Feasability of Grid Compatible Microgrids

by

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Abstract

There are 1.1 billion people in the world who lack access to electricity, mostly in rural areas. The expansion of the central grid has been slow in many developing countries, hampered by a lack of supply, poor finances, and politics. Distribution companies in these countries are often cash strapped, in a tremendous amount of debt and are unable to make adequate investments in infrastructure.

Off-grid technologies can be the most cost-effective choice in remote areas, and they also can offer a solution for communities that will not receive reliable centralized electricity for many years. These solutions include solar home systems and microgrids. However, investment in microgrids has been discouraged by the risk of the central grid expanding into the service area of a microgrid. An attractive solution is to create technical standards for microgrids such that they are able to connect to the grid if or when it arrives, and to provide regulations for the integration of these systems into the operation of the main grid. This arrangement could reduce the risk to microgrid investors significantly. While existing literature speculates on the value of such a system, the costs and benefits have not been quantified.

This analysis uses the Reference Electrification Model, a tool developed in collaboration by the Massachusetts Institute of Technology and IIT Comillas - Madrid, to assess the costs and benefits that might arise when using grid compatible microgrids. These results and an assessment of the regulatory context and forthcoming regulations show that grid compatible microgrids can provide significant social value, but only if supported by sufficient subsidies and a recognition of the costs imposed on society by depriving so many people of electricity.

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Contents

Chapter 1

Introduction

1.1 Overview - The Energy Access Challenge

There are 1.1 billion people in the world who lack access to electricity, mostly in rural areas [55]. Electricity access could dramatically improve their quality of life and reduce poverty [46]. The expansion of the central grid has been slow in many developing countries, hampered by a lack of supply, poor finances, and politics. Even having a grid connection in a developing nation does not always mean access to quality electricity. For example, villagers interviewed in Bihar, India, reported that the average number of hours of service per day was 1.3 hours in bad months, and 6.3 hours in good ones [40].

The scale of investment needed to build the electricity infrastructure for these people is phenomenal. At the same time, climate and other environmental objectives necessitate that planners and policy-makers consider how to best provide electricity service in light of the grave dangers posed by climate change. While greenhouse gas emissions should not be used as an excuse to deny access to a basic level of electricity, neither should electricity access be planned without regard to the climate implications of growing access and consumption. The creation of a new electricity system in these parts of the world presents a tremendous opportunity to design the best, cleanest system possible, without the obstacles technological lock-in and stranded assets present in developed-world electricity systems. Williams paints a rosy and optimistic view of the opportunity that developing countries have in exploiting off-grid electrification, both for accelerating electricity access and for developing a more modern, sustainable grid;

> "In the absence of legacy systems, many developing countries have the opportunity to leverage decades of technological advancement and experience in developed countries as they build innovative modern infrastructure systems. Microgrids, small electricity networks that have the ability to operate autonomously, can play a key role in developing an electricity infrastructure built around decentralized renewable energy technologies. At the same time, microgrids can accelerate electricity access to areas the central electricity grid cannot reach in the short to medium term. As these microgrids develop, they can be easily interconnected, creating a decentralized network that can aggregate loads and generation capacity, while maintaining the ability to operate as isolated systems should the need arise. Many developed nations are now devoting significant resources to retrofit existing infrastructure and permit the integration of decentralized technologies. **Countries with underdeveloped electricity systems are well positioned to leapfrog outdated centralized approaches**." [emphasis added] [60]

Putting this vision into action and balancing the two moral imperatives of electricity access and GHG reduction in developing countries is no small feat. India and China, for example, are building out their coal capacity just as fast as they can to meet growing demand, and the developed countries have not been as forthcoming as hoped in providing additional financing and other support for low-carbon power. However, the attractiveness of renewable energy sources for many rural, unelectrified people presents a glimmer of opportunity to meet both of these objectives at once. Such technologies can be the most cost-effective choice in remote areas [30]. Off-grid systems can offer a solution not only for extremely remote locations that will never see the centralized grid, but also for communities that will not receive reliable centralized electricity for many years.

Distribution companies in many developing countries are cash strapped. India provides a dramatic case study in the dysfunction of distribution companies; they are in a tremendous amount of debt and are unable to make adequate investments in infrastructure. These cost pressures mean that cost-efficiency is key for any rural electrification program. Appropriate use of off-grid systems should be considered as an important aspect of such a program, since these systems can be more cost-effective than traditional centralized electrical infrastructure for many small, poor, and remote communities. Even if they are not more cost-effective, they may still be available sooner and be able to deliver electricity more consistently at more useful times.

Microgrids and solar home systems could be installed in many communities years before the central grid might be able to reach them. Their ability to leverage many sources of capital could give them a huge advantage in nimbleness and scalability over government-funded utilities which must negotiate bureaucracy, infrastructure, and finances that are often arrayed against their progress. Additionally, in places where the centralized grid is known to be highly unreliable, off-grid systems could more reliably provide electricity for critical loads at peak hours. Finally, off-grid systems built to be compatible with the centralized grid could retain their usefulness after the grid reaches them; they could be integrated into the grid, ultimately providing savings on distribution wiring costs for the utility, while providing electricity faster to remote communities.

There are several obstacles limiting the potential of distributed, renewable energy sources. First, regulators and state-controlled utilities may not know the magnitude of the cost savings that could come from using a mix of on-grid and off-grid approaches, so they may not even be aware of the opportunity. As a result, they may not have put in place policies that could create a fertile environment for off-grid electricity businesses to grow. Second, many of the countries with low levels of electrification lack sufficient funds for a comprehensive electrification program; private investment is almost certainly needed to provide a significant portion of the funds needed. Creating a favorable investment environment is challenging in these countries, but there are several routes by which regulators might do so.

Many nations have a two-pronged approach to electrification, both through promoting the extension of the centralized grid and through supporting distributed electricity sources like solar home systems and microgrids. However, for such a scheme to work, regulators must craft a clear plan for what happens when the two approaches meet [54]. Without such a plan, investors in a local microgrid run the risk of losing their entire business to the centralized grid, which is typically able to provide much lower tariffs to customers thanks to significant government subsidies. Recent studies have shown that this risk is a key obstacle hindering growth in the microgrid sector in India [14]. There are other downsides to the grid taking over in addition to putting local microgrids out of business. Any renewable generation that might have been supplying customers of that microgrid will probably be replaced by electricity generated by coal or other fossil fuels that dominate the centralized grid. If the centralized grid is unreliable, as it is in many parts of the rural developing world, customers additionally may lose reliability (especially during peak hours) by switching over to the centralized grid. This is clearly an undesirable scenario.

A potentially attractive solution is to create technical standards for decentralized electricity systems such that they are able to connect to the grid if or when it arrives (hereafter referred to as 'grid-compatible microgrids'), and to provide regulations for the integration of these systems into the operation of the main grid. This arrangement could assure investors in the original system of a continued return on their investment in the event of the arrival of the grid, or at least an attractive exit strategy.

However, such an arrangement would impose higher initial costs on microgrid projects, and brings up a host of regulatory and financial questions. How should tariffs be set before and after the microgrid is connected to the grid to ensure equitable payment by customers and cost-recovery for investors? Will the reduction in uncertainty create a sufficiently attractive investment environment, despite higher upfront costs? What level of subsidy will be needed to maintain this approach, and is such a subsidy feasible? These are the types of questions addressed in this thesis. This analysis will focus on the specific context of India, but my conclusions should be broadly applicable in developing countries.

The official policies of India have focused on the expansion of the central grid as the main means for providing electricity. Although they have allowed the development of off-grid systems, and even promoted them for extremely remote areas, there is still significant room for Indian policies - and, indeed, for the policies of many developing countries - to exploit the benefits of off-grid electrification.

1.1.1 Research questions

Putting numbers to the benefits that grid-compatible microgrids could provide would help direct policy discussions towards more effective electrification solutions. With so much money and so many livelihoods on the line, it is important to base policy decisions on the best available data and analysis. The Reference Electrification Model (REM), a rural electrification planning tool developed at MIT over the last three years, gives us the tools to address the questions surrounding grid-compatible microgrids quantitatively, and to frame policy discussions around a firm understanding of the magnitude of the tradeoffs. In light of all this, this analysis examines the following questions:

- What is the potential for grid-compatible microgrids to enable societal cost-savings? Under what conditions would the higher up-front costs be outweighed by the benefits?
- What type of regulatory factors are necessary to make these projects feasible and financially appealing?

We focus on the Indian context but my results can be useful in a variety of contexts.

In order to answer this question we employ REM, a planning tool that is completing its initial development phase, as well as financial analysis, and available literature and stakeholder interviews. We will use the district of Vaishali, within the Indian state of Bihar, as a case study.

1.1.2 The viability gap

Any discussion of rural electrification is incomplete without acknowledging the so-called 'Viability Gap.' This concept refers to the gap between the cost of building the infrastructure to supply electricity to rural areas, and the revenue collected from rural customers. For rural systems, the upfront infrastructure to reach them is more expensive, and the cost of operating and maintaining the infrastructure and collecting tariffs will be higher due to the remoteness of the area. Electrical losses may also be greater, leading to an additional financial penalty. The issue is not just that providing electricity to rural consumers is more expensive than supplying urban consumers; rural consumers also often have lower demand and a lower ability to pay for electricity services, especially in developing countries. The combination of these factors means that rural consumers often may not be able to pay for the cost of their electricity [8]. The gap between what they can pay and the actual cost gives rise to the Viability Gap.

The idea of the viability gap is not a new one. The cross-subsidization of rural consumers by their urban counterparts is common throughout the world and through the history of electric grids, both in developed and developing countries. In the 1930s, electricity was uncommon in rural parts of the United States; it was only through the Rural Electrification Administration (REA), established by President Franklin D. Roosevelt as part of the New Deal, that electricity services were extended to rural America. The REA provided grants, loans, and loan guarantees to rural electric cooperatives, and it still exists today, providing loans and loan guarantees to cover the viability gap[1].

[1]More info available at https://en.wikipedia.org/wiki/Rural_Electrification_Act and

Today it is common for utilities to charge the same tariffs to their urban consumers as their rural consumers, although the latter are more costly to provide for; this arrangement allows the cross-subsidization of rural consumers by their urban counterparts, and helps utilities remain solvent while extending their service to everyone. Many developing countries face the issue that there are not enough urban consumers to subsidize all the rural consumers. With a smaller urban to rural ratio, utilities have few options for providing universal access while remaining solvent. Government subsidy is vital. A key lesson from rural electrification programs in Brazil, China, and southern Africa is that "in most successful programs, a substantial proportion of the investment has been obtained at reduced or low interest rates or in the form of subsidies/grants," [54]. Even reduced-rate loans may not be sufficient to meet the viability gap; grants are usually necessary.

These same conclusions hold true for off-grid investments; there is likely to be a gap between the cost of service and what consumers can pay, and that gap will need to be filled by the government, or a philanthropic organization. The inability of many off-grid systems to turn a profit in the absence of a subsidy, then, should not be seen as grounds for dismissing them as a solution. All we can strive to do is identify ways to narrow that gap, and provide subsidies to bridge it while still encouraging efficient business practices. Experience has shown that even poor consumers are able to pay for a low level of service, such as the few hours of evening electricity for a light bulb and mobile charger provided by the minimalist microgrids of Mera Gao [3]. However, above these basic levels, ability to pay may drop off sharply. Encouraging private investment can open access to greater quantities of capital, encourage greater experimentation with business models, and provide better incentives for efficiencies. However, expecting it to eliminate the need for subsidies may ultimately be too high a bar in many parts of the world.

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http://blogs.usda.gov/2015/05/11/rural-electrification-celebrates-80-years-of-rural-productivity/ and http://www.rd.usda.gov/about-rd/agencies/rural-utilities-service. Accessed April 29, 2016.

1.1.3 Indian context of energy access

Although the Indian government has made repeated pledges and funded numerous programs aimed to bring electricity to all people living in India, 29% to 37% of Indians have no electricity access, or else have access to electricity that is extremely unreliable [32]. The lack of adequate electricity supply in India has been widely reported, and its effects felt in large blackouts as well as the persistence of regular outages. The lack of sufficient generation is compounded by the problem of degraded and insufficient transmission and distribution infrastructure to bring electricity to users. Even when there is sufficient generation capacity, the distribution companies may be unwilling to purchase electricity when wholesale prices are high, since tariffs are not high enough to cover the costs of supply. India's government is aware of the issues and has made significant efforts to improve electricity supply through reforms like the Electricity Act of 2003 and many other policy programs for rural electrification [28].

1.1.3.1 Electrification regulation & programs in India

Electricity Act of 2003: In 2003, the Indian government passed the Electricity Act of 2003, which remains the landmark piece of legislation governing the electricity sector, and led to significant reforms. It led to the break-up of the State Electricity Boards, which had been large vertically-integrated utilities that owned everything from generation to local distribution. The State Electricity Boards were broken up into separate generation, transmission, and distribution companies. The transmission businesses and distribution businesses were allowed to exist as regulated utilities, and regulatory bodies were created to oversee them. Generation was delicensed, allowing private generation operators to sell to any licensed distributors or, in some cases, directly to customers [9]. However, open access, though required by the Act, is being implemented only haltingly by regulators [28]. The Act does not distinguish between distribution and retail activities, although it does allow regulators to introduce some measure of retail competition at their discretion, though this has not come to pass [9].

However, if regulators did so, it would likely be in name only, since retailers be unable to compete with the heavily subsidized service provided by state-owned distribution companies.

The Act containes several parts that were very relevant for rural electrification. It encoded the 'universal service obligation', which mandates that the states, through the distribution companies, are responsible for providing access to electricity to all villages and hamlets. In many states this obligation is far from being met, and, as discussed below, distribution companies are far from being able to meet it in the near-term. Acknowledging that this mandate is outside the ability of local distribution companies, regulators have often turned a blind eye to this requirement.

Perhaps the most important impact of the Act was that it allowed the generation and distribution of electricity in rural areas (e.g. through a microgrid) without a license. This law lowered the barrier for countless microgrid companies to enter the market where the distribution companies were not able to reach. There is a legitimate debate surrounding the sagacity of such a lack of regulation for microgrid electricity service providers, but it does seem to have jump-started the market. These issues are discussed further in Section 5.

