of un-electrified and under-electrified people globally. To extend electricity services to this share of the population, analysts have estimated that the power generation capacity in India must expand from its current 235 Gigawatts (GW) to 440 GW which would entail capital investments estimated in the range of $250 billion to $400 billion (Times of India, 2014; McKinsey Electric Power and Natural Gas Practice, 2008).

The government of India has set ambitious goals for electrification through central grid extension to rural areas of the country.[2] Yet, actual electrification rates have been lagging considerably behind those goals, in part because many of the public companies in this sector, the so-called Distribution Companies (or discoms), have been in financial distress. It is generally believed that the financial situation of the discoms, in turn, reflects that some customer segments receive electricity services at highly subsidized rates. These rates are insufficient to cover the full cost of generating and distributing electricity. In the absence of central grid electrification, generation systems that serve only a small number of customers while balancing supply and demand appear to offer an immediate pathway towards rural electrification, in particular mini-grids.[3] Unlike smaller-scale electrification approaches such as pico-lighting or solar home systems, mini-grids have significant potential to enhance economic growth and productivity. By doing so, they can enable the use of capital equipment that can yield high value added products and services (Alstone, Gershenson, and Kammen, 2015). These products and services can serve as the base for economic growth and develop-

[1]There is no generally accepted definition of "acceptably unreliable electricity", but the Indian central electricity network falls short of the 99% reliability standards observed in North America and Europe. Some rural areas receive at most 6 to 8 hours of electricity supply per day, much of it irregular and unscheduled.

[2]National electrification targets for India are formulated in MNRE (2015); MOP (2014).

[3]We define mini-grids as isolated, small-scale distribution networks typically operating below 11 kilovolts (kV) that provide power to a localized group of customers and produce electricity from small generators, potentially coupled with energy storage system (Tenenbaum et al., 2014).

ment (Pueyo et al., 2013; Kirubi et al., 2009; Gibson and Olivia, 2010). In the context of India, private capital has flowed to both very small-scale electrification projects and to extensions of the central electricity grid, but such capital has been virtually absent in mini-grid electrification.[4]

The motivating question therefore becomes whether private capital can be attracted to deliver electricity services at a smaller scale via distributed generation and mini-grids. To address this question, this paper first examines whether mini-grid deployment makes economic sense when compared to alternative methods of providing energy services. Absent any grid-based infrastructure (either the central- or a mini-grid), consumers and business customers in rural areas generally rely on kerosene, diesel based or small renewable-based generation for energy services.[5] Additionally, a large pool of the population does not have access to even these means of generation and must rely on local biomass to meet their energy services. Such highly localized energy production results in relatively high costs per unit of energy service.

Since rural customers tend to have relatively modest incomes in the first place, they end up consuming rather small amounts of energy services which still amount to a significant expenditure in terms of income. Our analysis provides select cost calculations that provide an economic rationale for mini-grids in so far as the attendant long-run unit cost per kilowatt hour for electricity provided would be substantially smaller than what rural areas currently face under the status quo without any grid infrastructure. These calculations are based on a model in which the mini-grid developer can rely on a mix of pooled diesel and solar photovoltaic installations combined with battery storage. Our cost calculations therefore raise the question as to why there has not been more mini-grid development as of today. Our main hypothesis in this regard is the existence of one or several regulatory barriers that effectively becomes a deterrent for potential entrepreneurs.

Under current law in India, a prospective entrepreneur would not require any license or certification in order to develop a mini-grid and subsequently provide electricity services in the area covered by said installation. Conversely, there is no legal or regulatory framework that specifies what would happen if the central grid were to be extended to an area that

[4]Through primary and secondary research explained further in this work, we observed a paucity of mini-grid developers relative to very small-scale electrification.

[5]Such infrastructure is defined as the interconnected network of generation, transmission and distribution assets, having the ability to provide services to all customers physically connected to it.

is already covered by a mini-grid. We report detailed survey evidence from interviews with entrepreneurs, analysts and policymakers whose assessments converge on the same point: mini-grid investments would be jeopardized in the event of central grid extension, precisely because discoms would, by regulatory necessity, provide electricity services at current subsidized rates, well below their full economic cost. We submit this *threat of central grid extension* as the *gateway barrier* in India and believe it should be a primary target for policymakers.[6]

The gateway barrier identified through our fieldwork interviews has several elements of the so-called *holdup problem* that has played a prominent role in the economics of organizations; see Williamson (1985, 1986), or Bolton and Dewatripont (2005). Holdup problems occur when one party can make relationship-specific and irreversible investments, yet there are no long-term contracts, or other safeguards, in place that give the investor the necessary prospect of earning an appropriate return on his/ her investment in subsequent transactions with other parties. In the context of mini-grids, investors arguably do not need to worry about being "held up" by customers due to the absence of long-term contracts. Instead, they perceive some likelihood of central grid extension, accompanied by mandatory subsidized electricity prices, that would severely compromise their future revenue opportunities. As a consequence, potential entrepreneurs will effectively be deterred from making grid investments in the first place.

Holdup problems can be addressed either through institutions or contractual mechanisms.[7] In recent guidelines, the Indian Forum of Regulators (FoR) developed a framework that would regulate the terms on which an entrepreneur could develop a mini-grid, become a licensee of the discom and continue to provide electricity services. In addition to technical standards, the terms of the initial agreement would set prices on a cost-plus basis so as to provide the licensee with a normal expected return. Importantly, the FoR proposal also includes provisions for the contingency of central grid extension to the area in question.

[6]Such prioritization acts to address barriers in sequence, enabling policymakers to enact instruments to address the highest priority first, then others iteratively (Hoppmann, Huenteler, and Girod, 2014; Lindblom, 1959). Other literature has documented multiple barriers to mini-grid deployment (Bhattacharyya, 2013; Painuly, 2001; Chaurey and Kandpal, 2010; Ahlborg and Hammar, 2014; Gershenson et al., 2015; Tongia, 2015; The Climate Group, 2015; Shrimali et al., 2013) without prioritization of these barriers from a policymaker's perspective.

[7]Most of the economics literature has focused on-long term contracts that can be renegotiated in response to new information (Maskin and Tirole, 1999; Edlin and Reichelstein, 1996; Noeldeke and Schmidt, 1995).

In essence, the licensee's relationship specific generation and distribution assets would be protected despite the arrival of the central grid. We regard the FoR proposal as a major step towards addressing the holdup problem that prospective mini-grid developers face in the current regulatory environment of India.

We also suggest several modifications of the FoR proposal, which in our assessment would go substantially further in safeguarding investments and promoting the flow of private investment capital towards rural electrification. These modifications pertain to the role of the discoms, or some federal assistance program, to fill in revenue gaps during those years in which the central grid has not been extended. Our discussion also highlights the need for proper accounting rules with regard to the licensee's assets so as to ensure that the possibility of grid extension would not affect the entrepreneur's willingness to invest.

The remainder of the paper is organized as follows. Section 2 provides a summary of the structure and political economy of the Indian electricity sector. Section 3 presents results showing that there is indeed an economic rationale for the deployment of mini-grids in rural areas. Our survey evidence regarding the gateway barrier to mini-grid development is presented in Section 4. Section 5 describes and subsequently discusses the proposal by the FoR regarding a regulatory framework for licensing off-grid electrification. Concluding remarks are provided in Section 6. The Appendix contains supplementary material about (i) mini-grids, (ii) cost assessment, (iii) qualitative study methodology, analysis and interview protocol, and (iv) details regarding the accounting for asset values under the modified FoR proposal.

2 Electrification in Rural India

We use the framework developed by Malerba (2002) to outline the system that makes up the rural electricity industry in India. This framework describes a sector on the basis of its *technologies*, *agents*, and *policies* (*institutions*), as well as the *interactions* between these factors. Following the categorization by Alstone, Gershenson, and Kammen (2015), we segment electrification *technologies* into five scales. The smallest scale provides only the infrastructure required to charge household goods, such as mobile phones. Pico-lighting solutions, the next scale, provide small-scale lighting, such as that provided by solar lanterns. The third scale, solar home systems (SHS), is comprised of a small solar system that is designed to meet some share of a household's or firm's demand for power. SHS are capable of providing charging and lighting services and of powering high efficiency appliances. Fourth, mini-grid systems entail a generation source and the capability to balance the supply and demand for power across a set of homes and businesses (see Appendix for a schematic description of mini-grids). The final and largest scale is electrification provided by the central grid.

India's main rural electrification program focuses on two primary tools for electrification: extensions of the central grid infrastructure and, where this is cost prohibitive, the use of small generators and distribution networks (i.e., mini-grids). These two methods are not necessarily mutually exclusive. If small generation and distribution facilities are deployed such that future interconnection with the central grid is possible, such deployments become complementary to the central electricity network.

Agents within the rural Indian electricity sector include both public and private entities, operating within the policies and *institutions* that organize and shape the industry. Perhaps the most relevant public sector actors are the Distribution Companies (discoms), which are analogous to regulated utility companies in the North American and Western European contexts in their roles as the procurer and retailer of electricity. India's discoms are generally in poor financial health and ill-suited to mobilize the capital required to advance India's electricity infrastructural and investment requirements (Tongia, 2015). This condition is attributable to both a long history of selling electricity at a price below cost and a significant degree of aggregate technical and commercial losses on the electrical system. The pricing behavior of discoms reflects a social policy of providing access to electricity at a low price to the rural poor. In addition, since India's Green Revolution of the 1970s, the agricultural sector has received unmetered electricity, often free of charge (Mukherjee, 2014). Discom tariff schedules attempt to compensate for this subsidy by charging large commercial and industrial consumers high rates for electricity. However, this structure has often provided an incentive for commercial and industrial (C&I) customers to bypass the electricity service provider through their own power generation capacity. As C&I demand decreases, the revenue streams of the discoms do so at an accelerated rate.[8]

The lack of public capital to finance large-scale electrification points to the need for private capital in rural electrification efforts. The Government of India has recognized the need to attract private capital to realize its electrification goals. The Electricity Act of 2003,

[8]Mukherjee (2014) provides a comprehensive overview of the Indian electricity sector.

which governs the operation of the Indian electricity sector, sets three mandates to encourage private investment. First, it requires both the central and state governments to formulate policies for stand-alone systems for rural electrification. Second, it requires the governments to craft policies for rural electrification. Finally, it removes licensing requirements for a private participant to enter the generation and distribution components of the electricity system.

In practice, the record of private participation in rural electrification differs by the scale of electrification. Below the mini-grid scale, there are numerous suppliers providing rural electrification. Firms such as Mera Gao Power provide both charging and small-scale home lighting solutions, while companies such as Sunlite, Kavita Solar, and d.light provide stand-alone solar-powered lanterns. At a larger scale, Orb Energy, Simpa Networks, and Onergy are among the many firms that are active in the SHS sector. Above the mini-grid scale, a large number of firms are financing and developing utility-scale generation capacity for the central grid. For example, the Jawaharlal Nehru National Solar Mission has encouraged multiple utility-scale investments by private investors of at least 5 megawatts (MW) of generation capacity.

While private capital has also flowed to mini-grid scale investments, deployments have been limited. Companies such as Husk Power have installed a number of biomass-based mini-grids but have reduced their pace of deployment as they refine their business models and consider re-directing capital towards African markets (The White House, 2013). Similarly, most capital at scales larger than the SHS has been invested in micro-grid solutions by a small set of firms including Kuvam Microgrid, Gram Power, and Azure Power. Micro-grid solutions typically use direct, as opposed to alternating, current.[9] Households or firms that are electrified by direct current would not be able to scale up their demand by purchasing appliances or equipment that require alternating current. This technical limitation constraints the economic potential of micro-grids.