RGGVY and DDUGJY: The Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY) program, which has been since subsumed within Deendayal Upadhyaya Gram Jyoti Yojana (DDUGJY) program, facilitates India's goal of providing universal access to electricity for rural households. RGGVY was launched in 2005, with the ambitious goal of providing universal access by 2009. In 2013, it was subsumed under DDUGJY. The program aims to provide an electricity connection to all Indian villages with 100 people, with an emphasis on grid extensions, and provides for the strengthening of the distribution system. Electricity connection is provided for free to households under the poverty line under these programs. Where grid extension is deemed infeasible or not cost-effective, there is some support for off-grid systems. However, the focus of the program has been primarily on grid extension. The costs of rural electrification are funded by a 90% subsidy from the Ministry of Power, or 100% subsidy for the connection of households below the poverty line. Preferential loans are available through the Rural Electrification Corporation (another Indian governmental organization) for the remaining 10% of the cost. [39], [3] and [30] provide a detailed description of the program and its effectiveness. In theory, states must meet requirements including reliability of supply, and provision of supply for at least 6 to 8 hours per day, or else the grants will be converted into interest-bearing loans. In practice, this punishment has not been enforced [30].

DDUGJY added two additional goals to those of RGGVY, meant to address supply in agricultural regions. It provides support for the separation of electricity feeder lines in agricultural areas, so that agricultural uses will be fed by one line, and household and commercial uses fed by another line. It also provides for the strengthening of the sub-transmission and distribution network in rural areas, notably including the metering of transformers, feeders, and customers [36]. The significance of this move is discussed below.

RVE: The Remote Village Electrification Program (RVE) picks up where RGGVY and DDUGJY leave off. It provides support for hamlets with less than 100 people, and for areas where grid-extension has been deemed infeasible or not cost-effective. It provides a 90% capital subsidy from the Ministry of New and Renewable Energy. Under the program, electricity supply can be provided from the most economical local resources, including conventional and non-conventional generation sources. In practice, many households are provided with solar PV home lighting systems, which are often seen as a second rate service, making this program politically unpopular [39].

1.1.3.2 The trouble with India's distribution companies

The poor state of distribution companies (discoms) in India is a major cause of the poor quality of electricity supply and the widespread lack of access. Discoms are deep in debt across India. As of March 2015 they had cumulative losses of 3.8 trillion Rs, or $USD 57 billion. Cumulative outstanding debt was 4.3 trillion Rs, or $USD 70.6 billion [45]. To put that in perspective, the amount owed to banks by India's distribution companies is 2.5 times India's defense budget, and larger than its national fiscal deficit [5]. The shortfall between tariffs and costs means that ongoing operating costs are covered by even more debt. Discom losses in 2013 were 3% of India's GDP [55]. Although the discoms receive substantial subsidies from the government, these subsidies are far from covering all losses, and even the subsidies that are promised are not always delivered [30, 28, 51].

All this debt reverberates across the electricity sector. Banks are reluctant to lend additional money to these over-leveraged institutions, so distribution companies often have difficulty coming up with money to cover investments and even operational costs. As a result, infrastructure is often poorly maintained, leading to outages, and due to low tariffs discoms buy less power than their consumers demand when wholesale prices are expensive, necessitating power cuts. Their lack of credit-worthiness makes them a suspect counterparty for contracts with generation companies, which has a chilling effect on investment in additional generation [30].

Reasons for poor finances of discoms These large and growing losses have their root in the political capture of electricity regulators, tariff schedules that do not allow discoms to cover their costs, and large subsidies that states do not always refund. Solving these issues will be key to providing better electricity access across India. Although this situation is evolving and some hopeful developments are on the horizon, it remains an important and sobering backdrop to the discussion of off-grid electricity in India, and understanding it will put the discussion of the regulation of microgrids in a helpful context.

Low tariffs are the major reason for the poor financial situation of discoms [30]. High levels of theft and uncollected tariffs (collectively referred to as 'non-technical losses') as well as actual losses also contribute to the substantial gap between the cost of supply and collected revenue for distribution companies. Social and political pressure to keep tariffs low has meant that tariffs are rarely revised upwards, despite mandates from the Electricity Act of 2003 for annual revisions of the tariff. Tariffs are now significantly below the cost of providing service. Between 2007 and 2011, the average gap between cost of supply per kWh and the tariff ranged from 1-1.4 Rs, or 1.5-2 cents in USD [30]. For the North Bihar Power Distribution Company, fiscal year 2015-2016 saw collected revenues that were only 70% of the calculated revenue requirement[2], a figure that is especially astonishing given that the revenue requirements are often calculated using overly optimistic estimates of the discom's ability to improve their efficiency and reduce nontechnical losses. Distribution companies are increasingly dependent on subsidies to cover their operational costs; in Bihar, such subsidies comprised 33% of the state budget in 2011, an huge fraction in a state that scarcely has the resources to afford such subsidies [30].

There are indeed many poor customers who should rightly have access to electricity below the cost of providing it, as a humanitarian right. However, such a program should be ideally limited in its scope to those who truly need it. Instead, the government provides limited subsidies, and the distribution companies often attempt to recoup some of this extra cost by charging higher tariffs to commercial and industrial customers. This cross-subsidization creates a vicious cycle wherein commercial and industrial consumers are charged a rate above the cost of service, encouraging them to set up their own private generation facilities which may be more reliable and more cost effective. As more companies do this, the revenue received by the discom drops, forcing them to raise commercial and industrial tariffs further to support the cross-subsidization scheme [28].

Tariff reform is necessary for improving the electricity sector in India. Many in the sector are aware of this fact, yet tariff reforms have not happened. The reason for this lack of tariff reform can be attributed to the political capture of utilities and,

[2] Table 6.66 of the Tariff Order for the North Bihar Power Distribution Company. Found at http://berc.co.in/media/Tariff-Order/Tariff%20Order%20NBPDCL%20FY%202015-16.pdf Accessed April 6, 2016

importantly, the state regulators of electric utilities. The utilities owned by the state government, and many appointments within them may be through political cronyism (which also contributes to an inefficient hiring). Electricity is a major political bargaining chip in India, and the close relationship between state government, distribution companies, and electricity regulators allows politicians to manipulate its price and supply. A 2015 study showed convincingly that state governments frequently manipulate the supply of electricity, especially in strongly contested areas [7]. In November 2015, in the lead up to state elections in the state of Bihar, the state's Chief Minister directed the distribution companies to provide electricity connection to all customers for free (though they would still have to pay for the electricity once connected) [24]. Reduced or free electricity is a common promise in Indian election cycles.

The Electricity Act of 2003 created independent regulators to oversee the electricity sector, including the discoms; part of their job is to ensure that the discoms do not abuse their monopoly power, that they operate efficiently, and that they comply with governmental mandates. The current status of the distribution companies indicates that they have not been able to do so. The regulators are often 'captured' by the state government, and tend to comply with the political will therein. Often, the regulator is appointed not based on competence but rather based on political ties. As well, they are dependent on grants from the state government to fund their activities, so a government which disliked the regulator's activities could retaliate by defunding them [28, 8]. Even if a regulator did have the desire to enact reforms or to punish a discom for missing agreed-upon milestones, they would have few tools available to them. Financial incentives and penalties are the main tool of the regulator, but such instruments do not have a great effect since the state can ultimately absorb any fines, for example penalties levied for not meeting the universal service obligation or the renewable portfolio obligation. The lack of independence and useful enforcement tools makes it difficult for the state regulators to enforce sensible tariff adjustments, especially when such adjustments are a politically hot issue.

The political capture of the utility and regulator has consequences beyond tariff reform. Since efficiency can be less important than politics, utilities may maintain an unnecessary number of employees, some of whom may be there through political favors. The discom is incentivized to purchase power and other materials not from the cheapest bidder, but rather from a politically favored company. They are also unlikely to be open to key electricity sector reforms like open access, which would allow private parties to buy and sell generation over the distribution grid in private contracts [28].

Reasons for Poor Supply The factors outlined above and a few other issues as well have combined to provide the discoms with an array of reasons and even incentives to provide unreliable electricity service. The most important of these reasons is that tariffs are below the cost of service, so that the more electricity the discoms sell, the more money they lose. Discoms would rather purchase less electricity when wholesale market prices are very expensive and cut supply to their own customers, because tariffs are not high enough to cover electricity purchase costs [30]. The lack of adequate installed generation capacity in India has received significant attention overseas, yet the issue of willingness to purchase may be considerably more important. Arguably, if discoms were able to reliably purchase electricity, there would be significantly more investment in generation.

The lack of supply is compounded by an aging infrastructure. Without sufficient funds to maintain and upgrade their infrastructure properly, distribution companies are often forced to cut supply even when electricity is available. These supply cuts could be caused by the failure of a component like a transformer. Often, as well, they are the result of upstream medium voltage distribution lines being too small to meet the full demand of all the attached feeder lines at peak hours, so some of the feeder lines must be cut to prevent over-capacity on the medium voltage line. Our conversations with the operators of several grid substations during visits in 2015 and 2016 to Bihar indicated that this was a more common cause of blackouts than the lack of generation.

When supply cuts must be made, rural agricultural areas are disproportionately likely to have their service cut, further contributing to the miserable quality of service in rural areas. Electricity supply to agricultural areas is often subsidized to extremely cheap or even free levels. In 2011-2012 the agricultural sector consumed around 22% of the total power sold in India, yet it accounted for only 8% of sales revenue for power companies [51]. Agricultural subsidizes were 64% of total subsidies provided by states for power sales in 2011-2012; to make matters even worse, states often do not fully cover those promised subsidies, leaving discoms even further in the red [51]. Since supply to agricultural areas is so unprofitable, the utilities are incentivized to cut power to these areas first. Perversely, since the amount of power in these feeders is often unmetered, discoms are incentivized to hide higher-than-expected non-technical losses within the reported agricultural sales, in order to appear more efficient. Because poor, rural consumers are typically on the same feeder lines as agricultural customers, they end up with much less reliable power supply. One could ask if the free power for agriculture is worth the abysmal reliability to these consumers.

These worries could make off-grid electrification seem even more attractive by comparison. Even if grid extension were the most cost-effective way to provide electricity to a community in theory, in practice implementing this solution could be very difficult. If the infrastructure were built, it could still provide only very unreliable service, rendering the few hours that a microgrid or solar home system might provide attractive by comparison, since the supply could be more reliable.

Recent Reforms The issues with agricultural supply are why the DDUGJY program has included as part of its objectives (1) the metering of supply on rural feeders and (2) the separation of agricultural and household loads onto different feeder lines. With these measures in place, rural households might suffer less collateral damage from supply cuts, and discoms would be forced to be honest about their agricultural sales. It remains to be seen how quickly this program has effect.

In the last year, India announced the UDAY (Ujwal DISCOM Assurance Yojana) Scheme, an attempt to overcome the disastrous financial situation of the country's distribution companies. It is an optional program, but incentivizes states to join it by providing more funding for several electricity-related initiatives, including DDUGJY and several other schemes. UDAY has four major parts [45]:

1. Improving operational efficiency. This is to be accomplished through smart metering, upgraded transformers, energy efficient appliances and agricultural pumps, among other things.
2. Reduction in the cost of power, primarily through making greater use of cheap domestic coal, and other measures to make coal cheaper.
3. Removing a substantial amount of debt from distribution companies, and transferring it to states. By 2017, states are to take on 75% of existing debt from distribution companies, which will allow the interest rates to be lowered from 14-15% to 8-9%. Debt remaining with the distribution companies will be converted into lower-interest loans or bonds which must be at the bank's base rate plus 0.1%.
4. Aligning the financial incentives of distribution companies and states. States will be required to take on 50% of discom's losses at the end of every year.

Past efforts to bail out the distribution companies have failed, mostly due to political reasons, but there is some reason to hope that this scheme is more comprehensive and will be more effective than previous attempts [5]. The key political roadblock will be getting the states on board with this plan, as they will be apprehensive to take on so much of the distribution company's debt. However, if the incentives of extra funding - and the threat of losing funding for federal electricity programs - is enough to drive compliance by the distribution companies, this policy could have a major impact on the state of India's power sector [5].

Forcing the state to take on the debt of the distribution companies could be a very effective way of aligning incentives between the distribution company, the state regulator, and the state government. As the government is often unwilling to raise tariffs for political reasons, and able to exert that will through the capture of the regulator, tariffs stay low and losses stay high. The idea is that states will now have an incentive to reduce those losses, potentially creating political will for significant tariff reform. The reduction in interest rates for distribution company debt will also have a noticeable impact; the requirement that debt be converted into loans or bonds with an interest rate that is the base rate plus 0.1% represents a a significant improvement over the current rates of 14-15%, given that base rates in India are currently around 9.3%. Stronger distribution companies with less debt will, in theory, be able to invest in better infrastructure, purchase more power, and thus encourage positive developments in the Indian power sector as a whole. Time will tell how effective this scheme will be.

1.1.3.3 Barriers to investment in off-grid electrification

[14] presents a very compelling analysis showing that the risk of central grid expansion is the 'gateway barrier' preventing investment in microgrids. Through a series of interviews with many people across the off-grid electricity sector, they show the pervasive worry that the grid will arrive and bankrupt a local microgrid business, since they cannot compete with the low tariffs provided by the distribution company. One of their interviewees notes that "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." Most distribution companies do not have long-term plans for how the expansion of the grid will progress, providing potential project developers and investors with no certainty regarding the magnitude of this risk [14]. Indeed, since the discom is so closely tied to the state government, where to extend the grid next is a decision often made on short-term political considerations. This issue could be addressed by publicizing (and following) expansion plans, and through the creation of a well-defined process for the off-grid business to receive some

value from the arrival of the central grid provided that they are grid-compatible, e.g. by being bought out by the discom, or remaining as a franchisee in some capacity. While the former option sounds easier in theory, the close political ties between the discom and the state government, and the short tenor of many governmental administrators (many rotate after 2 years), mean that it could be much easier said than done. Meanwhile, recent amendments to the Electricity Act have started to address the issue of integrating grid-compatible microgrids. This development is discussed in section 5.

Although this risk of grid expansion is perhaps the most preventative barrier, there are still many hurdles to creating a viable microgrid business. Below are several of the most prominent.

- **Slim profit margins:** Profit margins for microgrid businesses remain slim, given the low ability to pay of many rural customers. Microgrid businesses must achieve scale to realize greater efficiencies and more attractive revenue, but progress in this direction has been sporadic, except for some ideal cases such as those involving anchor loads, or physically isolated communities [14].
- **Untrustworthy state subsidy**: Although the government does provide a subsidy for solar projects and for decentralized distributed generation in rural areas, it does not always provide it reliably [30, 28]. The uncertainty and paperwork involved in obtaining the subsidy is burdensome for entrepreneurs; several microgrid companies we spoke with in India indicated that they prefer to operate without the subsidy as a result[3].
- **High transaction costs:** Community engagement is key to the success of a microgrid, and doing it properly requires a significant investment of time and resources [3]. If it is not done properly, it can contribute to political retaliation and theft of electricity and system components. This requirement makes it difficult for an outside company with no local knowledge to come and establish a business quickly.

[3]e.g. Meeting with Boond Power, July 2015

- **Low availability of finance:** Off-grid entrepreneurs have had difficulty obtaining finance from banks and investors, especially at reasonable interest rates and tenor [3]. This situation is especially true for microgrid businesses, in part because of the risks imposed by grid expansion; smaller-scale solutions such as solar lantern businesses have slightly more access to capital [14].

1.2 Grid-compatible Microgrids

The concept of grid-compatible microgrids refers to the idea that a stand-alone microgrid could be built to certain specifications that allow it to interface with the central grid if and when the occasion to do so arises. In theory, many types of microgrids could do this. From a technical standpoint, the ability to synchronize local generation with the main grid, if operating in AC, is the biggest hurdle. Even DC microgrids could technically be connected to the central grid, if they had an inverter/rectifier at the interface. However, in practice, due to political and regulatory constraints, a grid-compatible microgrid must meet minimum standards for safety and quality in the construction of its network. It is unlikely to be in DC due to the cost of an inverter/rectifier and the desirability for consumers of being able to purchase the same appliances as everyone else. In the rest of this section I will discuss the situations in which such microgrids might be useful, and the standards that they must meet.

1.2.1 When and why they are useful

There are three main situations for using microgrids[4] to provide electricity access in rural, developing areas; when customers are so remote and have such low-demand that grid-extension will be economically unfavorable, where the existing grid is woefully unreliable, and where the existing grid may not reach a set of villages for many years. While the central grid may never reach customers in the first situation, negating the

[4]While some studies distinguish between minigrids and microgrids, I will refer to any collection of households connected to the same isolated network with its own generation as a microgrid.

utility of making it ‘grid-compatible,’ for the latter two situations, a grid-compatible microgrid could provide several benefits. It could provide a more attractive investment framework for private developers, result in better quality service in the future, and contribute to the sustainability of the electricity sector by encouraging distributed renewable energy [60]. Unlike the solar home system kits typically sold in the developing world, a microgrid can be easily connected to the main grid when it arrives, and can operate as an island in case of central grid blackouts [47]. (While isolated solar panels can theoretically be attached to the main grid, it is less likely that this arrangement would be feasible and attractive for poor rural customers, given the high transaction costs and upfront equipment costs needed to sell electricity to the grid. The panels could be retained for self-supply for a few appliances, however.)

For some remote, low-demand communities, a microgrid could be much more cost-effective for supplying their electricity needs than the extension of the central grid [40, 4, 25, 60, 29]. Several studies have tried to estimate a radius outside of which grid extension is no longer cost effective; although this approach is quite crude, it gets across the point that under some combinations of factors, microgrids will make more sense. The cost of building a grid line to reach a remote community may never be recouped by the utility if demand is not high enough or tariffs are too low, because the utility will never collect enough tariffs to come close to offsetting the investment cost. Even for non-remote communities, if the grid is unreliable or there is no certain date for grid expansion in sight, a microgrid could be cost-effective at addressing their needs and ensuring that they do not have to wait years to receive reliable electricity supply.

However, microgrids in any of these three scenarios have not yet achieved scale – most remain pilot projects funded by philanthropic organizations or subsidized by international development banks as investors endeavor to find a sustainable business model and policymakers try to create an attractive environment [31]. Attracting investment to microgrid projects remains an issue, as it is difficult to cover project costs with the limited payment capacity of poor rural villagers, and the risks of such projects remain high [31]. Microgrid companies have had difficulty creating scalable business models that turn a profit; even those that have figured out how to develop sufficient demand and affordable supply often "struggle to find a replicable business model that allows them to leverage the economies of scale that are critical for growth," [6].

Figuring out a favorable policy and business environment for such projects remains a key objective. Doing so would unlock vast quantities of capital for rural electrification [60]. The limited budgets of developing countries will not be enough to provide electricity to the many who lack it in the near future, so this private capital would be truly helpful. Utilizing private-sector investment in microgrids can also result in better service than often-beleaguered state-owned utilities are able to provide; these state-owned utilities are known to suffer from "inefficiency and poor technical performance" [60, 22].

One of the key risks of investing in a microgrid is the risk of the central grid extending to the location of a microgrid; [49] reports that they observed this in multiple case studies [49]. Grid-compatible microgrids, and an accompanying regulatory framework, can help address this uncertainty and reduce the risk to investors [49, 16]. There is a significant need to regulation for what happens when the grid is extended to meet microgrids and what is required for the interconnection [4, 54]. Despite the substantial literature on the need for microgrids and the advantages of grid-compatible microgrids, there is no literature addressing the cost savings that could result from smart grid-compatible microgrid regulation when electrifying a region. Such a study would need to take into account not only the savings in upfront and ongoing costs, but also the need to provide subsidies to private microgrid operators. These subsidies are needed so that owners can cover their costs and customers can pay a uniform tariff (the uniform tariff could be for central-grid-connected customers only, or for all customers of microgrids and the central grid alike; this issue will be discussed later). Even accounting for this subsidy, a regional electrification scheme incorporating grid-compatible microgrids could still be cheaper for the government and state utility than grid extension. The newfound analysis capabilities that REM provides will allow us to address the question of cost.

1.2.2 What Makes a Microgrid Grid-Compatible?

When the central grid reaches a microgrid, several requirements must be met if the existing network and generation will continue to be used connected to the central grid. This situation raises three sets of issues for compatibility. First, if the network is to be maintained, it must meet certain standards for quality of components, voltage limits, quality of service and safety and for the type of connection needed. Second, if the generation is retained, it must be able to inject power to the grid at utility standards, and to disconnect and reconnect safely from the central grid when it blacks out and comes back online [21]. Third, if the microgrid developer wishes to be able to operate in 'islanded' mode while the central grid is down (a functionality that could be quite useful in countries with unreliable grids), they must meet the above requirements while also being able to shed load as needed while disconnected from the 'big' grid.

1.2.2.1 Network requirements

The microgrid network needs to be of sufficient quality to connect to the utility network. Safety requirements must be met, which may require giving the lines a certain berth, having a minimum pole height and line height, and having the necessary electrical protections like circuit breakers in the event of short circuits.

In theory, there is no reason that a DC microgrid could not interconnect with an AC utility grid; an inverter at the interface could connect them. However, in practice it is highly unlikely that a microgrid not originally built as AC would be attached to an AC centralized grid. DC microgrids are typically built in the developing world to reduce cost; such microgrids may not be built to sufficient safety standards for the central utility, and for communities where the cost constraint is so significant, the cost of the inverter may be prohibitive.

Additionally, many of the appliances consumers might wish to use once they have access to a larger amount of power require AC supply; consumers might be unhappy that they are constrained to a limited (though admittedly growing) selection of appliances designed especially for DC power supply. For these reasons, it is a reasonable requirement that microgrids built to be grid compatible should be AC. Beyond this requirement, it is possible to have compatible microgrids with a variety of configurations: three phase, single phase, single phase earth return, or others. Single phase earth return has been noted for its low cost, though it can result in large voltage drops.

1.2.2.2 Generation interconnection

For the generator to remain useful after the microgrid has connected to the main grid, it must be able to connect at the right frequency and phase, and produce power of sufficient quality for the utility's standards. These specifications will impose different requirements for synchronous generators, asynchronous (induction) generators, and inverters (e.g. solar panels) [21].

If an isolated microgrid has a diesel generator, it is likely to be a synchronous generator, since it does not need an external power source to start, unlike an asynchronous generator. These types of generators are the most difficult to connect to the grid, as their phase and frequency must be matched to the main grid's before interconnection. This matching can be performed by electrical equipment or by a trained technician [21].

However, it is unlikely that a developer would find it economical to run their diesel generator for power when significantly cheaper power can be purchased from the grid. What is more likely is that existing renewable generation will be used, and any diesel generation will be used only as a backup if the central grid is down. Asynchronous (induction) generators are common in micro hydro installations, as well as in wind turbines. Their interconnection requirements are not as complex as those for synchronous generators, as they do not need to be synchronized before interconnection [21].

Solar panels on an AC grid require an inverter to convert the DC output of the panel. These inverters may contain all of the protective relays needed to connect to the grid. However, it is important to note that many inverters are made either for islanded operation or grid-tied operation, and fewer are able to do both. Many inverters used for off-grid applications are not able to export power to the main grid [21]. Investors expecting their microgrid to be able to interconnect to the grid one day must ensure that the project uses the correct type of inverter to do so.

1.2.2.3 Islanded operation

One of the potential advantages of a grid compatible microgrid is that it could continue to provide some service to customers while the central grid is blacked-out, a frequent occurrence in India. There are several technical requirements with this functionality; resynchronization (discussed above), ensuring worker safety during islanding, and managing undersupply during local operation.

During a blackout, utilities worry about distributed generation causing some lines to remain 'live' without warning, which can present a hazard to workers who may be working on the lines while trying to restore power [21]. Actions must be undertaken to ensure that worker safety is protected if the microgrid is live while the central grid is down.

If a grid-compatible microgrid is to retain the ability to operate in an islanded mode after being connected to the central grid, there are several additional requirements it must meet. First of all, the microgrid must have the proper electronics in place allowing the microgrid to disconnect from the central grid quickly and safely when central power is lost or a major disturbance is detected. It also must be able to determine, either through power electronics or human assessment, when it is safe to reconnect to the central grid, and it must be able to reconnect at the correct frequency and phase [21].

Consumers connected to the microgrid will be able to draw more power once the microgrid is connected to the central grid. They may purchase additional appliances and equipment that has a higher power draw because the grid can now support it. As a result, after interconnection power draw from the microgrid consumers may grow to a level that cannot be supplied by the local generation and storage of the microgrid. In order to take advantage of the 'backup' capabilities of the microgrid, the developer/operator would need to devise a method of ensuring that the power supply of the microgrid is not exceeded by demand during periods of isolated operation. This could be accomplished in several ways:

- Having two separate sets of electrical lines for the centralized network and the microgrid. While this would create significant redundancy, it would give each household a second set of plugs that could provide them with a limited amount of power in case the central grid was out. Controls, such as load limiters, could ensure that household draw on the backup plug was not too high. This method would be simple for consumers to understand but would involve significant redundant expenditure, and would raise other questions, too. Would the customers use the 'backup' outlets when both services were available? Would the same tariff be charged for each?
- Variable load limiters that can be controlled remotely could be used to constrict household power draw during a central grid blackout. If a blackout occurred and a household was drawing too much power, the limiter would shut down their power, until the household reduced their power load and reconnected their breaker.
- The much less high-tech way of accomplishing this control is to have the micro-grid operator communicate with the villagers regarding the status of the grid, informing them that if they use more than a minimum number of appliances they will cause the mini-grid to destabilize and black out. While inexpensive to implement this solution might create some 'tragedy of the commons' incentives,

wherein it would be difficult to enforce cooperation.

These choices will be dictated by how the investor and community values the tradeoff between efficiency and upfront cost; automated systems can raise the cost of the system significantly.

1.3 Preview

In the rest of this document, I will lay out my approach for addressing the questions described above. In section 2, I will describe the Reference Electrification Model (REM), a model which has been developed by my team at MIT over the last three years, and is useful for identifying the most cost-effective methods for rural electrification. In section 3 I describe my methods for applying REM in order to arrive at useful comparisons between different strategies of providing electricity. Section 4 lays out the results of those analyses, as well as an assessment of the sensitivity of REM to key parameters. In Section 5, I analyze the current regulatory structure in India for off-grid systems, and suggest ways in which their proposed regulation regarding off-grid electrification and grid-compatible microgrids could be improved. Section 6 provides the conclusion.

Chapter 2

The Reference Electrification Model (REM)

2.1 Overview

The Reference Electrification Model (REM) is a planning tool meant to assist policy makers, utilities, entrepreneurs, and investors in identifying the most effective approaches to providing electricity in a region. REM aims to design a near optimal least-cost electrification solutions for a region at a highly granular level. It decides between three electrification 'modes' – grid extension, microgrids and individual home systems – for each household or other type of customer. The resulting design includes the type, size, and locations of electricity generation, storage, and distribution assets, and takes into account the specific amount and timing of consumer demand.

This model could be used by planners, including distribution companies, policy makers, and regulators, to estimate electrification costs and appropriate electrification modes at a regional level. It is not meant to give a definitive implementation design but rather to allow the decision-maker to understand the key factors influencing the optimal design. REM can help answer 'what-if' questions like 'how important is central grid reliability?' and 'if off-grid systems are restricted to low-carbon generation sources, how does the cost change?'

Engineers and designers intending to provide electricity to specific areas could use this tool to facilitate design decisions that appropriately balance level of service and costs; since affordability is a key issue for many customers it may make sense to sacrifice a certain amount of reliability in return for lower costs, but only up to a point. Entrepreneurs could use the model to identify locations where their technology is likely to be the most cost-effective solution. REM can also be used on a local scale for the design of single microgrids. Entrepreneurs can use this capability to design a local project and assess the financial viability of that project.

2.2 Precedents for REM

There are a sizable handful of papers assessing the suitability of on-grid vs. off-grid electrification modes within a region. A number of them are focused on a regional scale, incorporating high-level parameters that may be easier to find yet offering a less detailed assessment. A few are more complex and able to handle more granular local data and produce detailed designs, though none of them rival the granularity and specificity included in the REM.

There are a number of papers that illustrate regional-level models using various combinations of regional parameters to show which areas are too remote and low-demand to justify on-grid over off-grid; these papers, too numerous to discuss individually, include [4, 40, 10, 38, 63, 52, 25]. There are also a handful of reviews, [60] and [26] being the most notable.

For example,[29] estimates a radius around the existing grid, outside of which off-grid systems would be considered more cost-effective. Their calculation uses a combination of factors including the Levelized Cost of Energy (LCOE, \$/kWh) for each generation option, the project and component lifetimes, operation and maintenance costs, and demand. Although the approach of applying a radius is rather crude, it can serve to illustrate order of magnitude of the on-grid vs. off-grid tradeoffs, though it may not accurately capture many costs.

A more granular approach than used above can provide a more accurate estimate of the costs of electrification. Most significantly, the actual distribution of houses and settlement patters can have a significant impact on the cost of the network required to connect houses to a grid or a micro-grid [60]; using population density alone, as done in many of these papers, could give a poor estimate of the cost-effectiveness of microgrids, which depends significantly on how tightly the houses are clustered.