Finally, while companies like SunEdison have been been building mini-grid systems in India, they have restricted themselves to areas that have been eligible for incentives through the rural electrification component of the Deendayal Upadhyaya Gram Jyoti Yojana (DDUGJY) program.[10] Such incentives include a 90% subsidy for both capital equipment and the cost

[9]A standard distinction in power capacity between micro- and mini-grids does not exist (Nordman, 2015). Both can be of any scale and operate independently of a utility grid and contain local central generation.

[10]The DDUGJY program is a policy intended to provide access to electricity to all rural households

of operation for 5 years on top of a 10% loan from the Rural Electrification Corporation (REC) or a state government (Government of India (GoI), 2015).

From a cost-competitiveness perspective, there are indications that the rate of rural electrification by mini-grids should be higher than that observed today. As argued in the next section, unelectrified consumers and businesses have shown a willingness-to-pay for electricity from traditional energy sources, such as single household level diesel and kerosene, which suggests that mini-grids relying on electricity generation from solar and diesel resources would be economically viable and cheaper than the alternatives that are currently more widely used.[11] We also note that the DDUGJY initiative for rural electrification is intended to coordinate and encourage the deployment of both public and private capital, including both the extension of the central grid and the development of mini-grid systems, towards this goal.

Our observations of private participation in rural electrification efforts across different scales indicated that charging, pico-lighting, SHS and central-grid electrification investment opportunities have been progressing. In contrast, the development of mini-grids appears to be stalling, aside from idiosyncratic cases, such as the presence of an "ideal" anchor load or a village site that has been deemed too expensive for centrally-provided power.

3 Economic Rationale for Mini-grids

We compare the costs of mini-grid capacity relative to both incumbent energy services available to households without a connection to the central grid and retail rates from the central grid. We find that the cost of mini-grid-based electrification is lower than that implied by kerosene- or small pooled household-level diesel-based energy services. This implies that consumers' willingness to pay for energy services is likely to exceed the full cost of mini-

and electrification of all villages, stipulates the villages for which grid supply has been deemed infeasible. Until August 2013, this program was know as the Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY) program, which is still the unofficial reference to the support program. Banerjee et al. (2015) notes that the RGGVY (now DDUGJY) initiative aspires to electrify all Indian villages with more than 100 people, provide free electricity connections to households below the poverty line, and, where grid extension is not cost effective, install small generators and distribution networks (i.e., micro- and mini-grids).

[11] Pueyo et al. (2013) provides similar findings, where willingness to pay is not necessarily the barrier to rural electrification – especially in those areas where there is relative affluence.

grid-based electrification.[12] At the same time, the cost of mini-grid-based electrification is higher than indicative retail tariffs, suggesting the mini-grid would be unable to compete on a price basis with the central grid and would be exposed to substantial revenue risks upon the extension of the central grid without appropriate protections.

We organize our cost assessment around the levelized cost of electricity (LCOE) metric that is commonly used to compare alternative electricity generation technologies; our formulation is as defined in Reichelstein and Yorston (2013):

$$LCOE = c \cdot \Delta + f + w \tag{1}$$

In the expression above, c, f, and w are the cost of capacity, the time averaged fixed costs, and the time averaged variable costs, respectively.[13] Δ is the so-called "tax factor" that accounts for the effect of tax-related cash flows and the depreciation tax shield on the cost competitiveness of alternative technologies. Note that we assume a tax rate of 0% for household-level energy services, including kerosene lighting and pooled household-level diesel-based generation, as these are household-level costs. In contrast, we assume that mini-grids are operated by firms and apply a 35% corporate tax rate. Finally, we assume a cost of capital of 10% in our cost calculations. This reflects a real, as opposed to nominal, interest rate.

Although the majority of individuals who are unconnected to the central grid infrastructure lack any electrification, others generally have two options with which to access energy services. The first entails a kerosene-based lighting option. Table 4 in Appendix B details our assumptions about the kerosene technology. While kerosene solutions traditionally provide niche services such as lighting and cooking, consumers use diesel generators for more general electricity services.

The second alternative includes a diesel-based generation system in which a set of households share a small scale diesel generator to meet their cumulative power demand. We assess the LCOE of a diesel generator that meets household demand. In particular, we assume that each household's demand equals the per capita daily consumption of electricity among rural consumers in India, 1.80 kWh (The Energy and Resources Institute (TERI), 2013). To

[12]Though we of course expect that the willingness to pay will weakly decrease with the quantity consumed, we do not make any assumptions about the slope of the inverse demand function.

[13]Our explanation of these components is intentionally terse, as Reichelstein and Yorston (2013) explain them in depth.

construct an hourly demand profile, we split this cumulative daily consumption into hours of the day in proportion to the split observed by Banerjee et al. (2006). Figure 1 presents our assumed demand profile. We assume that households use a diesel generator to meet the nine hours of load of the greatest magnitude. Table 5 in Appendix B details our assumptions about the diesel technology.

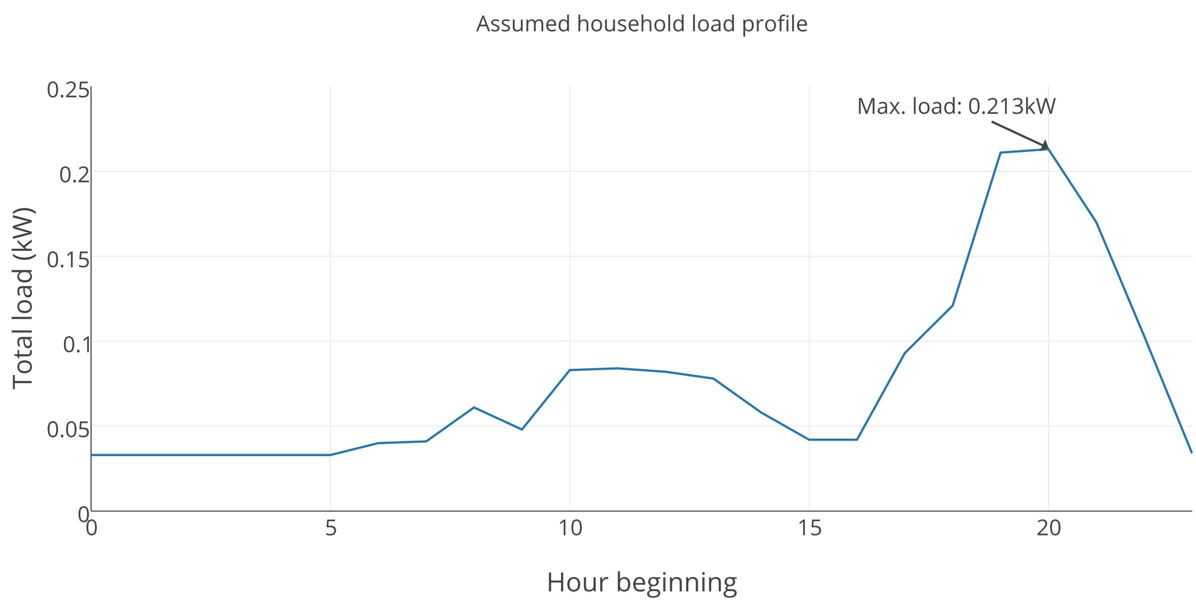

Figure 1: **Assumed demand profile.**

In calculating the cost of mini-grid electrification, we present cost estimates for three technological assumptions, namely mini-grids with (1) diesel, (2) solar and battery, or (3) solar and diesel generation technologies.[14] We assume that the profile is a scaled version of the profile presented in Figure 1, with the load in each hour scaled by 270.[15] To ensure comparability with the household-level diesel generation strategy, we assume that the mini-grid meets the nine hours of load of the greatest cumulative magnitude. We assume that each mini-grid is accompanied by a distribution network of 3 kilometers.[16] Finally, the mini-grid

[14]For more details, Appendix B presents our mini-grid cost estimation methodology.

[15]The median number of households in Gujarati villages is 270 (Registrar General, 2011).

[16]The length of this network reflects the spatial patterns of village housing in India. Consider the state of Bihar, where the median size of a village, net of irrigated land, is 51.84 hectares. Assuming that agricultural land is at the periphery of the village, we represent the inhabited area of the village with a circle of radius 406m. We further assume that households are not at the edge of the village but rather at a distance equal to half of the radius, or 203m. If households are clustered in sets of 20, such that each household does not require separate wiring, with 247 households in the median village in Bihar, we would require about 12 lines.

is assumed to provide electricity with 90% reliability. Accordingly, the mini-grid provides a cumulative amount of electricity service equal to 90% of the cumulative demand over the 3285 ($= 9 \cdot 365$) hours of service. As a consequence, we allow the solar- and solar combined with diesel mini-grids to drop load in the 10% of hours with the lowest solar resources. In contrast, the diesel mini-grid is allowed to drop the periods of lowest load so as to increase its operating efficiency.

Table 1 summarizes our mini-grid cost estimates, including distribution costs in USD.[17]

Table 1: **Summary of mini-grid cost estimates**

Generation source	**Generation LCOE**	**Distribution LCOE**	**Total LCOE**
Diesel	$0.556/kWh	$0.013/kWh	$0.569/kWh
Diesel and solar	$0.539/kWh	$0.013/kWh	$0.552/kWh
Solar and battery	$0.431/kWh	$0.015/kWh	$0.446/kWh

The full mini-grid LCOE is the sum of the generation and distribution LCOEs. The distribution LCOE differs for the solar and battery mini-grid because, when required to meet a 90% reliability criterion, the entrepreneur would operate this mini-grid to achieve 90% reliability. In contrast, the entrepreneur would operate the diesel and diesel combined solar mini-grids to achieve 100% reliability, given our assumption of free disposal of excess production. The distribution network is thus levelized over a larger base of production for the diesel and diesel and solar mini-grids.

Figure 2 summarizes our cost competitiveness assessment. The figure emphasizes two points. First, mini-grid solutions, across a range of technologies, are less costly than incumbent energy services that consumers who are not connected to the central grid are currently using. Second, all of the distributed (i.e., non-central grid) technologies greatly exceed an indicative retail rate offered by discoms, $0.062/kWh (INR 3.74/kWh at 1USD = 60INR).[18] Thus, an extension of the central grid would imply substantial revenue risks to the mini-grid entrepreneur in the absence of adequate protections. Households could opt away from the mini-grid and purchase lower-priced electricity from the central grid.[19]

While our cost assessments entail a range of assumptions, the directional conclusions are

This implies 12 lines * 0.2km/line or about 2.5km of wiring.

[17]Cost estimates are presented in USD for ease of comparability, and we note the assumption that the developer borrows in INR from a domestic lender and that the investment does not entail exchange rate risk.

[18]This retail rate is offered by Madhya Gujarat Vij Company Ltd., a distribution company in the state of

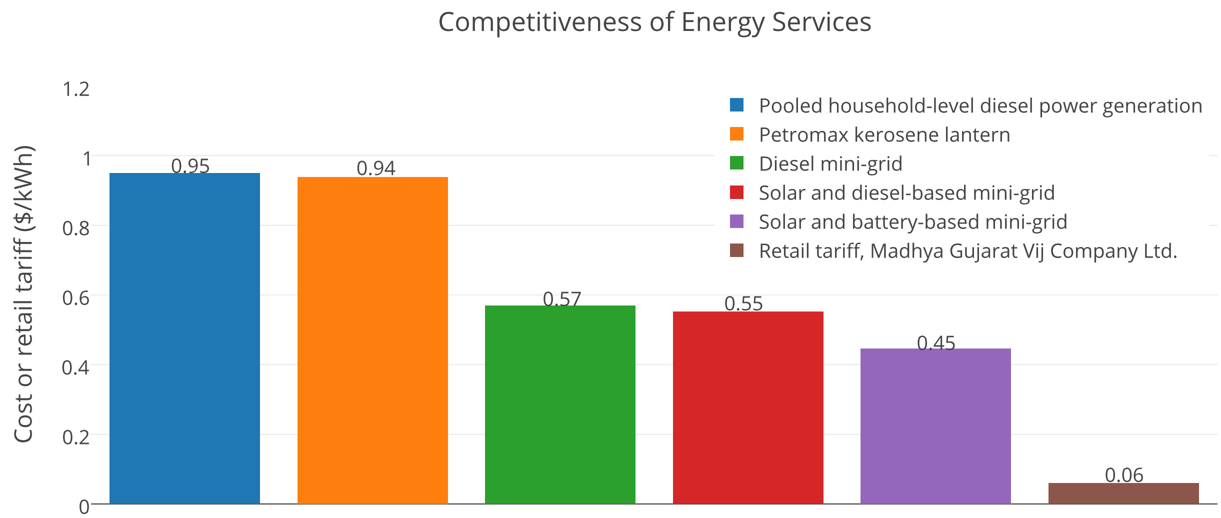

Figure 2: **LCOE of alternative energy services.**

robust to alternative specifications. For example, the temporal pattern of load could shift. Figure 4 in Appendix B presents an alternative load profile with a smoothed load profile between the late morning and evening. Under this load profile, we observe a similar relative ranking: mini-gird-based electrification is cheaper than either pooled household-level diesel power generation or kerosene-based lighting. In particular, we estimate that diesel-only, solar and battery-, and solar and diesel-based mini-grids cost \$0.52/kWh, \$0.36/kWh, and \$0.30/kWh, respectively, while the pooled diesel solution costs \$0.95/kWh. The cost of the kerosene solution and tariff from the central grid remain at \$0.94/kWh and \$0.06/kWh, respectively.

Finding 1: *Mini-grids powered by solar PV combined with battery storage are cost competitive in comparison to diesel based power generation.*

Gujarat, to its rural customers.

[19]The low price from the central grid does not reflect the full cost of central-grid based electricity. One of the primary differences between the cost and residential price of power from the central grid in India originates in cross-subsidies provided by commercial and industrial customers. as well as the fact that the discoms are not breaking even.

4 The "Gateway" Development Barrier

4.1 Methodology

The results in the previous section suggest the presence of other barriers that have thus far precluded the development of mini-grids. To identify a potential *gateway* barrier, we apply the qualitative case study method outlined in Eisenhardt (1989) and Yin (2013). As the name suggests, we seek to identify a barrier to mini-grid development that appears most crucial and, if addressed first, could allow the policymaker to follow a pathway of addressing subsequent and less important barriers (in similar fashion as outlined in Hoppmann, Huenteler, and Girod (2014)). Following Eisenhardt (1989), our process can be summarized in six steps.[20] First, we performed a literature review, focusing on the barriers to mini-grid deployment in developing economies. Such literature included experiences from countries other than India and studies that focused on other forms of off-grid electrification (i.e. solar home systems) in order to build a comprehensive set of potential barriers. We created an initial structured listing of barriers, providing a basis for the interview protocol, and a framework to measure each barrier's importance to the investment/development decision process. Table 9 in Appendix E presents our final typology, which reflects an iterative set of updates to this structure.[21]

Second, we performed a comprehensive search through business academic databases, industry associations, professional colleagues and online Indian newspapers to identify firms currently or previously active in the mini-grid development space. We described firms – amongst others – based on business model (e.g. pay-as-you-go, leasing, electricity-as-a-service, etc.), types of products/services offered (e.g. level of service, appliances, etc.), geographic focus and domesticity of headquarters. These firms provided a first set of interviewees, from which we learned both the specific vocabulary to use and the relevant policies, business models and consumer responses at play. This background data led to the third part of our approach – the development of initial interview questions, which were iteratively honed to be both sufficiently general to cover a wide range of experiences and narrow enough to elicit and elaborate specific experiences. Questions were tailored for each interviewee based

[20] Additional details of this approach are found in Appendix C.

[21] Frameworks for categorizing kinds of barriers have been developed in the past for renewable energy technologies in India – such as Painuly (2001) – we present a specific typology for mini-grid barriers.

on collected primary and secondary sources.[22]

We began our fieldwork in part four of our approach, conducting a set of first round interviews to enrich our understanding of potential barriers to mini-grid deployment. We then expanded our first round interview set to include philanthropic funds, multilateral development entities, academics and industry observers in order to broaden the perspectives.

Next, in step five, we performed initial grounded theory coding (Charmaz, 2014).[23] The preliminary findings from this exercise suggested that entities which could address identified barriers fell broadly into two categories: public sector entities and private sector entities. The former broadly included (but was not limited to) developers, investors and entrepreneurs. The latter broadly included municipal, state and central government regulators and policymakers. Preliminary findings further suggested that the Regulatory category (see Table 9) may likely contain the gateway barrier, given the many actors within the private sector which would not be fully capable of addressing it completely. In contrast, many of the barriers in the other categories appeared solvable with business model innovation.

This led us to step six: given our preliminary finding, we used theoretical sampling to identify Indian energy policymakers and conducted a second round of interviews in India. We identified entities within the central, state and local levels of government who had authority and responsibility related to electricity generation, transmission and distribution, including the determination of pricing schemes and enforcement of collections. Table 2 presents details about our 71 interviewees.[24,25] Interviews revealed that a variety of barriers across the typology contributed to mini-grid developers' decision to (i) exit the mini-grid space and not re-enter, (ii) exit and re-enter offering products and services focused on systems of smaller capacity as mini-grids, or (iii) avoid entering the mini-grid space altogether.

4.2 Interview Results

While interviewees cited revenue collection risk and the potential for theft as substantial hurdles to mini-grid deployment, a large proportion of this subset agreed that solutions to

[22]General protocol for the semi-structured interviews is provided in the Appendix D.

[23]In essence, grounded theory coding attaches labels to segments of data that depict what each segment is about

[24]We conducted 71 interviews in total.

[25]This second set also included India-based mini-grid entrepreneurs, NGOs and industry analysts, in addition to uni/multilateral development banks which had substantial presence in India working on rural, low-income electrification as a mandate.

Table 2: **Categorization of interviewees (first and second round).**

Category	**Interviewee Description**	**Count**
Policymaker/ Regulator	Federal Level - Senior/Executive Level Government Official MOP, MNRE, CERC, POSOCO	15
	State Level - Senior/ Executive Level Bureaucrat KERC	4
	Municipal Level - Senior/ Executive Level Bureaucrat BESCOM	5
Capital Providers	Director, Philanthropic Fund	1
	Managing Director, Multilateral Bank	2
	Managing Director, Development Fund	3
Project Developer/Investor	CEO/ Managing Director - Mini-grid/DER	5
Project Developer	CEO/ Managing Director - SHS	3
	CEO/ Managing Director - Mini-grid/DER	7
Industry Analyst/ Observer	Managing Director/ Analyst, India-based	22
	Senior Associate, Professor, Other-country based	4
Total		71

MOP: Ministry of Power — MNRE: Ministry of New and Renewable Energy

CERC: Central Electricity Regulatory Commission — POSOCO: Power System Operation Corporation

KERC: Karnataka Electricity Regulatory Commission — BESCOM: Bangalore Electricity Supply Company

such challenges can be found in carefully executed business models. Of note, challenges identified that fell into the barrier categories of financial, economic, socio-cultural and technical were routinely explained as those that are in the control/purview of the project developer and the investor, which together could decide whether to enter a market (village or villages), and if so, determining which technology to employ and how to address such risks within the project developer's business model.

Focusing on the remaining barrier category – regulatory – then became a natural focus. Interviewees across type and level of seniority identified the threat of central grid extension as the most prevalent regulatory barrier to mini-grid deployment. There appear to be two major reasons this is a fundamental challenge to mini-grid developers: (i) the uncertainty of the timing of central grid extension and, (ii) the tariff differential between what is regulated by the central grid and what needs to be charged to mini-grid customers to achieve economic viability from the perspective of the developer and investor. Whereas the central grid is mandated to charge a subsidized rate that is altogether less than the full cost of electricity.

In particular, the seeming unpredictability of central grid extension that is particularly vexing regarding this gateway barrier. The absence of a legal standing as an entity entitled to provide electricity and services removes any protection an operational mini-grid would have in the incidence of central grid expansion. This may be seen as an unintended consequence of the Energy Act of 2003, which effectively eliminated the need for a license to build, own and operate an electricity generation and/or distribution entity (Government of India, 2003). As central government official A pointed out *"Not needing a license is like a double-edge sword."* As stated by a project developer/investor *"It is hard to quantify, but 25, 30 percent of our customers will get disconnected. Which may make the mini-grid on a standalone basis financially not sustainable."* Paradoxically, removal of licensing requirement was expected by the central government to unleash private investment but may actually have had the opposite effect.

Next, the inability to plan for a central grid expansion and interconnection with a mini-grid removes the ability of a project developer – and by extension, investors – to plan the business model and/or use an alternative site selection approach for project development. The inability to plan is directly related to electricity being used as a political tool, where central grid extension planning could be readily co-opted by a motivated political force. As industry observer D noted *"Electricity is used as a political tool."* Further, industry observer C noted: *"So although there is on paper today a mechanism which says that there is a separate regulatory institution and there is a separate government policy-making mechanism – the government can actually influence in a big way what happens. And that the utility is actually an independent entity. But independence is only on paper. In almost all the places it is still a very big political issue."* Table 3 below provides further quotes from interviewees regarding the centrality of threat of central grid extension.