Several tools have been developed that operate at a higher level of detail, and begin to approach REM's granularity. [34] goes down to a 2.5 km^2 resolution, and thus lacks the household-level resolution of REM, but it does consider planned network expansion, a greater variety of generation technologies (micro-hydro and wind, in addition to solar and diesel), and uses the same basis for the calculation of diesel fuel costs as REM. It decides between technologies on the basis of LCOE, which takes into account the level of energy access desired, population density, grid characteristics (though grid reliability is not considered), and the availability of renewable resources. It does not consider the timing of demand, just the annual level; this omission could result in a poor representation of the adequacy of resources like solar.

The United Nations' Dept. of Economic and Social Affairs offers a web-based tool called the 'Universal Access to Electricity model,' which also helps the user determine the most effective electrification mode on a regional scale, using a 10 km^2 grid [1].

Modi Labs at Columbia University has produced several papers addressing this topic[2], culminating in the release of the Network Planning tool [27, 41, 43, 48, 64]. [64] describes the use of a minimum-spanning tree for developing the least-cost distribution network, based on household locations taken from satellite imagery, and defines the 'homogeneity index' for describing the amount of clustering of houses in a region. [43] has been widely cited in this literature; it introduces a model that selects the most

[1] Available at https://unite.un.org/sites/unite.un.org/files/app-desa-electrification/index.html
[2] Available at http://sel.columbia.edu/publications/

cost-effective electrification mode, and aggregates households into 'demand notes' which are typically aligned with the smallest administrative unit in a country, to best take advantage of demographic data and reduce computational complexity. It uses a clustering algorithm based on a minimum spanning tree, and allows the user to select a 'penetration rate,' representing the fraction of the households that the planner wishes to have connected to an electricity source (presumably to represent the gradual expansion of access). [43] finds that this penetration rate has a strong influence on household connection costs; they also find that their model is not very sensitive to the existing location of the grid, a result that seems counterintuitive.

The Network Planner, available from Modi Labs, is available online and allows the user to upload their own datasets. This tool, described in [27] and applied to a case study in [41], provides least-cost electrification mode decisions and a detailed cost projection for off grid and on-grid solutions, and can be used on a variety of scales, but does not go to the individual household level. It clusters individual households at the community level, and considers the options of grid extension, diesel-powered microgrids, and small solar systems with a diesel backup. While this tool is quite detailed and sufficiently developed to be useful to planners, it does not have the same household-level spatial resolution that REM does. It also does not consider the relative timing of generation and demand; for hybrid PV-diesel systems, the tool assumes that household, educational, health, and public lighting demand is met by PV generation, and commercial and productive demand is met by diesel generation; this assumption is questionable as PV generation would be unable to meet evening and nighttime demand created by public lighting and household uses, unless a battery is used (which would significantly affect the price).

In sum, although there is a considerable volume of work attempting to provide tools for evaluating the best way to provide electricity, no available paper or tool that I have found rivals REM's temporal and spatial granularity. While lower-resolution data can make such tools easier to use, as data can be scarce in unelectrified areas, representing higher-resolution data could significantly improve the realism of the model's outputs. In particular, the clustering of households within a community, and the temporal relation between demand and renewable generation potential can have significant impacts on the most cost-effective plan; REM is the only model examined that captures both of these. Additionally, it is more flexible in determining the source of generation for off-grid systems than most examined tools, and appears to be the only option that places a value on the reliability of the electricity provided.

2.3 Description of REM

Here I will provide a mid-level overview of the algorithms used by REM to determine the most cost-effective electrification mode. I will go into the detail necessary to understand how the following analyses are conducted and understood. For a more detailed examination of the algorithms within REM, see Ellman (2015), the original thesis describing this model[17]. This model is also described in [12]. Updates to the algorithms since the Ellman and Borofsky 2015 theses are described below.

The broad objective of REM is to determine the most cost-effective way to serve predicted demand, choosing between the options of extending the main grid, or building a microgrid or isolated system. Included in the 'cost' of any possible option is the cost of not meeting predicted demand. This parameter represents the cost of intermitted supply. Requiring that any option meet 100% of predicted demand would likely result in a system that is overbuilt and too expensive. This cost tells REM how to trade off reliability against cost savings, and the determination of this parameter is discussed extensively in section B. With this representation of the social cost of unmet demand, REM determines the most cost-effective way forward for society to address the lack of supply.

2.3.1 Inputs

REM requires a broad variety of inputs, detailing the location and type of customers, the existing electricity infrastructure, and the prices of various options available for meeting demand. The level of detail of the inputs can be adjusted based on the available information.

The model requires the location and load profile of all the individual customers to be connected. The geographic location of each connection can be gathered using individual household census data, satellite image processing or crowd-sourced pinpointing of users. Our satellite image processing algorithm is under active development, in this analysis I use the latest results from our building extraction efforts based on images taken from Google Maps. This algorithm makes use of convolutional neural networks to identify pixels that most likely belong to houses, based on an initial set of training data. Census data from 2011 tells us that there are 600,000 households in the district of Vaishali, so we sample (without replacement) that many pixels from those identified to arrive at a set of possible household locations. While this method is imprecise, it provides a sufficiently accurate representation for large-scale planning. Larger buildings may be assigned more than one connection point, but as such buildings are likely to have a higher demand, this outcome may actually improve representation of demand.

For each identified household connection point, we must also determine an expected demand profile. The accuracy of the load profiles will vary greatly depending on the available information. It might be estimated according to the average income level of these customers or, where a increased precision is needed, deducted from specific surveys that assess the energy services required by these users, and accounting for factors like weather and sunset times. In the future, we may be able to moderate this profile based on building size. For this case study of Vaishali, we use the same demand profile parameters for all connection points, based on demand for a light, phone charging, and fan, with the timing of these loads based on temperature and sunrise and sunset timing, with an additional stochastic component.

REM also requires data on the existing power infrastructure, especially the location of existing medium voltage lines and MV/LV transformers. This information is used to determine the distance of a settlement from the centralized grid, and future iterations of REM could use it to determine upstream alterations that might need to be made to the existing infrastructure to accommodate increased demand. The data used in this analysis was obtained from the North Bihar Power Distribution Company as described in [17].

Available components, including wires, power electronics, batteries, and generation options, with their respective costs, are another important input to REM. These should reflect any relevant standards for grid infrastructure in the relevant locality. Finally, the tradeoffs that REM makes are influenced by inputs like reliability constraints (how much of existing demand must be served), penalties for not serving demand, and discount rates. These inputs are discussed further in Section 2.4.2 and Appendix A.

2.3.2 Algorithm

Below, I outline the overall process for determining and designing the optimal electrification options for a region[3]. Many of these steps could be performed in an automated fashion, in the case of regional planning, or performed with more user-interaction, in the case of design for a specific location. These steps are briefly described below:

Division of area into separate analysis regions: If the area of interest is large (e.g. a country) it must first be divided into regions, which can be analyzed and optimized separately, in order to manage computational burden. This could be done, for example, based on demand density or based on distances between demand points. REM currently employs a k-means clustering methodology for this process.

[3]The version of REM used in this study and described here refers to the version that was current as of April 10th, 2016. This corresponds roughly to the 0.3.1 version.

Division of analysis regions into electrically isolated clusters: It is non-trivial to determine which demand points will be electrically connected together (into microgrids or grid extension clusters) or remain isolated with home systems. REM's approach to clustering houses into groups starts with creating a minimum spanning tree (MST) that connects all the houses. The MST identifies the nearest connection to another house for each house, and this set of connections defines the possible connections that can be made in grouping houses into clusters. REM first groups houses into clusters for off-grid electrification, and then determines the clusters for on-grid electrification.

The process of off-grid clustering trades off the additional costs of building more electrical lines with the economies of scale of larger generation units. In order to avoid the computationally-intensive task of determining the proper generation technology and capacity for every candidate microgrid, REM first builds a 'look up table' which contains estimates of the generation needed for microgrids of a sample of different numbers of households, following the process described below. If different types of demand are used, the lookup table will contain samples with different fractions of each type as well. In the clustering process, REM interpolates between the samples in the lookup table to arrive at an estimate for the relevant size of microgrid, where size is defined by peak demand. This table is designed for each analysis region, to account for possible differences in diesel prices and insolation which might affect the optimal generation set-up in different places.

For the off-grid clustering, REM tries connecting houses together, starting with the shortest branches of the MST and working up to the longest. To decide if the MST branch should be a physical electrical connection, it compares the cost of electrifying the houses on both ends of the branch to the cost if they remain unconnected. Note that either or both ends of the MST branch may be single households or clusters already connected houses. To do this, REM compares the cost of an electrical line between the geographical centers of each cluster with the difference in cost of generation, operations, and management for the unconnected and the connected clusters.

If the cost of providing electricity to the houses or clusters on either side of an MST branch is cheaper, then REM puts the two into the same cluster. REM loops over all possible branches in the MST several times, until no additional lines are connected or until a maximum number of loops is reached; this looping helps prevent the search algorithm from getting stuck in a local minimum.

In this way, REM determines the least cost way of clustering houses for off-grid solutions (microgrids and isolated home systems). It then determines optimal grid extension clusters, which consist of combinations of off-grid solution clusters. The logic for this process is similar to that of creating the off-grid solution clusters. It begins with the remaining unused MST lines as the candidate connections. For each possible connection of two clusters it considers five possible scenarios (which are described in more detail in [17]. The main change since the publication of [17] is the inclusion of operations and management costs in the comparison).

1. The two clusters are connected together, and cluster one is connected to the nearest grid connection point.
2. The two clusters are connected together, and cluster two is connected to the nearest grid connection point.
3. Each cluster is connected to the grid separately.
4. Cluster 1 is connected to the grid, while cluster 2 is off-grid.
5. Cluster 2 is connected to the grid, while cluster 1 is off-grid.

Just as is done for the off-grid clustering, REM loops through all the candidate connections for the on-grid clusters until no new connections are made in a loop or the maximum number of loops is reached.

Design of electricity supply for each isolated cluster: For each cluster, local generation and storage and/or a grid connection must be selected to optimally serve the cluster's demand. This will entail selection of supply components from a catalog of components, based on the cluster's demand, energy resources, and costs. Currently REM can choose between solar, battery storage, and diesel generation, employing whichever combination of the three is most effective. REM utilizes a heuristic-based pattern search to find the optimal design; this algorithm is based on the method described in Hooke & Jeeves, (1961) and its application in REM is described in [17]; however, since the publication of [17], the approach has been modified in a way that avoids local optima. REM can be used such that the generation for each cluster is the value interpolated from the lookup table, from the previous step, or it can re-optimize the generation for the particular parameters of the cluster in question; the former saves a significant amount of model run-time and so has been used here.

The search space for the generation optimization algorithm includes the size of the generator, the size of the battery, and the size of the PV panel. From a starting point, the algorithm will try changing one of the variables at a time and see if the cost is reduced. However, this arrangement can lead to getting stuck in local optima if getting out of the local optima requires changing more than one variable at the same time. A typical example of this would be a candidate design with a diesel generator but no PV or battery, when the optimal design has no diesel generator but a PV panel and a battery; adding either the PV panel or the battery alone will increase the cost.

To avoid getting stuck in these local optima, the Hook & Jeeves algorithm has been changed to be implemented in a master-slave setup, in which each 'master' fixes the size of the diesel generator at a certain level. The master's 'slaves' then search the space of PV panel and battery sizes, holding the diesel generator size fixed, and return the optimal design given the diesel generator size to the master. Comparing each master's result gives the optimal design, avoiding the problem of local optima.

REM identifies the cost of a generation design by simulating the operation of the microgrid over a sample of time periods. This simulation reveals how much fuel is used, how much demand is is not met, and how often the generator and batteries must be replaced. These costs are used in the design search algorithm, in addition to the upfront capital costs of the components. The simulation is done for a representative sampling of time periods throughout the year; the number of samples and the length of each sample can be determined by the user. The sample periods are evenly spaced throughout the year, ensuring that different seasonal effects are taken into account. See [17] for greater detail on how the simulation is implemented. The regional-modeling version of REM does this detailed testing only for generating the look-up table (using the interpolated values as the final design values), while the version of REM used for the design of local infrastructure runs the detailed simulation for determining the final design as well.

The current implementation of the simulation assumes that consumer's demand requests can be curtailed based on available generation, and that they can be differentially curtailed based on whether they are high or low priority. This assumption would clearly require some electronics to regulate demand in the actual implementation of a microgrid, and we have not included the price of such electronics in the current analysis. Please see the forthcoming MIT Masters thesis by Vivian Li (2016) for a greater discussion of the implementation of demand-response in the context of REM.

Design of distribution network for each isolated cluster: Given power profiles of demand and generation points, REM must select the appropriate wires, transformers, and other distribution network components for minimum cost, considering technical constraints and losses. This process uses the Reference Network Model (RNM), developed at IIT Comillas, with a few modifications to make it more appropriate for a rural setting.

The RNM was developed at the Institute for Research in Technology (IIT) at Comillas University in Madrid, and has been used by the Spanish Energy Regulatory Commission to remunerate the distribution companies in Spain, with about 25 million customers, with the agreement and collaboration of these companies [33, 44]. RNM has been used for similar purposes in several other countries and in several European research studies. RNM determines the most cost effective arrangement of wires, transformers, and other components to supply electricity to a given set of connection points with a given level of demand. Within REM, RNM is used to design both the wiring of grid extensions and microgrids, using a catalog of network components based on data we have received from the North Bihar Power Distribution Company. RNM also assesses the cost of operation and maintenance for the network it designs, based on expected preventative maintenance and maintenance in response to failures.

Determination of final power system: Multiple design options have now been created for each household; on-grid, off-grid and isolated system. REM selects the ones that are least-cost, where cost includes some penalty for not meeting consumer demand reliably. After this selection process, REM is finished and reports the optimal electrification design to the user.

2.4 Scenario construction in REM

2.4.1 User's perspective

By default, REM is geared towards a 'universal social planner' perspective, because it seeks to minimize all costs to society, regardless of who incurs them. However, some parameters of REM implicitly depend on the perspective and assumptions the scenario is meant to have. The user of REM must still be clear about what perspective they wish the analysis to take. The possible uses of REM are quite broad. The user can ask 'what if..' questions, such as 'what will be the best solution if grid reliability can be improved?', or 'what would be the impact of reducing the cost of capital available to off-grid businesses?'. These sorts of questions tend to be more 'predictive', in using the results of REM to attempt to forecast the most cost effective (and, thus assumed most likely) way forward. On the other hand, REM can be used for more 'prescriptive' questions. The user, for example an international development organization, could take the outputs of REM to determine how to intervene to improve electricity access most effectively. In any of these situations, the user must clarify what business models and regulatory environment they are assuming for all modes of electrification, as these will affect the inputs to REM. In particular, the proper selection of discount rate and cost of nonserved energy will depend on the source of funding and the objectives, as discussed below. As well, the user may wish to consider the timescale over which they are planning, and what changes to the physical and business infrastructure may occur over that time period. These changes may include the growth of the central grid, improvements in reliability, and increased access to financial services.