Finding 2*: The regulatory barrier characterized by the threat of central grid extension is the gateway barrier to mini-grid deployment in India.*

These observations strongly suggest that in the face of at risk revenues, project developers and investors will be reluctant to develop mini-grids . Our findings are consistent with the 'capital flight' literature, which draws a causal link between the presence of political risk and various removal of private capital from investments (Alesina and Tabellini, 1989; Lensink, Hermes, and Murinde, 2000; Le and Zak, 2006). Accordingly, with insufficient return expected in a mini-grid project, developers and investors exit the market. Alterna-

Table 3: **Exemplary Quotes**

Exemplary Quote	**Source**
...we also had to close six or seven sites because the centralized grid came in, and we decided not to take losses on those sites.	Project Developer, A
...the state... agency is not giving us the assurance that if you do these projects is the grid going to reach there in one year, three years, five years? So there is no solidity in all of that.	Capital Provider, B
The biggest risk for mini-grid[s]...is the availability of the grid...And the reason is of all of the 300 million people don't have access, about 90-95% of the villages covering the same population lives within 5 kilometers from the existing transmission network. So if the utility decides to provide access, then it can actually provide it the next day...that's one of the biggest risks.	Industry Observer, D
I mean, I have had projects in Karnataka where we have done these solar lighting systems projects, and in three months suddenly there is very high quality grid there, just because the local MLA [Member of Legislative Assembly] said I need this done. And the electricity company had to do it.	Capital Provider, A
...So that's how things happen when the centralized grid comes in. Most of the customers who typically pay for a basic package of two CFLs and cell phone charging, they switch to this government supplied power, and disconnect from our [system].	Project Developer, E
So having distributed generation, even if it's somewhat small, along those endpoints allows them [discom] to manage the grid a lot better...And so it's actually quite compelling for them [government] to actually do that. But that contract has never been written. Frankly, because there is no good business model in which you can go and show them [discom] that this is what I need you to do...You need a government that's ready to battle the [revenue] losses issue... And that's a political grenade.	Capital Provider, C
The other aspect is that you put up a micro-grid; you don't know what the government's plans are in terms of grid extension or strengthening the existing grid. Then your business model is in question. When is the grid coming? Do you have a plan to integrate with the grid if it does come in? What is your long-term plan, really?	Project Developer/ Capital Provider, A
[Unless]...the government figures out a way to work with the private sector to come together and come up with a solution that is sustainable in the long run it is going to be difficult for the micro-grid market really to take off.	Project Developer/ Capital Provider, A
With our portfolio, we are looking disproportionately at truly off the grid communities that will likely not be captured in the first or even second rounds of grid expansion.	Capital Provider, A

tively projects indeed are built, but only in locations where the investment opportunity is severely compromised. This scenario supports the push from a mini-grid to smaller, less productivity-enhancing generation sources (e.g. SHS). For example as project developer D revealed, *"[The solution is to] build even a smaller modular system so that you can take the assets and run. Build things that look more temporary than permanent, which is kind of sad. That's how we are trying to mitigate uncertainty around policies."*

What our finding do not demonstrate is that the gateway barrier is the only major barrier faced by mini-grid developers. Rather, our findings suggests the threat of central grid extension is a barrier that cannot be addressed by mini-grid developers. Therefore, to unlock the potential of mini-grids in India and the productive capacity they entail, the gateway barrier must be addressed as part of a policy in order to enable an efficient pathway for electrification.

5 Policies Enabling Mini-Grid Development

5.1 Guidelines from the Forum of Regulators

Taken together, the previous sections have argued that there is a clear economic rationale for mini-grids, yet the threat of central grid extension appears to be the gateway barrier to mini-grid development. Entrepreneurs are reluctant to invest because of the possibility of being held up on their capital investments. The immediate question then becomes how policymakers and regulators can address this hold-up problem so as to incentivize private capital flows directed towards rural electrification.

A noteworthy policy proposal in this regard has been put forth by the the Forum of Regulators (FoR) in 2010 under the heading "*Draft Guidelines for Off Grid Distributed Generation and Supply Framework*" (FoR, 2012; Joshi, 2012).[26] This proposal was first circulated in 2012 and has not yet been taken up by Indian legislators and regulators. In its current form, the scope of the proposal is aimed at electricity generation from renewable energy sources. For the purposes of our discussion, though, we will interpret the proposal more broadly as applying to distributed electricity generation that could rely on a combination of energy sources, possibly including solar PV and diesel-based power generation.

[26] The FoR is an assembly of state and central electricity regulators which meets regularly to discuss and comment on electricity regulation across India, and is a key advisory body for state electricity energy boards on how to shape policy within states and across the country.

The FoR proposal envisions that, contrary to the current legal stipulations provided within the Energy Act of 2003, an entrepreneur that would seek to develop a mini-grid in a particular jurisdiction would first need to be certified as part of an initial contractual agreement. In the language of the FoR, the entrepreneur is referred to as the *Rural System Operator* (RSO) who would enter into a *franchisee agreement* with the *discom*, subject to approval by the *State Regulatory Commission.* The entrepreneur (RSO) would thereby be licensed to operate the mini-grid on behalf of the Distribution Licensee and to provide electricity services to the community in question.

As part of the initial agreement, the potential franchisee would present an ex-ante cost calculation of initial investment expenditures and operating costs to be incurred in subsequent years. These costs would be broken out separately for electricity generation and distribution services. The FoR proposal envisions that the fees to be paid to the franchisee (RSO) would be determined on a cost-plus basis so as to cover all projected ongoing costs, including depreciation charges, and an adequate return on invested capital. Accordingly, the franchisee would be entitled to operating revenues that would include a fee related to the development and operation of the mini-grid as well as a feed-in-tariff, specifying a rate in rupees per kWh delivered, to compensate for the deployment and operation of the electricity generation assets. In particular, the RSO would enter into a Power Purchasing Agreement (PPA) agreement that would obligate the discom to buy pre-specified amounts of electricity from the franchisee at the feed-in-tariff for a time horizon corresponding to the useful life of the generation assets.

While the preceding guidelines specify a framework for revenues to be received by the RSO, the proposal also states explicitly that the retail electricity rates to be charged to customers within the jurisdiction of the mini-grid must conform to those that the distribution licensee charges to the same customer groups in other service areas of the discom. As noted in the previous section, electricity sales to households and agricultural customers are heavily subsidized. Accordingly, the FoR proposal anticipates a significant *tariff gap* between the mandated retail rates and fees that the RSO would be entitled to under the franchisee agreement. The proposal specifies that this gap would be made up on an annual basis in cash payments by either the discom or in the form of so-called *central financial assistance.*

Finally, Section 12 of the FoR proposal specifies the contingencies that would apply in case the central grid were to be extended to the service area covered by the mini-grid. In that case, the initial franchisee agreement for distribution services could be terminated. Specifically, the distribution licensee would have the unilateral right to acquire the distribution assets from the RSO at a transaction price given by the current book value of the assets. In contrast, the PPA for power generation and the attendant feed-in-tariff would remain in place. Since this tariff is likely to exceed the applicable subsidized retail rates, there would most likely still be a sizable tariff gap.

We note that the FoR proposal contrasts with the familiar form of rate-of-return regulation applied by public utility commissions in many countries. Whereas utilities (discoms) must submit to periodic reviews of expenditure, this is not needed under the FoR proposal, as all costs are budgeted upfront. This kind of 'price cap guarantee' does not require ongoing oversight, and shifts the subsequent operational risk to the entrepreneur. From an oversight perspective, the FoR proposal works well for renewable energy generation sources because future operating costs tend to be small.

In our assessment the FoR proposal has considerable potential to address the hold-up problem that a mini-grid developer would face in the absence of any regulatory framework. Importantly from the entrepreneur's perspective, the event of central grid extension would have no impact on receiving the feed-in-tariff for electricity produced, *if* (and this is a crucial "if") the entrepreneur were to be confident that any tariff gap would indeed be made up annually and independently of the grid extension event. The provision that distribution assets could be acquired by the distribution licensee at current book value is principally well-suited to provide an investment safeguard for the entrepreneur.

5.2 Evaluation of the Guidelines

The guidelines summarized in the previous subsection take, in our view, a significant step towards supporting the flow of private capital into mini grid development. In the current legal environment of India, a mini-grid developer does not require a license and conversely does not have any investment protection in case the local discom decides to extend the central grid to the jurisdiction in question. The guidelines of the FOR proposal regarding fees for the franchisee clearly limit the monopoly power of the RSO to the extent that future revenue claims are determined on a cost-plus basis so as to enable a target expected return return for the entrepreneur.

One significant concern regarding the FoR proposal relates to the credibility of the promise to make up the tariff gap. As noted above, discoms in India are generally cash-strapped and have weak balance sheets. From the perspective of the entrepreneur, there would be considerable residual risk regarding the ability to collect the remainder of the annual sales revenue claims from the discom or through central federal assistance. Furthermore, the chances of not being able to collect the tariff gap will arguably increase once the initial investment has been made and therefore becomes a sunk cost. This will be true in particular if the base revenues from subsidized electricity rates are sufficient to sustain the business operations on an ongoing basis.

We outline two modifications of the FoR proposal which, we believe, would significantly strengthen the investment safeguards for the entrepreneur and go a long way towards alleviating any investment holdup problem. First, while the overall fee structure for the RSO would be calculated in exactly the same manner as outlined in the FoR proposal, we suggest that the RSO should be allowed to collect these revenues *directly* from the customers in the domain of the mini-grid. While the initial tariff agreement with the distribution licensee may stipulate retail rates that are differentiated by customer categories, e.g., residential versus business customers, we envision the sales price per kWh delivered to mini-grid customers would in the aggregate be constrained by an overall revenue requirement. As a consequence, customers in the mini grid zone would, on average, gain access to electricity services at the full economic cost of mini-grid electrification. Clearly, this full cost will exceed the subsidized rates currently charged by the discoms.[27]

Our second modification of the FoR proposal pertains to the rights of the entrepreneur in case of grid extension. We suggest that in this event the entrepreneur should have the unilateral right to transfer ownership of both the distribution and the generation assets of the mini-grid to the distribution licensee. Consistent with the FoR proposal, the transaction price would be given by the current book value of these assets. In order for this provision to provide an effective safeguard, though, book values must be calculated so as to reflect economic fundamentals. In this regard, the accounting literature has highlighted the role of so-called *replacement cost accounting* for valuing operating assets; see, for example Nezlobin, Rajan, and Reichelstein (2012). It can be shown that if revenues are set so as to cover

[27]It can be shown that if one equates the allowed rate of return under the cost-plus fee structure with the cost of capital underlying our LCOE calculations in Section 3, the fee per kilowatt hour delivered, when calculated on a full cost basis, will also be equal to the corresponding LCOE figure. This follows from the observation that, by construction, LCOE is the break-even sales price in a net present value calculation.

operating costs (including depreciation) and a return on invested capital, the entrepreneur will be indifferent between (i) receiving the onetime buy-out payment equal to current book value or (ii) the stream of future revenues less operating expenses.[28] As a consequence, the entrepreneur would be indifferent between the event of grid extension and continuing to be franchisee on the original terms of the agreement. The potential event of grid extension would therefore not impact the initial investment incentives, effectively addressing the holdup problem.

Policies that address the hold-up problem are likely to affect the behavior of project developers and discoms. This change in behavior has implications for the spatial distribution of electrification by mini-grids versus central grid extension, and accordingly will have impacts on the extent certain segments of the rural and off-grid Indian population may capture the benefits of productive capacity through electrification.

There is evidence that, generally, those villages which are currently unelectrified but are most proximate to the central grid will benefit the most from electrification (Pueyo et al., 2013). This is because other pre-existing conditions may be in place such as access to markets and infrastructure, which in turn make it likely that electrification could yield the highest benefit based on the deployment of productive capacity. Further, these kinds of villages would also have – on average – a higher willingness to pay for electricity, specifically *high-quality, reliable* electricity (Winkler et al., 2011).[29] Villages closer to the existing central grid thus would seem likely targets for mini-grid developers.

Conversely, those rural, off-grid villages which are less proximate to the existing central grid, and perhaps have lower willingness to pay will be of lower priority to mini-grid developers. In addition, it may be more costly for the central grid to reach such villages, and even if it does, to provide reliable, quality electricity. While scholars such as Pueyo et al. (2013) and Banerjee et al. (2015) suggest that electrification should favor those with higher expected consumption levels, the Government of India has implemented efforts such as the DDUGJY to bring electricity to the remotest of villages. It remains a course of future study to predict the proportion of rural, off-grid villages that may "fall through the cracks" under particular regulatory policies.

[28]Appendix F reproduces the relevant identities linking discounted cash flows, depreciation schedules and book values.

[29]This adheres to the recommendation by Banerjee et al. (2015) that access to electricity should be provided first to those with expected higher consumption levels.