2.4.2 Definition of Key Inputs

Appendix A contains a definition of the vast majority of the inputs for REM. Here I will confine us to a discussion of the most interesting and relevant variables for constructing a scenario.

2.4.2.1 Cost of Nonserved Energy (CNSE)

This value refers to the penalty added to the cost of supply in REM when projected demand is not met, on a per kWh basis. The cost of nonserved energy, the demand curve, and the minimum reliability threshold all work in concert to determine the appropriate level of investment and type of service. Although the minimum reliability threshold parameter does ensure that the demand of all households is met to some extent, it does not ensure that the access happens at times of critical demand; as discussed in Appendix A, this parameter refers to a crude average over a significant length of time. Because it is currently a crude control, CNSE must account for some of the costs of not having electricity in the first place, as well as the costs of intermittency in supply. The selection of CNSE in REM is important to inform the proper level of investment. Through the value of CNSE chosen, the user can specify how important it is to build high-capacity, high-reliability electricity infrastructure, and how to make the tradeoff between cheaper infrastructure and more reliable infrastructure.

In reality, the concept of nonserved energy incorporates a variety of costs which vary along many dimensions, which are discussed at length in [15]. These dimensions include:

- Differences between customers: residential, business, urban, and rural consumers all may have different types of demand and possible substitutes for electricity, leading to a different valuation.
- Timing of the outage: the impact of an outage can vary depending on the time of day, of the week, and the season.
- Duration of the outage: longer outages are often seen as more costly per unit of electricity foregone and per hour as the length of the outage increases.
- Frequency of outages: more frequent outages may lead to larger costs, for example a business may decide it is necessary to purchase a back-up generator.
- Advance notice given for outages: if an outage is anticipated, consumers can mitigate its impact.
- Capacity restrictions: limited supply and the inability to have larger loads can restrict the usefulness of electricity supply, and reduce business opportunities.

Unfortunately, REM is not able to capture all of these dimensions. The only differentiation available is in the distinction between critical and non-critical load, which are assigned different values for CNSE. Critical values are higher than normal values, and are used for loads that are higher-value to the consumer. For example, a few lights at night would be considered critical, while a fan might not be. The assignment of critical or noncritical is made within the definition of the consumer demand. This distinction captures, somewhat crudely, an certain amount of preference for timing of service (since critical loads will be higher at particular times) and preference between appliances (since the value of CNSE is assigned to the particular use the electricity is put to in the demand curve).

The basis of CNSE should be in the value placed (either by the purchaser or by society) on the supply of electricity and the services provided by it. The perspective used will depend on the motivations of the planner and the anticipated business model and subsidy structure. For example, if the model is used with the assumption that the government will subsidize access to and quality of electricity, it may be more appropriate to use a 'social' CNSE. This more global cost could capture values like lost health from kerosene pollution, reduced hours for businesses and students to work, and reduced economic growth. Although REM would typically be used in cases where the planner has already decided that it is worth it to provide electricity services to all or most people, capturing these values is still important because they will be reflected in the level of service and reliability that is most appropriate for the situation.

Even though REM is meant to address situations where the user has already decided that it is worthwhile to provide electricity to everyone, the consideration of the cost of not having any access at all in determining the REM inputs can be useful in ensuring that REM makes the tradeoff between cost and reliability appropriately. Again, this is because the minimum reliability constraint in REM is currently a very crude tool. If the minimum reliability threshold is not a binding constraint, incorporating this cost is necessary. However, if it is high and/or binding, the CNSE may only need to include the costs associated with outages and capacity constraints. As well, it can be easier to put a value on the cost of not having access to electricity than the cost of outages, since it is difficult to know the preferences of consumers who have not yet begun to consume, and many methods of determining the CNSE for outages rely on consumer preferences.

2.4.2.2 Discount Rate

These figures (along with the lifetime of the investment) are used to calculate the annuity (i.e. the cost per year) from the upfront costs. They are critical inputs because the annuity is the basis on which REM compares different options. There is one for grid extension, for microgrid, and for isolated systems. They represent the time value of money for the relevant actor; typically this would come from the financing terms (i.e. debt or equity) that they receive, but more generally it reflects the opportunity cost of putting this money towards the system in question, rather than investing it elsewhere (for example to purchase other equipment that could be used to start a business). Thus, the actor who is providing the money to build the electricity infrastructure influences what the discount rate is, because they will have different opportunity costs for their money depending on who they are. For example, for a bank, that opportunity cost may be not investing in stocks or other projects, and for an individual consumer[4] who may decide to invest in an isolated home system it may be not purchasing medicine, food, or other necessities; clearly for these two actors the opportunity costs, and hence the discount rates, would be different. The discount rate would also be expected to vary based on government regulation, business model supposed for each mode of electrification, and financing arrangements.

The annuity value is what is used to compare different options of network and generation. The annuity is the sum of annual costs (like O&M costs, and non-served energy costs) and the annualized upfront capital cost. The discount rate is used to calculate the annuity with the following equation (where r = discount rate and L = lifetime of upfront capital cost):

$$Annuity = \frac{Upfront\,capital\,cost * r}{\left(1-(1+r)^{-L}\right)}$$

The discount rate depends significantly on the regulatory and business scenario we are considering. What discount rate we use depends on who will be funding the various modes of electrification and what the overall goals of the planner are. The discount rate encapsulates two main ideas; first is the opportunity cost of capital, and second is the risk associated with waiting for a return on investment in an uncertain world. The opportunity cost reflects the returns that one could get from putting that capital towards something else; what that cost is depends closely on what opportunities are available to the agent holding the capital. For a bank, this opportunity cost would be the potential returns they could get though investing in a different project or in the stock market. In the case of a local entrepreneur who might set up a microgrid

[4]The typical use of REM is to examine the options available to large-scale planners and investors, not to individuals. However, the consideration of the possibility of investment by individual households is useful in two scenarios: (1) the planner wishes that the scheme for isolated home systems is one in which the systems are purchased by individuals, possibly with the aid of subsidy and/or financing from the government, and (2) the planner wishes to use REM in a more 'predictive' (rather than 'perscriptive') manner, to estimate how electrification modes might evolve in the absence of intervention, assuming that the more cost-effective mode is likely to prevail in real life as it does in REM (acknowledging that this may be a heroic assumption).

business, these other opportunities could include other business possibilities, sending their children to school, or buying a new piece of farming machinery.

The risk portion of the discount rate refers to the idea that the future is unpredictable; there is uncertainty about market conditions, about the opportunities that might be available in several years, about the likelihood of your investment to yield the expected returns. Different businesses have very different levels of risk; a utility may be relative low-risk, since it has a regulated rate of return, while a microgrid could be significantly more risky, contending with issues like local acceptance, maintenance quality, demand growth, and the arrival of the central grid, among others.

The Capital Asset Pricing Model (CAPM), which is commonly used to determine the rate of return that investors should require from a project, exemplifies the dual nature of the discount rate. (Note that discount rate and interest rates/rates of return can be two sides of the same coin.) CAPM calculates the rate of return as the sum of the 'risk free' rate of investing, plus an added rate to account for the risk inherent in the specific project and the returns that are expected above 'risk free' returns.

Whose discount rate?

The resources used to purchase electricity and build infrastructure have different opportunity costs depending on whose wallet they are taken from, as well as the type of opportunity costs that are considered. For this reason, we have allowed REM to use a different discount rate for each mode of electrification; different sorts of actors may invest in them and own them. The function of the discount rate is to incorporate the time value of money and risk into the cost comparisons made within REM. Who bears these costs and what types of costs we allow our analysis to consider both affect the discount rate the user should use in REM.

With regards to who bears the cost, the actor or actors who actually invest their money in electricity infrastructure have different opportunity costs and hence discount rates. Even if REM is run from a 'global social planner' point of view, where the user is interested in finding a design that maximizes overall societal welfare, it might need different discount rates for different types of systems. The ownership structure and risks of different business models are important because by choosing to invest resources in electricity infrastructure, the actor in question would be forgoing investment in other opportunities that could also create value for society. For example, if we consider that a solar home system may be owned by a single household, the discount rate used will be different than if we consider that the system is owned and leased by a larger company; in the latter scenario, we would use lower discount rates because they have less uncertainty and different alternative opportunities.

The perspective of the analysis we wish to conduct with REM also affects what types of opportunity costs we wish to incorporate. There may be opportunity costs than an individual entrepreneur may not consider but that a social planner (for example in the central government) would want to incorporate. Examples of these opportunity costs include the GDP, development, and/or political impact of other investments the government could make with the money needed to fund or subsidize an electrification project. A user of REM who is more socially-minded would want to incorporate these broader benefits. Conversely, a user of REM who is more market-driven (like the owner of a business who wants to see where it is most likely that their off-grid technology would be preferable to customers) would not want to include these social opportunity costs in their analysis.

It is likely that a user of REM would be interested in funding or subsidizing to an affordable level all modes of electrification; such users include government and international development banks. In this case, since the source of the capital would be the same across all modes of electrification, the opportunity costs would be the same. This perspective, then, would dictate that the opportunity cost portion of the discount rate be the same for all modes. However, different modes would still have different risks associated with them, so this user may still wish to differentiate between the modes slightly based on risk level.

Sensitivity to discount rate

Discount rates typically vary within a rather tight window, and small changes in the rate can have significant impacts on the annuity calculated for different modes and, hence, the ultimate recommendation on electrification mode from REM. The sensitivity to discount rate also hinges significantly on the lifetime used for computing the annuity (which varies between components to reflect their different useful lifetimes). The longer the lifetime, the more sensitive the annuity is to the discount rate used. For high values of the discount rate, e.g. above 15%, extending the lifetime does not have a significant impact.

2.4.2.3 Annual Management Costs

This category includes the definition of the number of customers in a 'small' and 'medium' microgrid (the number for a large microgrid is assumed to approach infinity), as well as the annual management costs for a small, medium, and large microgrid. These figures are used to define the costs in administration and revenue collection associated with each additional household (or building) added to a microgrid. The distinction between small/mededium/large is used to simulate economies of scale, and these figures are used to fit a smooth exponential curve that is used to define costs for all sizes of microgrids.

2.4.2.4 Per Customer Costs

For each mode of electrification, we define the per customer costs as the cost of the meter or load limiters, if they are employed, any provided internal wiring, switchboards and lighting. It does not include labor costs for installing these components.

This value is not the same as the connection charge that is charged by the utility or microgrid provider. Sometimes the utility may inflate the connection charge in an attempt to balance their books, and the charge may also be used as a commitment mechanism to make customers invested in their new electricity infrastructure. Mera Gao, for example, reports that they charge a $2 connection fee as a commitment mechanism [13].

2.4.2.5 Network and component lifetimes

Each capital investment modeled by REM, from the network to the charge controller, has an associated lifetime, which allows us to calculate an amortized value (the yearly annuity) which we can use as a standard measure between options. The lifetime represents how long until the component in question needs to be replaced, or how long until the developer wishes to recoup their investment.

Chapter 3

Methods

3.1 Overview of Vaishali

All of the scenarios in this analysis use the data of the district of Vaishali, within the state of Bihar, India. Bihar has the lowest rate of electricity access in India. In 2011, the Indian Census observed that only 16.4% of people in Bihar had access to electricity. As of 2011, the district of Vaishali had a population of about 3.5 million people over its 2000 sq. kilometers, a population density of 1700 people per square kilometer. Vaishali is a flat, fertile, and mostly agricultural district. The high density and relative flatness of Vaishali mean that we would expect grid extension to be a cost-effective method of providing electricity to a large portion of its citizens if the reliability of the grid were good.

Over the last 2.5 years, our team has worked with the local government and the North Bihar Power Distribution Company to gather as much data as possible about the existing infrastructure. We have observed reliabilities in the rural feeders that are quite poor, as low as 15% in the peak hours of 6-8pm, and typically lower than 50% except in the middle of the night. The causes of this unreliability include lack of supply, but poor distribution infrastructure is a much larger cause; grid operators reported to us that the capacity of the line coming into a distribution substations

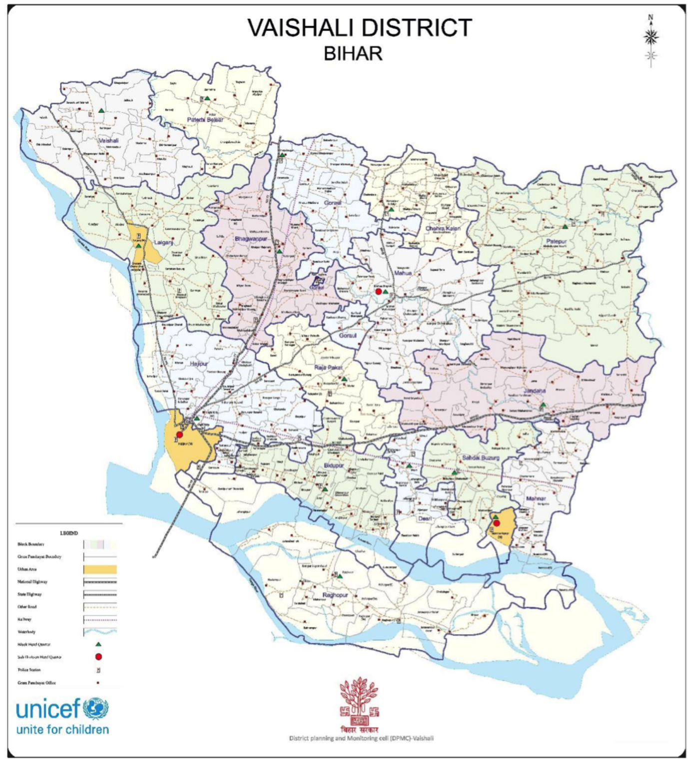


Figure 3-1: Map of Vaishali produced by UNICEF

was often insufficent to meet demand on all of the feeders, forcing them to shut down some of the feeders at peak hours. Since agricultural loads are given free electricity, the utility then has an incentive to cut the feeders leading to agricultural areas more frequently. Reliability can be significantly better in urban areas, though it is still far from ideal.

Vaishali is administratively divided into subdistricts, as shown in Figure 3-1. It includes three urban areas, shown in yellow. We have used the boundaries of these subdistricts to divide the region into separate analysis regions, which are processed individually within REM. Conversations with local officials indicated to us that microgrids would be less likely to cross the boundaries of these subdistricts, so it seemed a natural way to divide up the region in the analysis.

3.2 Inputs for Case Study Area: Vaishali, India

To assess the value of grid compatible microgrids we will make a comparison between three different scenarios run by REM. While each scenario requires its own set of assumptions and inputs, many of the inputs are common across all three scenarios. There are a great deal of assumptions that must be made to put together the inputs for REM. The most critical and complex of these assumptions are discussed in this section, and a comprehensive listing can be found in Appendix A. For each scenario, this section will discuss how the inputs are changed from the base case defined here and in Appendix A.

3.2.1 Cost of Nonserved Energy (CNSE)

Values Used:

Critical: \$2/kWh, based on [59]. This is higher than estimates from substitution analysis and from the Power Corp. of India's Value of Lost Load assessment (discussed below), but these numbers are known to be left-skewed and to not capture important effects like the GDP impacts of lack of electricity access.

Noncritical: \$0.51/kWh is a lower bound, taken from the Power Corp. of India's Value of Lost Load assessment.

Reasoning:

There are several possible ways of calculating the Cost of Nonserved Energy, but none of them are likely to ever find the 'true' value. Indeed, there is arguably no one 'correct' value waiting to be found. By examining several methods and taking into account what they miss, we can assess a reasonable estimate for the purposes of running REM.

<u>Via substitution</u>: See Appendix B for more detail on how to calculate CNSE by looking at substitutes for electric lighting. In summary, we use kerosene lighting

costs as an estimate for CNSE based on the units of ’cost to provide the service of illuminating a house’. This is a reasonable basis for a CNSE because people’s expenditure on kerosene is an indicator of the lower bound of the value they place on energy services – particularly on the service of lighting. Lighting is one of the highest value uses for electricity (with agricultural water pumps and cell phone charging the likely competitors), so a CNSE based on this use is likely to be ‘a lower bound on the upper bound’ of an individual’s valuation of electricity services.

This method does not capture added benefits of using electric lighting over kerosene such as health, increased quality of light, and the social value to development and GDP of energy access. While an individual consumer may not take all these factors into account, a social planner who has the interests of the whole country in mind would wish to incorporate these values into a higher CNSE.

Via reported VOLL: Power companies regularly determine a ‘Value of Lost Load’ (VOLL), representing the cost of an outage, to guide their investment decisions. While the cost of an individual outage is likely to be lower than the cost of chronically unreliable or low-capacity supply, this is still a useful yardstick. A report by Wartsila India (2009) reports that the Power Grid Corporation of India estimates the VOLL in India as Rs.34/kWh to Rs.112/kWh, or $0.51 - $1.67/kWh [58]. The range is used because the cost of an outage is dependent on a variety of categories. [59] notes that customer type (industry, service sector, households), perceived reliability level, time of occurrence, duration, and advance warning can all affect the determination of the VOLL [58].

[59]notes that for developing countries the literature strongly suggests a range of VOLL that is 1-10 $/kWh, and likely 2-5$/kWh, higher than the Power Corp of India’s suggestions [58] ([59] notes their values are likely to be left-skewed). The VOLL for rural consumers in India would likely be on the low end for variation within consumer type, low end for perceived reliability level, and the high end for variation based on time of occurrence, duration, and advance warning. Without information on the relative magnitude of these effects, it is difficult to say how these customers

are likely to compare to the average.

Summary: Substitution analysis suggests a minimum of $0.37 to $1.84/kWh (CFL vs Incandescent) for critical CNSE. VOLL studies from India suggest a range of $0.51 - $1.67/kWh and a literature review of VOLL studies in developing countries suggests a range of $2 - $5/kWh [15]. All of these values come with the caveat that they are likely to be left-skewed (i.e. underestimates).

3.2.2 Discount Rate

Values Used:

- Grid extension: 13.3% for NBPCDL
- Microgrid: 11% at minimum
- Isolated system: 14% based on SELCO financing rates

Reasoning:

Grid: For the extension of the grid, we could use 10% in the absence of other data. This number is based on a paper from Climate Policy Initiative "Solving India's Renewable Energy Financing Challenge" which bases their discount rate on the government cost of borrowing (7.83% at the time of writing, 7.77% on Jan '16, based on Indian 10 year bonds), plus a risk premium of 2% [50]. This risk premium is meant for large-scale renewable energy, so it may not be representative for a utility. Indeed, this number may be too low as evidenced by regulatory documents in India.

The regulatory documents for the North Bihar Power Distribution Company Ltd (NBPDCL) for Fiscal Year 2015-2016 from the Bihar Electricity Regulatory Commission (BERC) grant NBPDCL a rate of return on their equity of 14%, and an interest rate on their loans of 13%[1]. The rate of return on equity is established by Regulation 73 (2) (c) of the Bihar Electricity Regulatory Commission regulations of

[1] Taken from Table 6.57 and Table 4.62, found at http://berc.co.in/media/Tariff-Order/Tariff%20Order%20NBPDCL%20FY%202015-16.pdf Accessed April 6, 2016

2007. These regulatory documents assume that the debt:equity ratio for capital investments will be 70:30, which gives us a weighted average cost of capital of 13.3% [2]

Microgrids: This number will vary based on the regulatory context that we consider. The risk premium will be lower if we consider a regulatory structure that accounts for grid-compatible microgrids in a reliable and trustworthy way, but it will be higher if the regulation does not provide investors with sufficient reassurance that their investment will be properly valued and compensated when they connect to the main grid. The risk premium will again be higher when we consider non-grid-compatible microgrids, as the companies planning these will lose their whole investment when the grid arrives; additionally, previous conversations with them have revealed that they typically look for a relatively short payback period (on the order of 5 years).

TaraUrja, a microgrid company with several installations, uses a discount rate of 10% in the calculations that they sent to us, and the World Bank cites 10.3% as the interest rate "that usually meets the short and medium-term financing needs of the private sector." In light of the justification for 10% as an appropriate interest rate for a utility or large project (cited in [50]), this rate does seem optimistic. [50] cites 12.3% as the commercial rate of interest applied to renewable projects in India, so this is perhaps a decent lower bound, though it is meant for larger utility-scale generation installations. [3] and [23] use an interest rate of 12% for their calculations regarding solar microgrids (though neither specifies a source for this figure). It seems that 10% is a lower bound for microgrids. One would expect microgrids to have a higher discount rate than utilities as they are often riskier investments, so in that light a higher rate may be justified.

Individual home systems: Individual home systems could be provided through a variety of business models which could be relevant to REM. They could be provided

[2] However, these regulatory documents note that NBPDCL "has projected funding of capitalization through Grants at 94% and through Loans at 6%," meaning that the capital investments of NBPDCL could be more likely to be dictated by the preferences of the central government grant-maker than by NBPDCL and their discount rate.

through the utility or as part of a larger private off-grid service provider. They could be supplied on a fee-for-service model by a private company, similar to the business model used by Off-Grid Electric in east Africa[3]. Or, single households can purchase them themselves from the government or a private entity, with or without financing. In all of these models, the government could choose to provide a subsidy or subsidized loans; for example, the government may sponsor a program to subsidize the provision of such systems through the utility, or they may sponsor a program of discounted financing for households to purchase their own system. The business model supposed here has a large effect, perhaps even more so for this mode than the other two because they range of possible business models is so great. Very high discount rates could make individual home systems very unattractive relative to other solutions within REM.

Individual customers are known to have very high individual discount rates (on the order of 20+%), likely due to high uncertainty surrounding the future. However, a lower discount rate would be appropriate when financing is available to households, especially if government-subsidized financing is available. [23] observes: "Ekholm et al. (2010) use discount rates of 62–74% for rural households and 53–70% for urban. Reddy and Reddy (1994) estimate an internal rate of return of 28% for a switch from kerosene lamps to electricity- which could be a lower bound on the discount rate".

One highly-successful example of a business model for solar home systems is Grameen Shakti, a social enterprise which supplies solar home systems with financing through the microcredit scheme supported by the Grameen Bank in Bangladesh. Households wishing to purchase a system can have a 3-year loan with a 12% interest rate, 2 years for 10% interest, and 1 year for 9% interest [61]. In India, SELCO works to provide purchasers of solar home lighting with financing; they state interest rates ranging 5%-14% over 3 to 5 years with a 10-25% upfront deposit (25% is required by the Reserve Bank of India) [4].

[3] More information at http://offgrid-electric.com/#home
[4] http://www.selco-india.com/finance.html Accessed April 6, 2016

3.2.3 Taxes and Tariffs

Values Used:

- Tax: 14.5%
- On-grid tariff: Rs 170/month for the 65% of APL households, 60/mo for the 35% BPL.
- Off-grid tariff: Rs 120/month for a grid-compatible microgrid, Rs 100/month for a non-grid-compatible microgrid.

Reasoning:

These two values are not used by REM, but are critical for post-processing. TaraUrja reported[5] that the tax charged to electricity providers is 14.5% of tariffs collected.

Tariffs charged for microgrid service to households are typically a flat monthly fee. During a variety of conversations in India we have heard of tariffs ranging from 60 Rs/month to 150 Rs/month for very similar services, typically a light or two and phone charging for a few hours in the evening. Mera Gao reports that they charge 100 Rs/month for evening service from their solar-based microgrids[6], while Husk Power charges 60 Rs/month for evening service from their biomass-based microgrids[7]. The Subdistrict Magistrate of Mahnar District, Vaishali, India reported to us that many villages have a single diesel generator supplying some service to the village, and the charges are typically Rs 90-100/month for one to two lights[8]. TaraUrja reports to us that they charge 120 Rs/month for one light and a phone charger, and an additional 40 Rs/month for an additional light.

Some microgrids to have volumetric tariffs. TaraUrja charges volumetric tariffs to its larger customers, which range from 16-22 Rs/kWh, with lower rates for those demanding more capacity. In the Indian village of Darewadi, a microgrid operated

[5]Meeting held January 2016

[6]"Microgrids Lend a Shine to Solar" Times of India June 7, 2014. http://timesofindia.indiatimes.com/business/india-business/Microgrids-lend-a-shine-to-solar/articleshow/36168208.cms Accessed April 6, 2016

[7]Conversation with Sushanta Chatterjee, July 2015

[8]Conversation July 2015, Vaishali, India.

Category	Type of Charge	Rate in Rs (USD)
Kutir Jyoti (Below Poverty Line)	Unmetered	Rs. 60/month
	Metered (Rural)	1.7 Rs/kWh for first 30 kW (same as DS-1 after)
	Metered (Urban)	2.05 Rs /kWh for first 30 kW (same as DS-1 after)
DS-1: Rural single phase ≤2kW	Unmetered	Rs. 170/month
	Metered: first 50 kWh	2.1 Rs/kWh
	Metered: 51-100th kWh	2.4 Rs/kWh
	Metered: Above 100 kWh	2.8 Rs/kWh

Table 3.1: Selections from the Bihar electricity tariff schedule for FY 2015-2016. http://www.biharchamber.org/content/new-tariff-rates-electricity-nbpdcl-and-sbpdcl-fy-2015-16, Accessed April 6, 2016

by Gram Power charges 20 Rs/kWh [3].

Meanwhile, grid tariffs are heavily subsidized. Although most customers are not charged volumetrically, the charges come out to approximately 1.5-3 Rs/kWh [3, 28], significantly lower than microgrid costs. The approved tariff rates for the North and South Bihar Power Distribution Companies for fiscal year 2015-2016 are shown in Table 3.1. Data from the Reserve Bank of India indicates that 35% of rural people in Bihar are below the poverty line, and 65% are above it[9], so I use the appropriately weighted average tariff in my calculations.

3.3 Scenarios run in REM

REM's detailed cost projections allow us to compare the potential costs of a variety of scenarios, and to assess who will be responsible for those costs. In order to assess the attractiveness of policy supporting grid-compatible microgrids, we need to understand how much such a policy will cost, who will pay that cost, and who will receive the benefits. To answer those questions, we use the following three scenarios in REM. They are each described in greater detail in the following sections.

[9]Reserve Bank of India https://www.rbi.org.in/scripts/PublicationsView.aspx?id=15283, Accessed May 10, 2016.

1. **Mixed solution with grid-compatible microgrids**: This is the default operation of REM; it selects the optimal electrification mode for each cluster of houses and builds all systems to meet the grid code. This scenario is run for both a high and low grid reliability scenario.
2. **Mixed solution with non-grid-compatible microgrids**: This scenario is similar to the above; the main difference is that REM is given a different catalog of network components for use with the microgrids than for the central grid. As well, the discount rates and operational costs would be adjusted to account for a different business model.
3. **All grid-extension**: Force REM to connect all customers to the central grid by removing isolated generation as an option.

Each scenario will be run with a range of key variables to assess their sensitivity. Their output can be used in three main ways.

First, we can examine what the cost savings of using a mixed on-grid and off-grid approach would be for the region of Vaishali, by comparing the output of scenarios 3 and 1. It is important to get a good estimate of this number for discussions with policymakers, because it can help address the tendency we have seen in state-level administrators to prefer grid extension as a near-universal solution. These cost savings refer both to the change in overall, societal costs, as well as the difference in cost actually paid by the government (including costs to the state-owned distribution company as well as any subsidy paid to off-grid operators).

Second, we can assess how much additional investment is required to bring a microgrid up to compliance with grid-compatible standards - both for an average microgrid and for the region as a whole - by comparing scenarios 2 and 3. These costs include higher-quality network infrastructure, and power electronics capable of interfacing with the grid (for example, higher-quality inverters built for both modes of operation).

Finally, using the output of scenario 2 and an estimate of the rate of grid expansion we can assess the magnitude of the investment likely to be 'lost' as the grid expands and puts non-grid-compatible microgrids out of business. Unfortunately, difficulties with scenario 2 rendered the results of the second and third analyses less useful, but there are still worthwhile insights to be gained from these comparisons.

3.3.1 Business model and regulatory assumptions

Crafting these scenarios requires not only finding the proper technical data inputs, but also imagining the regulatory and business context, since these factors will influence costs of capital (e.g. the discount rate used), tariffs, and economies of scale in operational costs. We assume that the expansion of the central grid would be undertaken by the utility, while the microgrid projects could be undertaken either by the utility (as has been done in Tanzania [54]) or by private entrepreneurs, which has been the norm thus far in India.