6 Conclusion

Literature on rural development concludes that the presence of electricity has the potential to enable productive capacity, which in turn tends to alleviate poverty. (see e.g. Ebrahim et al. (2010)). It has been observed that public funds are insufficient to provide central grid electricity for large portions of rural India. In response, private capital has sought to fill this gap through off-grid alternatives. While the smallest scale of these alternatives has gained a relatively high level of penetration across rural India, mini-grids have seen comparatively little diffusion. From a cost perspective, we have provided evidence that the rate of rural electrification by mini-grids should be higher than observed today. Motivated by this deployment gap, our analysis explores the impediments to private capital being attracted to deliver electricity services via mini-grids.

Our analysis evaluates the cost-competitiveness of three different mini-grid systems against alternative means of off-grid delivery of energy services (namely kerosene latern and pooled diesel generation). Our calculations are based on an assumed level of service, overall village demand and local cost considerations. We find that, in general, mini-grids – especially solar-plus-storage systems – are distinctly cost-competitive when compared to their incumbent off-grid alternatives. However, the levelized cost of electricity for such a mini-grid far exceeds the subsided electricity price that is offered to customers who are connected to the central grid.

Given this cost advantage and the perceived willingness to pay for energy services in an off-grid setting, we explore potential barriers to widespread mini-grid deployments. Through a qualitative analysis of multiple stakeholders including Indian regulators, financiers and mini-grid developers, we identify the so-called gateway barrier. The gateway barrier stems from the inability for mini-grid developers to protect their revenues in the event of central grid extension. Provided that mini-grids are not afforded licenses, the difference between the mini-grid and central grid tariffs motivate electricity customers to defect to the central grid for energy services, leaving the mini-grid developer with stranded assets. The prospect of being held up with a significant exogenous probability causes investors to avoid mini-grid development in the first place. While other barriers to mini-grid diffusion exist, we argue that the gateway barrier needs to be addressed first, as it is not under the control of the developer, but strictly the purview of a regulator.

We explore what actions policymakers can take to address this hold-up problem and, as a consequence, to incentivize private capital flows directed towards rural electrification. We discuss the merits of the FoR proposal entitled *"Draft Guidelines for Off Grid Distributed Generation and Supply Framework."* which has been designed to address the gateway barrier, but as of yet has not been implemented. We propose two modifications to the proposal to strengthen its ability to remove the gateway barrier. The first modification asserts that the mini-grid operator can directly collect revenues from the mini-grid customers. The second suggests that the franchisee license grants the mini-grid owner the right of asset transfer to the discom based on current book-value of the mini-grid system (generation and distribution assets) in the event of central grid extension. These two modifications of the FoR proposal should be effective in removing the gateway barrier facing mini-grid developers.

There are several promising avenues for extending the analysis in this paper. An important consideration is the design of the institutional processes which grants and administers licenses in a way that limits the potential for corruption. Further, provided the presence of a license, it would be interesting to explore what additional effects (i.e. lesser barriers) are either fully or partially addressed, and in what ways. Such "derisking" effects can be applied to a mini-grid setting (Schmidt, 2015). Finally, it would also be useful to explore the extent to which the removal of the gateway barrier decreases the financing cost of mini-grid investments.

Appendix

A Mini-grids

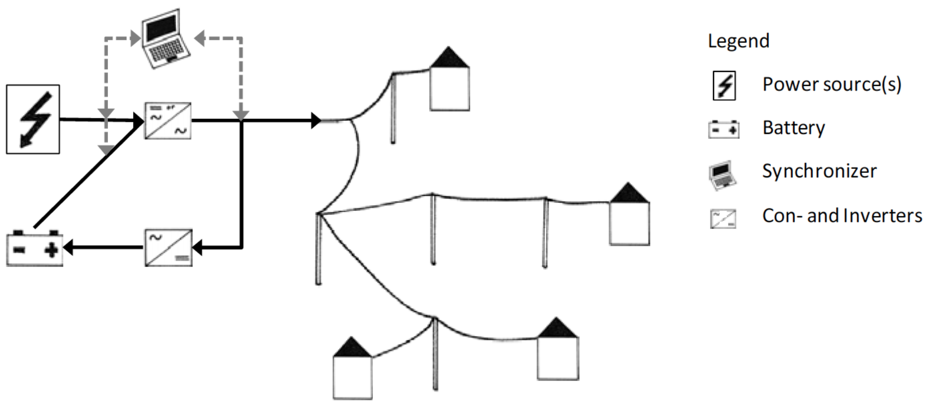

Figure 3: Mini-grids balance the supply of power from a small generation unit (i.e., power source) and the demand from customers. Figure is from Blum (2013).

B Cost Assessment: Assumptions and Details

We stress three points important to the interpretation of our kerosene cost estimate. First, our cost inputs are appropriate for a Petromax kerosene lantern.[30] Second, since consumers access a significant share of kerosene at subsidized rates through India's Public Distribution System, we present both unsubsidized and subsidized cost figures. Finally, since we use the levelized cost of electricity (LCOE) metric to compare the costs of alternative energy services, our kerosene cost numbers reflect assumptions about the electricity consumption that would be required to provide an equivalent lighting service. To provide the 1300 lumens of light intensity that the Petromax provides, a consumer would need to use either an incandescent bulb of 100 Watts (W) or an LED bulb of 12W. The LCOE of kerosene-based lighting is much higher if the consumer's alternative is to use a 12W bulb than if it is to use the 100W bulb. Since the same quantity of kerosene would be consumed to provide the service in either case, the LCOE will intuitively appear higher if the replacement technology is an efficient 12W bulb. Accounting for our two assumptions about kerosene prices

[30]The kerosene lantern market includes both Petromax and hurricane lanterns; the luminosity and efficiency of Petromax lanterns is greater than that of the hurricane lanterns.

Table 4: **Kerosene: assumptions and output.**

	100W	12W	Source
Price (2015 US$)	40.35	40.35	Miller and Hope (2000) Anil K. Rajvanshi (1989)
System price ($/W)	0.40	3.36	
Cost of capacity, c ($/kWh)	0.055	0.46	
Fixed operating cost (2015 US$/kW-year)	4.12	4.12	Miller and Hope (2000)
Time averaged fixed cost, f, ($/kWh)	0.02	0.16	
Kerosene fuel consumption (L/hour)	0.13	0.13	Miller and Hope (2000)
Kerosene retail price, subsidized ($/L)	0.25	0.25	
Kerosene retail price, unsubsidized ($/L)	0.67	0.67	
Kerosene cost per hour, subsidized (2015 $)	0.03	0.09	
Hours of use	6	6	Banerjee et al. (2006)
Lifetime	5	5	Miller and Hope (2000)
Discount rate	0.10	0.10	
Time averaged variable cost, w, subsidized ($/kWh)	0.33	2.75	
Time averaged variable cost, w, unsubsidized ($/kWh)	0.87	7.26	
LCOE ($c + f + w$), subsidized ($/kWh)	0.40	3.31	
LCOE ($c + f + w$), unsubsidized ($/kWh)	0.94	7.82	

and two replacement light bulb technologies, we present four kerosene cost numbers. If the replacement technology is a 12W bulb, the LCOE of kerosene-based lighting is $3.31/kWh and $7.82/kWh with subsidized and unsubsidized kerosene prices, respectively. On the other hand, if the replacement technology is a 100W bulb, the corresponding cost estimates are $0.40/kWh and $0.94/kWh.

Table 5: **Pooled household diesel generation: assumptions and output.**

	Value	**Source**
Generator capacity (kW)	1	
System price (2015 $/kW)	446	Alternate Hydro Energy Centre (2010)
Cost of capacity, c ($/kWh)	0.077	
Fixed operating cost (2015 US$/kW-year)	220	Schmidt, Blum, and Wakeling (2013)
Time averaged fixed cost, f, ($/kWh)	0.143	
Diesel consumption (L/hour), 25% utilization	0.15	Feinstein and Minnihan (2013)
Diesel consumption (L/hour), 50% utilization	0.15	Feinstein and Minnihan (2013)
Diesel consumption (L/hour), 75% utilization	0.15	Feinstein and Minnihan (2013)
Diesel consumption (L/hour), 100% utilization	0.14	Feinstein and Minnihan (2013)
Diesel retail price (2015 $/L)	1.30	Multiple of late-April 2015 price (INR 57/L)
Capacity factor	0.176	
Lifetime, T (years)	5	Miller and Hope (2000)
Discount rate	0.10	
Time averaged variable cost, w ($/kWh)	0.730	
LCOE ($c + f + w$), ($/kWh)	0.950	

Our calculations assume that four households pool to purchase and use a diesel generator.[31] Our assumptions about the household diesel solution imply a cost estimate of $0.95/kWh.[32]

B.1 Diesel mini-grid

Our estimated diesel mini-grid cost is based directly on the LCOE formula. Given the load profile, we calculate the LCOE of a mini-grid with a diesel generator of sufficient capacity to meet the profile's peak load. Table 6 presents our assumptions about the diesel mini-grid.[33] We highlight three important differences relative to the pooled household-level diesel case. First, the system price reflects the economies of scale characteristic of diesel generators; per

[31] This is a more conservative assumption than the scenario in which each household has its own generator, as the upfront cost of diesel generators decreases with the scale of the generator.

[32] We scale a late April 2015 diesel price of INR 57 per liter recorded by Indian Oil (see `https://www.iocl.com/Products/HighspeedDiesel.aspx`) by 1.37 to reflect the ratio of the average diesel price over the 36 months up to May 2015 to the diesel price in May 2015 (see `http://www.indexmundi.com/commodities/?commodity=diesel&months=60`). This adjusts for the drastic drop in crude oil prices that was observed in mid-2015.

[33] We estimate a system price (SP) by scaling the SP for a 30kW system from Alternate Hydro Energy Centre (2010) by the ratio of SP values for 55kW and 30kW systems provided by Feinstein and Minnihan (2013). We do not use their numbers directly because generators in India are cheaper than those in the U.S.

unit of capacity, diesel generators are cheaper at larger scales. Second, the diesel consumption entailed in larger generators is lower than that in smaller generators. Third, since we assume the mini-grid is operated by a for-profit firm, we account for corporate taxes and depreciation tax-shields associated with a 15 year straight-line depreciation schedule. We estimate a cost of \$0.56/kWh for diesel-based mini-grids, exclusive of distribution costs.

Table 6: **Diesel mini-grid cost assumptions and output.**

	Value	**Source**
Generator capacity (kW)	60	
System price (2015 \$/kW)	160	Feinstein and Minnihan (2013) Alternate Hydro Energy Centre (2010)
Cost of capacity, c (\$/kWh)	0.012	
Tax rate, α	35%	
Tax factor, Δ	1.24	
Depreciation $d_{t,diesel}$	Straight line over 15 years	
Fixed operating cost (2015 US\$/kW-year)	220	Schmidt, Blum, and Wakeling (2013)
Time averaged fixed cost, f, (\$/kWh)	0.127	
Diesel consumption (L/hour), 25% utilization	0.09	Feinstein and Minnihan (2013)
Diesel consumption (L/hour), 50% utilization	0.09	Feinstein and Minnihan (2013)
Diesel consumption (L/hour), 75% utilization	0.08	Feinstein and Minnihan (2013)
Diesel consumption (L/hour), 100% utilization	0.08	Feinstein and Minnihan (2013)
Diesel retail price (\$/L)	1.30	Multiple of late-April 2015 price (INR 57/L)
Capacity factor	0.176	
Lifetime, T (years)	15	
Discount rate	0.10	
Time averaged variable cost, w (\$/kWh)	0.414	
LCOE ($c \cdot \Delta + f + w$), (\$/kWh)	0.556	

B.2 Solar and battery mini-grid

To estimate the cost of the solar and battery mini-grid, we first determine which combination of solar module and battery capacities would minimize the LCOE of the mini-grid.

We use a search algorithm to select the solar module and battery capacities (P_{PV} and $P_{battery}$, respectively) that would meet all operational requirements at the minimal LCOE. The operational requirements are (1) that the combined solar and battery capacities meet the serviced area's demand profile over nine hours of service with a 90% reliability and (2) that the battery capacity adheres to depth-of-discharge constraints.

We follow four steps to identify the cost minimizing combination of solar and battery capacities, $\{P^*_{PV},\, P^*_{battery}\}$.[34] Our procedure searches iteratively larger sets of solar module and battery capacities, S_{PV} and $S_{battery}$, respectively.

First, we initialize our search by defining two one-point sets, with $S_{battery}$ equal to 0 and S_{PV} equal to P^{min}_{PV}. P^{min}_{PV} is the solar module capacity that would meet alone the cumulative consumption of the aggregate demand profile in a year, assuming an exact overlap between the demand and resource profiles and conditional on our assumption about the level of service from the mini-grid (i.e., 9 hours per day with 90% reliability). The sets define a unique initial candidate solution, $\{P^{min}_{PV},\, 0\}$ and an initial candidate LCOE, $LCOE_o$.

Second, we test whether the candidate solution meets the operational requirements. If so, we stop our search and infer that the cost minimizing combination of solar and battery capacities, $\{P^*_{PV},\, P^*_{battery}\}$, is equal to the current candidate solution.

Third, if it does not meet the operational requirements, we increase the current candidate LCOE by an increment, δ_{LCOE}, which we set to \$0.01/kWh. In tandem, we redefine the suprema of the sets S_{PV} and $S_{battery}$ to exceed the suprema of the sets of the previous iteration. Then, $sup(S^i_{PV})$ becomes $sup(S^{i-1}_{PV}) + \frac{\delta_{LCOE}}{K_{PV}}$, where K_{PV} describes the capacity and fixed costs associated with a unit of solar capacity and i denotes the present iteration count. Similarly, $sup(S^i_{battery})$ is $sup(S^{i-1}_{battery}) + \frac{\delta LCOE}{K_{battery}}$, where $K_{battery}$ describes the capacity and fixed costs associated with a unit of battery capacity. We then assess the ordered pairs of solar and battery capacities from S_{PV} and $S_{battery}$ that lie on an iso-LCOE line. In our search, we discretize S_{PV} at a granularity of δ_{PV}, which we set to 0.2kW.

Fourth, we repeat steps two and three until we reach a feasible solution. The first feasible solution is the cost minimizing combination of solar and battery capacities, $\{P^*_{PV},\, P^*_{battery}\}$.

Since we combine the system prices of the solar modules and the battery to derive the LCOE of the solar and battery mini-grid system, we present several required modifications of the LCOE formulation in Reichelstein and Yorston (2013). We calculate the cost of capacity as the sum of the module and battery costs. With c_{SBMG} representing the full cost of capacity, we have:

$$c_{SBMG} = \frac{(SP_{module} + SP_{BOS} + SP_{battery} \cdot \frac{P^*_{battery}}{P^*_{PV}}) \cdot \Delta}{8760 \cdot CF \cdot \Sigma_t x_t \cdot \gamma^t} \tag{2}$$

The $\frac{P^*_{battery}}{P^*_{PV}}$ term in the above equation normalizes the system price of the battery from a

[34] The model, which is implemented in Python, is available upon request to the authors.

dollar per kWh basis to a dollar per Watt basis. The system price of the battery assumes that 10% of the battery is replaced every year.[35] We follow Nykvist and Nilsson (2015) in assuming that battery costs will continue to decrease at an annual rate of 8%. Representing initial battery costs in dollars per kWh by $K^o_{battery}$, we thus have:

$$K^t_{battery} = K^o_{battery} * e^{-0.08t} \tag{3}$$

Above, t denotes the number of years since the initial period. Accounting for these cost dynamics, we have the following formulation for $SP_{battery}$:

$$SP_{battery} = K^o_{battery} \cdot (1 + 0.1 * \Sigma_{t=1}^{t=29} e^{-0.08t} \cdot \gamma^t) \tag{4}$$

While we assume that neither the solar nor battery capacities entail any variable costs, we must update the expression for fixed costs to accommodate the different units on the solar and battery components. With f_{SBMG} representing the full time-averaged fixed cost, we have:

$$f_{SBMG} = f_{module} + f_{battery} \cdot \frac{P^*_{battery}}{P^*_{PV}} \tag{5}$$

In the equation above, the rightmost term allows us to express the fixed costs of the overall system in terms of dollars per kWh.

Table 7 details our assumptions about solar and battery systems, which together imply an LCOE of \$0.431/kWh, exclusive of distribution costs.[36]

[35]By using the same tax factor for the solar and battery components, we assume that the firm effectively purchases a stream of battery components, the total cost of which can be depreciated in years 1 and 2.

[36]Blum, Wakeling, and Schmidt (2013) suggest that fixed costs are 1.5% of capacity costs, but we use the \$10/kWh-year figure to provide a conservative estimate. Note also that our capacity factor of 0.149 may seem low. However, this capacity factor reflects not only the resource availability, which would imply a capacity factor of 0.2355, but also the share of maximum potential generation that is used to provide the target level of service to the area served by the mini-grid.

Table 7: **Solar and battery mini-grid cost assumptions and output.**

	Value	Source
Module price, SP_{module} (2015 \$/W)	0.7	GTM (2015a)
Balance-of-systems price, SP_{BOS} (2015 \$/W)	0.8	GTM (2015b)
Lithium ion battery price, $SP_{battery}$ (2015 \$/kWh)	410	Nykvist and Nilsson (2015)
Solar panel size (kW)	71.6	
Battery size (kWh)	346	
Cost of capacity, c_{SBMG} (\$/kWh)	0.359	
Fixed O&M cost, solar, $f_{t,module}$ (2015 \$/kWp DC-year)	15	Comello and Reichelstein (2016)
Fixed O&M cost, battery, $f_{t,battery}$ (2015 \$/kWh-year)	10	Schalk and Cloete (n.d.)
Time averaged fixed cost, f_{SBMG}, (\$/kWh)	0.051	
Variable operating cost, w_t (2015 \$/kWh)	0	Reichelstein and Yorston (2013)
Time averaged variable cost, w_{SBMG} (\$/kWh)	0.000	
Module degradation rate, x_t	.995	Reichelstein and Yorston (2013)
Tax rate, α	35%	
Tax factor, Δ	1.06	
Discount rate, r	0.10	
Depreciation $d_{t,solar}$	80% and 20% in years 1 and 2	
DC/AC de-rate factor	0.85	Reichelstein and Yorston (2013)
Capacity factor, CF	0.149	
Lifetime, T (years)	30	
LCOE $(c \cdot \Delta + f + w)_{SBMG}$ (\$/kWh)	0.431	

B.3 Diesel and solar mini-grid

Since the diesel and solar mini-grid system represents a hybrid of generation technologies, our cost estimation procedure begins by determining the contribution of each of the generation components to meeting load. As in our cost estimation for the solar and battery mini-grid, we search over a combination of solar module capacities in the set S_{PV} and diesel capacities in the set S_{diesel}. Our search proceeds in five steps. We first select a particular solar capacity from S_{PV}. Given the solar resource and load profiles of the area served by the mini-grid, we next calculate the share of demand that can be met by a solar facility of that size. Third, we determine the residual demand that must be met by the diesel facility. Fourth, we select a diesel generator of an appropriate size to meet the residual demand. Fifth, we calculate the LCOE of the combined mini-grid system as the weighted average of the solar- and diesel-specific LCOEs, with weights defined by the share of load met by the solar and diesel capacities, as shown in the expression below:

$$LCOE_{DSMG} = share_{Solar} \cdot LCOE_{Solar} + share_{Diesel} \cdot LCOE_{Diesel} \tag{6}$$

Above, $DSMG$ denotes the diesel and solar mini-grid, and $share$, the fraction of load met by the solar or diesel generation capacity, as appropriate. To find the LCOE-minimizing combination of solar and diesel capacities, we proceed through the set S_{PV}.

Table 8 details our assumptions about solar and diesel systems, which together imply an LCOE of \$0.539/kWh, exclusive of distribution costs.

Table 8: **Diesel and solar mini-grid cost assumptions and output.**

	Value	**Source**
Module price, SP_{module} (2015 \$/W)	0.7	GTM (2015a)
Balance-of-systems price, SP_{BOS} (2015 \$/W)	0.8	GTM (2015b)
Solar panel size (kW)	20.8	
Cost of capacity, c_{solar} (\$/kWh)	0.245	
Depreciation $d_{t,solar}$	80%, 20% in t=1, 2	
Tax factor, solar, Δ_{solar}	1.06	
Fixed O&M cost, solar, $f_{t,module}$ (2015 \$/kWp DC-year)	15	Comello and Reichelstein (2016)
Time averaged fixed cost, solar, f_{solar}, (\$/kWh)	0.025	
Time averaged variable cost, solar w_{solar} (\$/kWh)	0.000	
Lifetime, solar, T_{solar} (years)	30	
Degradation rate, solar x_t	.995	Reichelstein and Yorston (2013)
DC/AC de-rate factor	0.85	Reichelstein and Yorston (2013)
Solar capacity factor, CF_{solar}	0.0712	
LCOE, solar ($c \cdot \Delta + f + w$) (\$/kWh)	0.284	
Diesel size (kW)	60	
Diesel system price, SP_{diesel} (2015 \$/kW)	160	Feinstein and Minnihan (2013) Alternate Hydro Energy Centre (2010)
Cost of capacity, c_{diesel} (\$/kWh)	0.017	
Depreciation $d_{t,diesel}$	Straight line over 15 years	
Tax factor, diesel, Δ_{diesel}	1.23	
Fixed O&M cost, diesel, $f_{t,diesel}$ (2015 \$/kW-year)	220	Schmidt, Blum, and Wakeling (2013)
Time averaged fixed cost, diesel, f_{diesel}, (\$/kWh)	0.146	
Lifetime, diesel, T_{diesel} (years)	15	
Diesel consumption (L/hour), 25% utilization	0.09	Feinstein and Minnihan (2013)
Diesel consumption (L/hour), 50% utilization	0.09	Feinstein and Minnihan (2013)
Diesel consumption (L/hour), 75% utilization	0.08	Feinstein and Minnihan (2013)
Diesel consumption (L/hour), 100% utilization	0.08	Feinstein and Minnihan (2013)
Diesel retail price (2015 \$/L)	1.30	Multiple of IndianOil Aug. 2015
Time averaged variable cost, diesel w (\$/kWh)	0.410	
Tax rate, α	35%	
Discount rate, r	0.10	
Diesel capacity factor, CF_{diesel}	0.1727	
LCOE, diesel ($c + f + w$) (\$/kWh)	0.576	
Load met by solar, $share_{solar}$	0.125	
LCOE $(c \cdot \Delta + f + w)_{,DSMG}$ (\$/kWh)	0.539	