The choice of business model will affect the discount rate and operational costs for off-grid projects. In the utility-runs-all scenario, there will be savings in capital cost and in operational costs. In the private entrepreneur model, there is a potential range of economies of scale. For example, we could envision a situation in which all isolated systems are owned and managed by one company (for example, in a business model like that of Off Grid Electric's), and each microgrid company is responsible for a number of microgrids. Alternatively, we could envision private investment happening in a more isolated way, in which each isolated system and each microgrid has its own owner/developer. Of course, there is a continuum between these two visions.

For the two scenarios involving off-grid projects, we examine two cases, one on each end of this business model continuum. One will assume that all projects are centrally owned, funded, and operated (e.g. by the distribution utility or by a large development investor). The other will assume that all projects are funded in a one-off fashion, resulting in higher operational costs and costs of capital; while there is very little data publicly available regarding how these cost might change exactly, I have made some assumptions based on the reasonable distribution I have observed of these costs in the field and the literature.

We can also envision two possible scenarios for how tariffs might turn out under either scenario. While this input is not relevant for REM, it is relevant for the subsequent financial analysis. Regulators may require tariffs to be harmonized between the microgrids and the central grid, or they may allow the microgrids to charge whatever their customers find reasonable. My assumptions for this regulation will be described in the sections for each scenario.

3.3.2 Scenario 1: Grid-compatible microgrids

In this scenario, REM is run under its standard settings; it is allowed to choose any electrification mode for each cluster of households, and it uses the same standards for building the central grid and microgrids. Since both are built to the same standard, the microgrid will meet grid-compatibility standards for its network. After running REM, additional costs for interfacing between the central grid and the microgrid will be added to the financial assessment.

This scenario assumes that there is sufficient regulation to enable investment in grid-compatible microgrids, meaning that the investors feel that the risk posed by grid expansion is sufficiently low to enable them to lend at rates that the project can pay for. This change in the cost of capital is a key effect, as it is the clearest benefit of regulation which aims to remove the downsides of the risk of grid expansion. Other benefits include changes in the greater structure of the grid to encourage more distributed, renewable generation, which could reduce losses as well as the climate impact. However, these effects are beyond REM's modeling scope.

This scenario assumes that grid-compatible microgrids are allowed to charge a different tariff from the grid prior to connection. The pros and cons of such an arrangement are discussed in Chapter 5. I assume the tariffs charged by the central grid are those charged by the North Bihar Power Distribution Company to households, shown in Table 3.1.

Scenario-specific inputs:

- discount rates for microgrids
  - Integrated business model: 13.3% (same as grid)
  - One-by-one business model: 11%
- per customer costs for microgrids: $25, includes a meter.
- Network lifetime for microgrid: 20 yrs
- Tariff charged for microgrids: Rs 120/month

3.3.3 Scenario 2: Non-grid-compatible microgrids

This scenario is similar to the above scenario except the microgrids are not built to the same standard, so they are cheaper but not grid compatible. This scenario attempts to replicate the requirement for a very basic microgrid, of the type that we have seen Mera Gao implement; these microgrids typically provide very basic service, 1-2 lights and a phone charger, for a few hours per evening. The wiring for these microgrids is typically in DC, not in AC; while RNM is not capable of handling DC grids, we attempt to replicate its characteristics as closely as possible by ensuring maximum power delivered and voltage drops are represented accurately. To do so, the resistance and current rating of the wires are adjusted - an important side effect of this adjustment is that losses are significantly under-estimated in the design of the wiring, which may lead to a slight underestimate in the cost of the system. The line characteristics are based on a set of aluminum wires with diameters from 1.1 to 2.5mm; this range is based on characteristics of a sample line provided by the microgrid company SELCO, who uses aluminum wires that are 1.78mm in diameter.

Ultimately, however, this method produced results that were somewhat nonsensical. As a result, we employed a cruder method which encouraged cheaper, low-quality microgrids by lowering CNSE to $0.4/kWh and $0.8/kWh for normal and critical load, respectively, and increasing the discount rate significantly.

We assume the tariffs charged by the central grid are those charged by the North

Bihar Power Distribution Company to households, shown in Table 3.1.

Scenario-specific inputs:

- discount rates for microgrids
  - Integrated business model: 13.3% (same as grid)
  - One-by-one business model: 14%
  - Additional runs assuming faster rate of grid expansion, with discount rate 200 basis points higher.
- Network lifetime for microgrid: 10
- per customer costs for microgrids: $15 (no meter)
- tariff charged for microgrids: Rs 100/month
- Network catalog attributes and costs
  - Impedance is 0
  - Inverter cost is 0
  - MV and HV lines eliminated
  - Assume aluminum wiring

3.3.4 Scenario 3: All grid-extension

In this scenario, generation option are so expensive that REM should never choose an off-grid system; instead, every household will be forced to be connected to the grid. The minimum reliability requirement will ensure that every household is connected to the grid. Tariffs charged by the central grid are assumed to be those charged by the North Bihar Power Distribution Company to households, shown in Table 3.1.

Scenario-specific inputs:

All inputs are the same as in scenario one except generation options have been made very expensive, so that REM is forced to choose all on-grid options.

3.4 Financial analysis and assumptions

After running these three REM scenarios, their output is used to calculate the cost of each scenario to the government. We assume that the government will make up any shortfall in revenue for both on-grid and off-grid projects through subsidies. This is common for the distribution companies, though currently the subsidy system in India is not very effective at subsidizing off-grid projects. Stakeholders in that sector report that obtaining the subsidies requires navigating a significant amount of red tape, and the timing is highly uncertain.

Since the question we are concerned with answering is 'how much government support would each of these scenarios require,' it is appropriate to assume that a negative NPV for a project would be made up in the form of government subsidy. For off-grid projects, clearly a more efficient method of providing the subsidy would need to be devised for this hypothetical scenario to play out.

REM outputs the costs of all components and their lifetime, allowing us to assess upfront and ongoing capital expenditures. Operations and maintenance costs are provided as well. REM also outputs information about the number of households within each electrification project, and the total demand served; this information allows for the calculation of revenue. With the costs and revenues in hand for each electrification project, we can determine the overall NPV of the project, assuming that the grid never expands.

If scenario 2 had worked for realistic simulation of non-grid-compatible microgrids, we could have determined the value invested in off-grid projects that is abandoned as the grid expands. It would be a worthwhile analysis to conduct if this functionality can be implemented successfully. This value is important both because it represents a deadweight loss to society, and because it will serve as a warning to other potential entrepreneurs and investors, potentially scaring them off or at least significantly driving up the rates of return they expect from the project, so they can make a profit before the grid arrives.

Assumptions regarding the rate of grid expansion could significantly affect the cost of different scenarios. Although REM determines an 'optimal' arrangement of on- and off-grid projects, it is reasonable to assume that the grid will continue to expand in at least some areas. This expansion will be driven by policy directives as well as by increasing demand for electricity, which will expand the range of locations where the grid is cost-efficient.

Grid expansion affects the government subsidy provided to off-grid projects, which would need more subsidy once they are connected to the central grid and must charge lower tariffs. As well, it affects government spending on the grid; although REM is not particularly well-suited to assessing this cost, but it can be estimated by comparing the financial costs of the grid in scenarios with low and high grid expansion. Assumptions about the rate grid expansion will also affect the risk to non-grid-compatible microgrids, and change the value that is abandoned when the grid arrives. A range of assumptions should be tested regarding how long it will take before the grid encroaches on the microgrid's territory.

Chapter 4

Results

4.1 REM Sensitivities

Before utilizing REM for a policy analysis, it is vital to understand how sensitive the model's results are to the values of various inputs, in order to assess whether the model behaves as expected as well as over what range we should expect the results to hold true. REM's inputs are comprised of hundreds of separate values, and not all of them have been tested in this analysis. Instead, the analysis focuses on those variables we suspect might have the greatest impact.

4.1.1 Results

Stochasticity of runs There is some inter-run variability, even between runs with identical inputs. This difference arises from stochasticity in the demand profile generation algorithm described in [17]; this is the only portion of the model with randomness involved. However because this aspect is very important for building the look-up table and determining the costs of supply, it can have wide-reaching effects within the model results. It is important to quantify this variability first, to determine at what point the effect of a change in inputs can be considered significant. Six identical runs

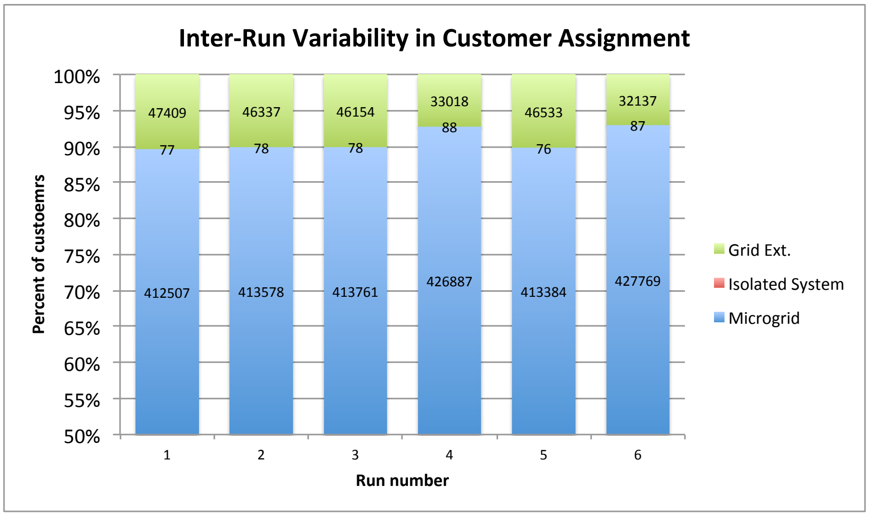
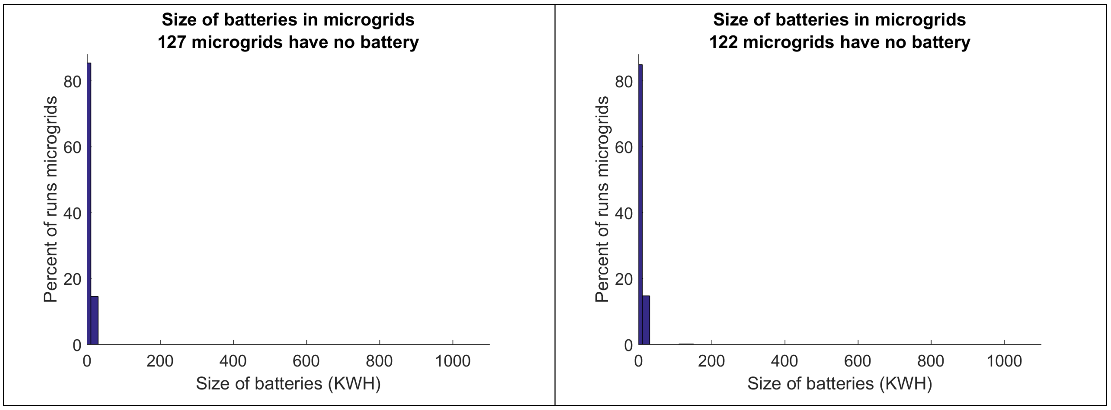


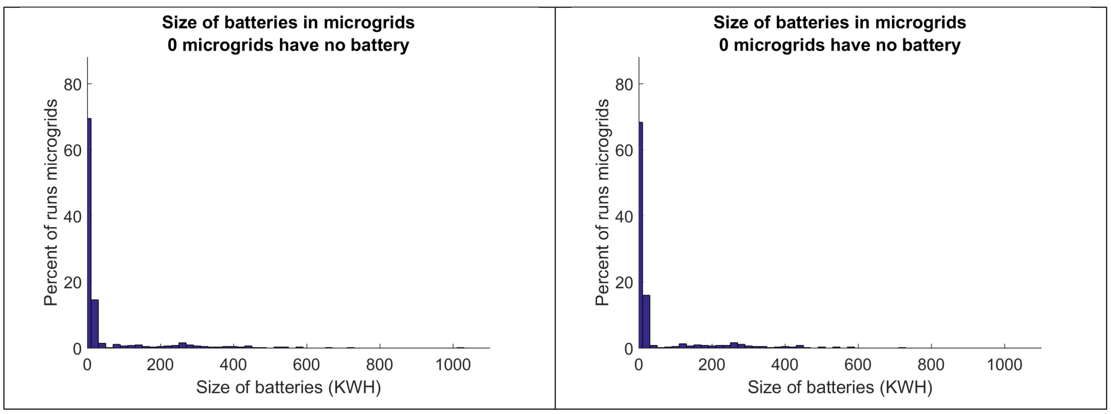
Figure 4-1: Inter-run variability for assignment of customers to different electrification modes. Please note that the Y-axis starts at 50%, to make the inter-run variability more visible.

using the input parameters described in Appendix A yielded the following inter-run variation, with surprising results.

- There appears to be a bimodal distribution of the model outputs, where there are solutions around two somewhat different optima. Figure 4-1 illustrates this bimodality. The two optima, or 'modes', are reasonably different from each other. However, within each mode the variations are tiny. Between modes, the average number of households in a microgrid shrinks by 20%, while the average battery size drops dramatically, from 46.2 kWh to 4.64 kWh. This difference is not due to an outlier effect; rather, the whole distribution of battery size changes significantly, as shown in Figure 4-2.
- Assignment of customers to electrification mode: The largest difference across the 6 runs was a change in assignment for 3.2% of consumers, who mostly switch between microgrid and grid extension. The variability in customers assigned to isolated systems was extremely low (.0025% of total customers). A graph of this variability is shown in Figure 4-1; it illustrates the breakdown in customers between microgrid (blue), isolated systems (red), and grid extension (green). The maximum inter-run variability for the number of customers in microgrids,



(a) Histograms of battery size distribution within the two runs that show the less common mode.



(b) Two representative histograms of battery size distribution from the four runs that show the more common mode.