B.4 Distribution costs

The levelized cost of distribution reflects both the capital cost of distribution wiring and the volume of electrical power distributed over the lifetime of the distribution network. Given our assumptions about the level of electricity service (i.e., 9 hours), length of wiring (3km), and demand profile (see Figure 1), and reliability (90%)[37], distribution costs are a function of only the capital costs of the distribution network. We follow Chaurey and Kandpal (2010) in assuming a capital cost of 2010 INR 150,000/km.[38]

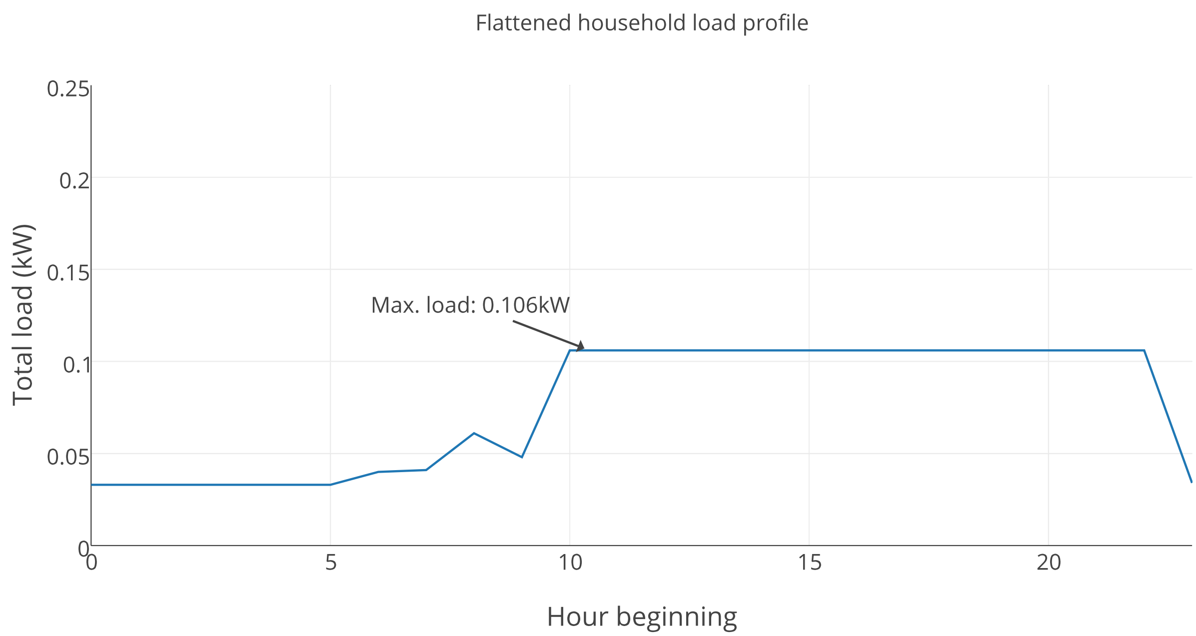

Figure 4: Alternative demand profile.

C Interview Methodology: Additional Details

Interviews were served by continual updates to the research framework, which in turn was informed by inclusion of additional primary and secondary research. All interviews took between 45 and 90 minutes and were conducted by at least two researchers to help ensure reliability of findings and capitalize on novel insights. Interviews were audio recorded, and later transcribed and independently verified for accuracy. We closed our information collection

[37]Except for the diesel-based mini-grid, in which case the reliability is 100%.

[38]We scale this to 2015 INR by the ratio of the Indian wholesale price index in April 2015 to that in April 2009. We source wholesale price index data from `http://www.eaindustry.nic.in/home.asp`.

stage once the marginal value of additional interviews yielded little new insight (Eisenhardt, 1989). In addition to the description of the interview methodology provided in Section 4, the following provides additional details of the interview approach.

C.1 Access to Private Sector Interviewees

Given that project developers are faced with the barriers to mini-grid deployment, we focused on this interviewee group. We contacted project development firms by email or through the professional networking site, LinkedIn. Since our interest lies in understanding how project sponsors chose the scale and location of electrification to pursue, we interviewed the founders of companies, unless they were no longer at the company. For only two firms, we were unable to interview the founder, given the company's size and diversified portfolio. The vast majority of firms we interviewed were solely focused on one technology type and one business model and were small in revenue-terms. It was important to interview the entrepreneur to full understand what they considered and what barriers they faced that shaped the creation of the present business model. The firms we interviewed represented 60% of the mini-grid/off-grid industry in India. To generate a sample of industry analysts, NGOs, uni/multilateral and academics, we used email to reach an initial set, and used snowball sampling (Rowland Atkinson, 2004) to identify those who would provide expert opinion given the focus of their work.

C.2 Access to Indian Government Interviewees

To access government interviewees, we identified relevant entities, such as the Ministry of Power (MoP), Ministry of New and Renewable Energy (MNRE) and the Central Electricity Regulatory Commission (CERC). Whereas MoP and MNRE set energy policy in general (MoP) and specifically for renewable energy (MNRE), CERC is mandated to set tariffs for central generation stations and importantly, develop mechanisms to efficiently and effectively meet the policy goals of the ministries. A similar structure exists at the state level, where a State Electricity Regulatory Commission (SERC) sets the operating and tariff structure by which the associated discoms abide. We focused specifically on the state of Karnataka, its regulator (KERC) and its largest discom, located in Bangalore (BESCOM).[39]

[39]With respect to electricity, Karnataka has one of the more advanced regulatory and technical systems in India. As such, its policymakers have a nuanced view of different kinds of electrification processes. This, coupled with ready access to senior policymakers, made the case to focus on Karnataka compelling.

We selected senior level people from the websites. We contacted those individuals whom we did not know with direct mailings and those we knew or were in our network of professional contacts, with emails. Further, in India, we identified and interviewed additional senior level leaders through snowball sampling. In total, we conducted 52 interviews while in India; of these interviewees, 20 were senior policymakers. In an effort to increase both internal and external validity, we intersperse interviews with industry analysts and other experts with policymakers. Where feasible, we interviewed multiple representatives from a given policymaking and/or regulatory entity to provide further sources for triangulation.

C.3 Transcription and Coding

The majority of interviews that were not recorded were those involving senior electricity policymakers and regulators in India. It was indicated by the interviewees that it was culturally and professionally inappropriate to record a conversation of such a nature. In the cases of not transcription, owing to no interview, interviewer notes were used as primary evidence of the assertions made during such interviews. All transcripts were saved in a secured, central case study database. The online collaborative qualitative assessment tool Dedoose was used for all coding exercises. Interview transcripts were independently reviewed and assessed for statements which referred to the constructs identified in the research framework. To ensure that the codes were understood as to be applied consistently given the multiple kinds of elicitations expected in the interviews, we employed pre-consensus coding. Through an iterative process, this increased the inter-rater reliability (i.e. consistency in comprehension and application of codes by the project team) (Gibbert, Ruigrok, and Wicki, 2008).

D Interview Protocol

The general interview protocol used follows.

Date:
Interviewer(s):
Interviewee(s) and role(s) in firm/agency/organization:
Firm/agency/organization name and type of firm:
Location of firm/agency/organization:
Location of interview:
Start time/End time:
Guiding script for opening statement / project description and goals: Thank you for taking the time to share your thoughts with us in this interview. This is part of a study exploring the deployment of solar photovoltaic electricity generation systems in developing economies. We anticipate that the interview will take approximately 60 minutes. We would like to record the interview, but all collected information will have identifiers removed to protect interview respondents. You do not have to answer every question and can stop the interview at any time...
Recording code / reference #:

1. Can you please tell us about your business/agency, its purpose and the context or situation in which you work, and how you got started doing this?

2. [Private Sector] Please share more about the kinds customers you serve, where they are located, and how you chose to serve them. [Public Sector] Please share more about how customers are segmented and what are the structures/philosophies behind such decisions

Potential [Private Sector] Prompts:

- *[Define market / opportunity with the interviewee. Is this micro-grid, mini-grid, etc.?]*
- *Larger Market: Can you tell us a little bit more about what you currently see as the overall market for solar mini-grids in India?*
  - *Can you please share how you defined and estimated this market opportunity? (Are the numbers you're providing revenue, profits, households, individuals, etc.?)*
    - *History: Has the situation changed in the X years since you've been in this business?*
    - *Future Projections: Do you anticipate the demand to change as time goes by? If so, how? What needs to happen for the market to "take off"?*
  - *Categorization: How do you think about the mini-grid market in different situations or sites?*
    - *PROMPT: Do you consider what this market looks like in urban, rural, peri-urban communities separately? If so, how?*

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- *PROMPT: Do you consider what this market looks like in communities that are off-grid, on an unreliable grid, or using backup? If so, how?*
- *PROMPT: Do you consider residential compared to commercial demand?*

- *Other considerations:*
  - *Does this estimate consider alternatives, such as kerosene replacement?*
  - *Does this estimate consider how customers are using electricity, particularly customers getting access for the first time?*
  - *Can you please share how you think about the dynamics of the demand curve?*

- *Serviceable Market: Thank you for explaining the large industry demand to us. Could you now tell us a little bit about what you see as* ***your*** *market? How much of the larger market can be reached by your firm?*
  - *PROMPT: What are your products or services, and how do these fit into the larger market?*

  - *Can you please give a sense of how much you think this could be scaled up in the future?*
    - *PROMPT: In terms of doing more of what is currently being done?*
    - *PROMPT: In terms of diversification of products/services (i.e. different generation options, different storage configurations, different product/service combinations or offerings)?*
    - *PROMPT: In terms of replicating in more locations (similar or different from where your services are now)?*

- *Assumptions: Is there anything you do not know about the market you are in, or are assuming about this market?*

Potential [Public Sector] Prompts:

- *What are the major governing rules that segment customers? How have they changed? Who has jurisdiction over them? How are retail and wholesale electricity rates determined? How is quality of service measured? How do different segments of electricity customers behave in terms of rate changes?*

3. [Private Sector] What activities and processes are parts of your approach to address the market opportunity? Can you please share more about your business model and how you developed it? [Public Sector] What models have been used to address off-grid or rural electrification?

Potential [Private Sector] Prompts:

- *Where does your firm operate, and how did you decide on those locations? (What geographies have you considered for X and how did you narrow them down?)*

- *Can you share more about your targeted customer segmentation?*

- *Can you share more about your value proposition?*
  - *How did you take advantage of market opportunities?*
  - *Did you use any novel ideas/innovations (USP: unique selling proposition)? If so, which ones?*

- *Can you share more about how you connect to customers?*
    - *What networks or channels do you use to reach the customers?*
    - *How do you maintain customer relationships?*

- *Can you share more about the revenue streams you created? (e.g., INR/kWh)*
    - *Are you charging customers upfront, or over time?*
    - *PROMPT: If you charge over time,*
        - *What pricing models are you using, or what is the implied per unit charge?*
        - *How do you make this model incentive compatible?*
        - *Do you use a pay-as-you-go (PAYG) model?*
    - *Can you share how you decided on this pricing model? (e.g., outside options)*
        - *[Discuss if the model is incentive compatible?]*
    - *If you're using a combination of products, can you share more about why you chose those products?*
        - *[We want to ensure we know what is in the portfolio of the firms' offerings.]*

- *Can you please share more about your cost structure?*
    - *What is the plant size? What factors helped you decide to size the plant this way?*
    - *What are the costs per plant? Please include fixed costs, variable costs, and levelized cost of electricity (LCOE).*
    - *What are the costs at the company level?*
    - *Can you share if your firm is profitable? Can you share what are your margins? What would help your firm increase its profitability?*

- *What has been your access to capital like? What has influenced your ability to obtain financing? [We want to ensure that we ask about access to capital and whether the underlying technology affects the interviewees' abilities to obtain financing.]*

Potential [Public Sector] Prompts:

- *What models have worked in engaging the private sector?*
    - What are the different methods by which electrification of the rural populations occurs?
    - How are decisions regarding off-grid electrification rendered?
    - Who is ultimately responsible for rural and/or off-grid electrification?
    - What incentive structures have been used? How were these developed? How is success measured? How successful have these structures been?

4. [Private Sector] What has been your experience with trying to deploy your products or services? [Public Sector] Provided how rural and off-grid electrification is occurring and the described rate, what could be improved (leading to discussion of barriers, outlined below).

Potential [Private Sector] Prompts:
What is your current installation rate? How does this compare with what you would like your installation rate to be? Are you deploying at different rates in different locations/settings? If so, why do you think this may be the case?

[Follow-up on any mentions of difficulties during the deployment process, or begin prompting questions below to learn more about potential barriers – ideally, we could try waiting to see if interviews bring up

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challenges or barriers on their own? ● *Possible approach 1: Start general, then follow-up on specifics* ● *Possible approach 2: Prompt interviewee around each type of barrier that's of interest to us*

Please describe the ecosystem in which your firm operates. What influences have shaped your actions? Has anything helped, or hindered you in deploying your product or replicating your model? *PROMPT:* ● *What has helped determine if you are successful or unsuccessful - when/where? why/how?* ● *What risks, if any, do you perceive? What concerns you most?*	If you have encountered any challenges *(wait for them to bring up challenges, if possible)*, how has your business made adjustments to address or overcome them? What has been your learning process? *PROMPT:* ● *In terms of approaches or adaptations that you've tried, what has worked and what hasn't worked - when/where? why/how?*

Can you please tell us more about ______(type of barrier mentioned)?

Economic barriers? [e.g. high transaction costs, small market size, low demand, low customer ability to pay, etc.]	*Addressing economic barriers?*
Financial? [e.g. high capital cost, long payback period, long investment tenor, etc.]	*Addressing financial barriers?*
Technical? [e.g. lack of local expertise, durability and quality, intermittency, etc.]	*Addressing technical barriers?*
Regulatory? [e.g. institutional capacity, tariff structure, lack of technical standards and codes, etc.]	*Addressing regulatory barriers?*
Social/Cultural? [e.g. community acceptance, perceptions of inferior quality, theft and non-technical losses, etc.]	*Addressing social/cultural barriers?*

5. [Private Sector] How do you plan to scale or diffuse your product? [Public Sector] Thinking about private participation in rural and offgrid electrification, how would you coach/advise entrepreneurs in this space to be successful?
6. Closing: Is there anything else you think is important in deploying mini-grid electricity generation systems that we have not talked about during this interview?

E Barrier Typology

Policymakers, academics, entrepreneurs and industry analysts have identified several barriers to the widespread adoption of mini-grid electrification solutions in rural India. As outlined in Table 9 in Appendix E, we identify five kinds of barriers to entrepreneurial activity: economic, financial, technical, socio-cultural and regulatory. Within each kind, there are multiple sub-categories – of which some are mentioned more frequently in the literature than others. We note that all barriers are addressable by the investor/project develop, except for regulatory barriers which are either partially or completely addressable only by legislators and policy makers.

Economic barriers are those which focus on the business model related to the mini-grid, whereas financial barriers relate to the ease of acquisition of necessary capital to implement the business model. Technical barriers are those that refer to the capabilities, operation and performance of the underlying technology of the mini-grid. Socio-cultural barriers are broadly concerned with the extent to which a technology and its associated factors are accepted by the receiving community (Wolsink, 2012). Regulatory barriers are the most wide-ranging as they relate to the institutions that influence the success of a business model in the context of technical, financial and socio-cultural considerations. External institutions affect the performance of the economy by their effect on the cost of production and exchange, i.e. the full cost of transacting good/service in exchange for remuneration (North, 1990). These institutions manifest themselves broadly in the forms of policies and regulations, which in turn interface with firms (and their business models) and investors. In the context of mini-grids, regulatory barriers are those policies, regulations and legal frameworks which either favor energy technology solutions at different scales to mini-grids, or actively (intentionally or otherwise) discourage mini-grid deployment.

Table 9: **Barrier Typology**

Category	Sub-categories	Source
Economic	High transaction costs	Painuly (2001); Palit and Chaurey (2011); Gershenson et al. (2015)
	Small market size	Painuly (2001); Palit and Chaurey (2011); Bhattacharyya (2013)
	Low demand	Painuly (2001); Palit and Chaurey (2011); Bhattacharyya (2013)
	Cust. ability to pay	Bhattacharyya (2013)
	High cost of capacity	Painuly (2001); Alzola et al. (2009); The Climate Group (2015)
	Revenue collection uncertainty	The Climate Group (2015); Franz et al. (2014); Bhattacharyya (2013); Ulsrud et al. (2011); Blum, Wakeling, and Schmidt (2013)
Financial	High capital cost	Painuly (2001); Chaurey and Kandpal (2010); Gershenson et al. (2015); Tongia (2015); The Climate Group (2015); Shrimali et al. (2013)
	Long payback period	Painuly (2001); cKinetics (2013); GNESD (2014)
	Insuff. capital (developer)	Painuly (2001); Ulsrud et al. (2011); GNESD (2014); Gershenson et al. (2015); Shrimali et al. (2013)
	Insuff. capital (consumer)	Painuly (2001); Ulsrud et al. (2011); GNESD (2014); Gershenson et al. (2015)
	Lack of familiarity (capital providers)	Gershenson et al. (2015); Schmidt, Blum, and Wakeling (2013)
	Long investment tenor	Shrimali et al. (2013)
Technical	Lack of local expertise	Painuly (2001); Ulsrud et al. (2011); Chaurey and Kandpal (2010); Tongia (2015); Schmidt, Blum, and Wakeling (2013)
	Durability and quality	Painuly (2001); Shakti Foundation (2015); Gershenson et al. (2015)
	Intermittency	Shakti Foundation (2015); Schmidt, Blum, and Wakeling (2013)
	Lack of interoperability (with central grid)	Ulsrud et al. (2011); cKinetics (2013); Chaurey and Kandpal (2010)
	Monitoring and control	GNESD (2014); Gershenson et al. (2015)
Social/Cultural	Community accept.	Painuly (2001)
	Percept. of inferior quality	Chaurey and Kandpal (2010); Bhattacharyya (2014); Franz et al. (2014)
	Theft & non-tech. loss	Gershenson et al. (2015); Chaurey and Kandpal (2010)
	Limited understanding of the benefits of elect.	Bhattacharyya (2013)
Regulatory	Institutional capacity	Bhattacharyya (2013); Chaurey and Kandpal (2010); GNESD (2014)
	Discom tariff structure	Bhattacharyya (2013); GNESD (2014); Ulsrud et al. (2011); Blum, Wakeling, and Schmidt (2013)
	Lack of technical standards and codes	Painuly (2001); Chaurey and Kandpal (2010); Franz et al. (2014); GNESD (2014); Schmidt, Blum, and Wakeling (2013)
	Threat of grid extension	cKinetics (2013); Bhattacharyya (2013); Shakti Foundation (2015); Kobayakawa and Kandpal (2014); The Climate Group (2015)
	Lack of enforcement	Painuly (2001)
	Permitting & licensing	Gershenson et al. (2015)

F Determination of Book Values

It suffices to consider a representative investment project, consisting of generation and distribution assets. This project requires an up-front expenditure of b at time 0 and entails (expected) operating cash flows of CF_t in the next T periods. These cash flows are given by the sales revenues that the entrepreneur (rural systems operator) receives less current operating costs. Consistent with the proposal by the FoR, the allowable sales price per kWh of electricity would be determined upfront so as to cover all (expected) costs and provide the entrepreneur with a normal return on the capital invested in generation assets and as well mini-grid infrastructure.

The remaining book value of assets at any date $1 \leq t \leq T$ is determined by the depreciation schedule that is used to allocate the cost of the initial investment across time periods. Denoting the depreciation schedule by $\{d_t\}_{t=1}^{T}$, the depreciation charge in period t becomes $d_t \cdot b$. The depreciation charges are restricted to add up to the initial investment. Thus:

$$\sum_{t=1}^{T} d_t = 1.$$

Assuming that all current revenues and current operating costs are incurred on a cash basis, *Income* in period t is given by:

$$Inc_t = CFL_t - d_t \cdot b,$$

while the current book value is determined recursively as:

$$BV_t = BV_{t-1} - d_t \cdot b.$$

Here, $BV_0 = b$, and therefore $BV_t = [1 - \sum_{i=1}^{t}] \cdot b$ and $BV_T = 0$.

The fair market value of the investment project at time t is equal to the value of future operating cash flows discounted back to time t:

$$MV_t = \sum_{i=t+1}^{T} CFL_i \cdot \gamma^{i-t}. \tag{7}$$

where $\gamma = \frac{1}{1+r}$ and r is the applicable cost of capital which would be determined as part of initial licensing of the project. Our modification of the FoR proposal outlined in Section 5 envisions that in case of grid extension the entrepreneur would have the unilateral right to transfer ownership of the generation and distribution assets at a price given by the current book value. The entrepreneur would be indifferent towards grid extension to the area of his/her mini-grid (and therefore have unbiased investment incentives in the first place, provided the book value of assets is equal to their fair market value.

A fundamental result in the accounting literature is that for any (proper) depreciation schedule, there is the following relation between fair market- and book values:

$$MV_t = BV_t + \sum_{i=t+1}^{T} [Inc_i - r \cdot BV_{i-1}] \cdot \gamma^{i-t}, \tag{8}$$

which holds for all periods $0 \leq t \leq T$. The term in brackets on the right-hand side of (8) is usually referred to as *Residual Income*, given by Income less an interest charge on the remaining book value.[40] In order for fair market values to equal book values at each point in time, depreciation and book values must therefore be calculated so that residual income in each period is equal to zero. Hotelling (1925) showed that there is a unique depreciation schedule that achieves zero residual income in each period, provided the investment project has zero net present value to begin with, that is, $MV_0 = b$. Consistent with the FoR proposal, the allowable revenue per kWh of electricity in period t will then be set equal to current operating costs plus depreciation charges plus imputed interest on the remaining book value.

The corresponding depreciation schedule is usually referred to as *replacement cost accounting* in the accounting literature; see Nezlobin, Rajan, and Reichelstein (2012) for further details. In the special case where the assets can deliver the same electricity output in each year of their useful life, the depreciation charges amount to the so-called *annuity depreciation method* for which $d_{t+1} = d_t \cdot (1 + r)$. In that case, the sum of the depreciation charge plus imputed interest charge, that is, $d_t \cdot b + r \cdot BV_{t-1}$ is equal to b times the reciprocal of the annuity value of \$ 1 paid in each of the next T years at the interest rate r. For example, if $T = 20$ and $r = 10\%$, then the corresponding annuity value is 8.5, with reciprocal $\frac{1}{8.5} \approx .18$. Thus the price per kWh in period t would be equal to current operating cost per kWh plus 18% of the initial investment expenditure, after dividing by the annual number of kWh delivered by the system.

[40]The result in (8), which goes back to Preinreich (1937) is sometimes referred to as the *conservation property* of residual income. Over the entire lifetime of the project the stream residual incomes conserves the value of the stream of cash flows

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