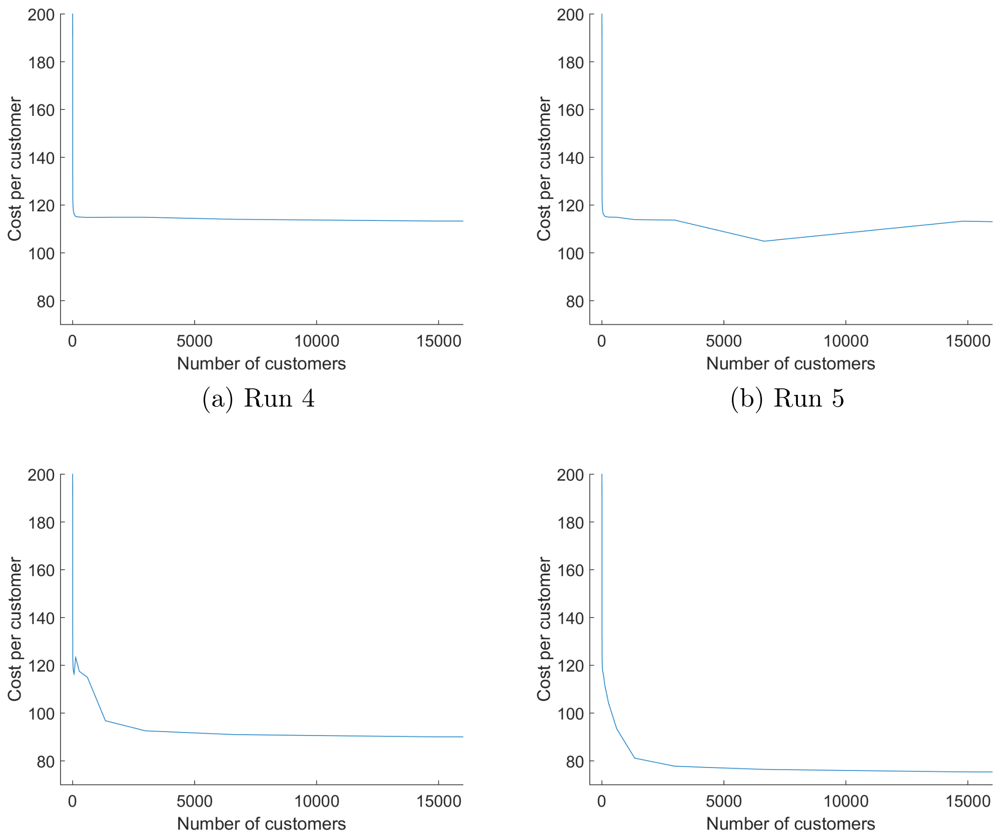
Figure 4-2: Difference in distribution of batteries between identical REM runs. There appear to be two 'modes' that exhibit little variation within themselves, but great variation between the two modes. Note that the Y axis is the percent of microgrids in the simulation with the relevant size of battery.

isolated systems, and grid extension within the more common mode is 0.27%, 0.0004%, and 0.27%, respectively.

- Cost of electricity per kWh: There is little variability here. Microgrid cost per kWh varied by 0.75%, grid extension cost by 4.04%, and isolated system cost by 5.6%. Within the more common mode, the inter-run variability is 0.21%, 0.12%, and 1.1%.
- The variation in total financial cost (i.e. cost excluding the cost of non-served energy) was 0.14%. Excluding the less-common mode does not affect the spread in financial costs.

Changes in the lookup table The lookup table is generated by the algorithm described in section 2.3.2. For a sample of microgrid sizes it produces sample designs and an associated cost. In theory, the relationship between the number of households in a microgrid and the cost per customer should be a smooth curve. If it is not so, then the clustering step may become stuck in a local optima that is not a global optima. It important to check this intermediate output before interpreting any runs, because on rare occasions the model can produce lookup table curves that have local optima. In the 50 or so runs done for this thesis, 2 had undesirable lookup table curves, which would arise unpredictably. Figure 4-3 shows an example of the lookup table curves for a set of four runs, which only differ in the diesel price used; they have values of 1.75, 1.5, 1.25, and 1 $/liter. Run 5, in the upper right, and Run 6, in the lower left, have local minima which could result from switches between generation. However, the actual curve used to determine prices in the clustering step is a smoothed version of the curve displayed. Nevertheless, knowing this, we might be more skeptical of the results from these runs.

Impact of diesel price The price of diesel is a strong determiner of the model's outcome. Especially because Vaishali is a relatively flat, dense region, grid extension is a relatively competitive option for a large number of households. When the cost of diesel drops such that microgrids are competitive with grid extension, it changes how customers are assigned to electrification mode quite dramatically. Figure 4-4 illustrates this sharp transition as microgrids reach cost parity with grid extension. Even at high diesel prices there are a number of communities for whom microgrids are still the most cost-effective option, and that choice remains constant up to very high diesel costs. Diesel appears to make very large microgrids economical, and at this scale they can compete with the grid. In the absence of large diesel generators, the average size of a microgrid drops to below 100 households; diesel generation is not completely absent in all these smaller microgrids, but they do tend to be based on PV with a battery, and maybe a small supplementary diesel generator.



(a) Run 4

(b) Run 5

(c) Run 6

(d) Run 7

Figure 4-3: Changes in lookup table over a small range of diesel prices. Run 4 has a price of 1.75 $/liter. Run 5: $1.50/liter. Run 6: $1.25/Liter. Run 7: $1/Liter.

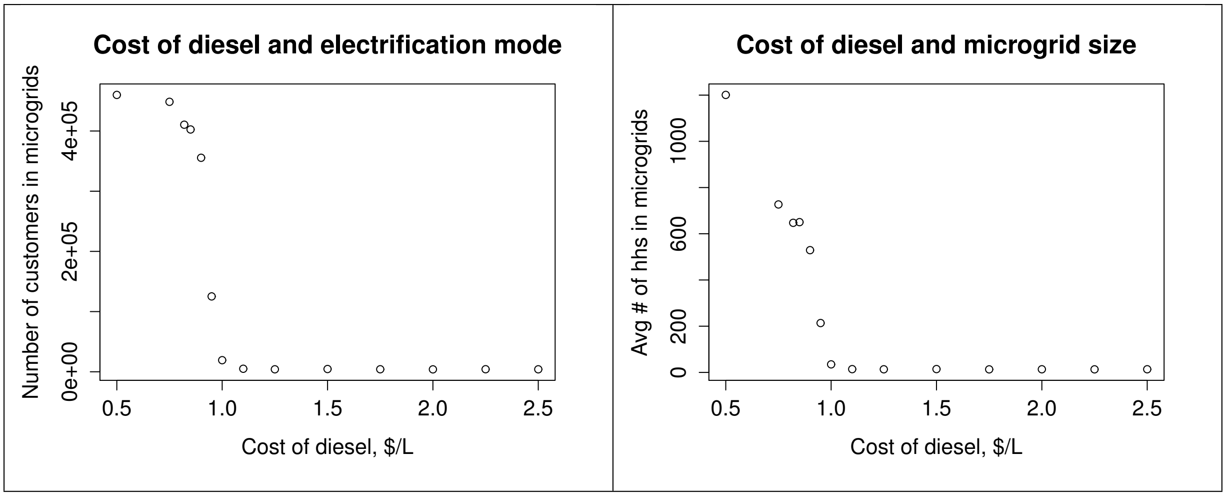
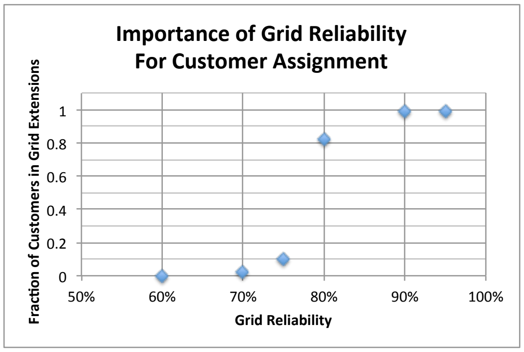


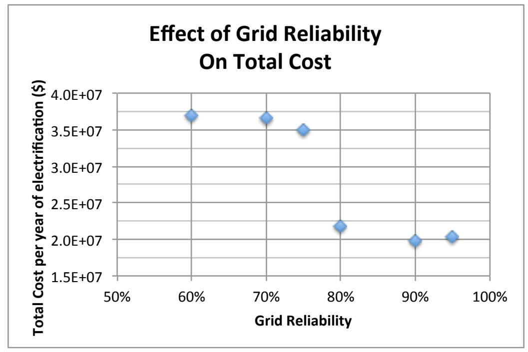
Figure 4-4: The price of diesel causes sharp transitions in the decision outcome of REM

Interestingly, the most current price of diesel we have, from January 2016, is \$0.82/liter, right at the transition point in Figure 4-4. Two years earlier, when oil prices were much higher, we would certainly be below the transition shown. Of course, this transition might happen at different values if the costs of the grid were to change, for example by changing the cost of supply or changing the reliability.

Grid reliability The reliability of the grid also has a very strong impact on REM's output, creating sharp transitions similar to those observed for diesel price. See Figure 4-5 for an example of this tipping point; under the current model settings, the transition happens between 75% and 85% grid reliability. This tipping point indicates that for many households in the study area, the cost of the grid extension is less than the cost of a microgrid or solar home system, if the costs of non-served energy are ignored. Of course, these results have the caveat that upstream reinforcement in the transmission and distribution system is ignored because the model cannot currently capture it, though it would certainly be required and would likely be expensive. We do not know how the magnitude of that cost would change the difference between grid extension and microgrids.



(a) Effect of changing grid reliability on assignment of customers to grid extension



(b) Effect of changing grid reliability on the annualized cost of building and maintaining electricity infrastructure for Vaishali

Figure 4-5: These figures show the strong effect of grid reliability on the assignment of customers to electrification mode, and the effect on total financial (i.e. excluding the value of unmet demand) cost.

Discount Rate The discount rate, both in absolute value and the relative value between the various modes of electrification, has a modest effect on REM's output. The absolute value of the discount rate has a small effect; with discount rates for all modes set equally, a shift from a 5% to a 10% discount rate changes the assignment of the customers from 12% connected to a grid extension to 21%. A higher discount rate appears to favor grid extension in the scenarios examined. Smaller changes in discount rate, in the 10-14% range, appear to have a dramatically smaller impact on model output. Shifting the discount rate for microgrids from 12% to 14% decreased the customer assignment to microgrids for only 1.2% of customers, and increased the financial cost by 1.9%.

The relative value of the discount rates can have a much stronger effect. A 5% discount rate for grid extension and a 10% discount rate for microgrids leads to 87% of the customers assigned to a grid extension, although no parameters other than the discount rate were changed relative to the all-equal runs. It is very likely that the discount rate exhibits a similar characteristic to grid reliability and diesel price, in that its effect has a sharp transition between two modes, and the values tested tend to be near this transition, creating large differences between otherwise similar runs.

Number of Customers	Management Cost per year Case 1	Management Cost per year Case 2	Management Cost per year Case 3	Management Cost per year Case 4
1	$15	$15	$11	$10
100	$11	$12	$10	$10
Infinite	$7	$10	$9	$10

Table 4.1: Sample inputs for defining economies of scale in annual management costs

Management Costs REM contains some parameters for defining the economy of scale in the management and collections costs for microgrids. Since the strength of economies of scale is important for the clustering algorithm, we might expect this value to have a strong impact on the outcome. In order to define this curve, REM fits a curve to data such as that provided in Table 4.1; everything but the definition of 'infinite' for a large microgrid is changeable by the user. The table shows the input values used for the range of cases tested, which were chosen to examine the impact of economy of scale.

From case 1 to case 4, the average microgrid size shrank by 25.6%, indicating that these management costs do have some impact on clustering decisions. The results are shown in Figure 4-6. However, despite these changes, the assignment of customers to different modes of electrification was not strongly affected by differences in management economies of scale. There was no clear trend within the four cases, which varied between each other by less than 1% of the total customers. The total nonserved demand and the total financial costs likewise showed no clear trends.

Cost of Nonserved Energy (CNSE) The cost of nonserved energy has a very strong effect on the model outcome. It determines the preference for reliability vs. cost. Table 4.2 shows the change in total financial cost, cost of nonserved energy incurred, and customer assignment to the three modes of electrification under different CNSE assumptions. The effect exhibits a sharp 'tipping point' effect, much like diesel cost and grid reliability. This tipping point occurs because most consumers and most

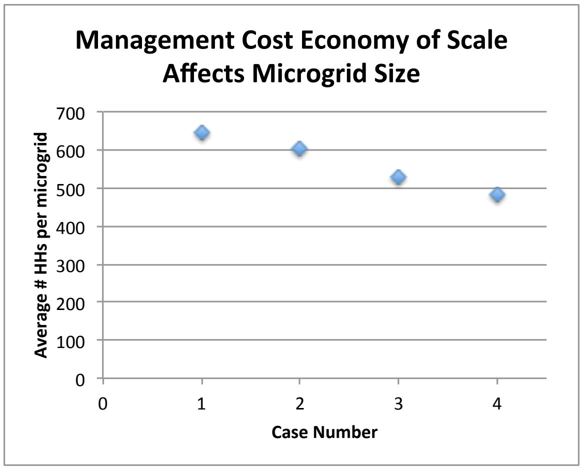


Figure 4-6: Decrease in microgrid size with increase in management economies of scale.

clusters of consumers are relatively similar, so if one option is more cost effective for one cluster, it is likely that many others (anywhere from 80 to 99% of customers) will have the same result.

A low CNSE for critical demand biases the results towards grid extension in this case, as the grid has a 75% reliability in these runs and generally a lower financial cost per person. A high CNSE biases the results for low demand biases away from grid extension. Because the microgrids designed in these scenarios are better at meeting critical demand than a grid with 75% reliability (which in actuality is much better than what we have observed for reliability during peak hours), when emphasis is placed on meeting this demand microgrids are preferred.

Operations and Maintenance Costs for Generation To test the impact of operations and maintenance (O&M) costs for generation, we run three scenarios in addition to the base case. In the base case, the cost of labor is \$0.93/hr, a figure roughly derived from the monthly salaries we have heard from the microgrid company Tara Urja. O&M costs for generation are divided into two components; a fixed component and a component that varies by the size of the generation. The former is given as a fraction of the initial cost, and the latter is given as a number of service

	Base case	High CNSE	Low CNSE
Critical CNSE	2	2	1
Normal CNSE	0.51	1.5	0.51
% customers with microgrids	89.23%	99.94%	1.45%
% customers with grid extension	10.75%	0.030%	98.53%
% customers with isolated system	0.018%	0.028%	0.016%
Annualized financial cost ($ million)	$34.88	$38.70	$18.51
Annual cost of nonserved energy ($ million)	$3.59	$0.49	$16.75
Average microgrid size (customers)	647	472	16
Average $/kWh, microgrid	$0.590	$0.587	$0.638
Average $/kWh, grid extension	$0.324	$0.378	$0.285
Average $/kWh, isolated system	$2.197	$1.179	$2.081

Table 4.2: Assumptions about the cost of nonserved energy have significant effects on several key outcomes of REM. A few illustrative cases are shown in this table; a base case, a case where the 'normal' CNSE has been raised, and a case where the 'critical' CNSE has been lowered.

hours per year[1]. For the fixed maintenance requirements, the battery is assumed to require 5 hours of maintenance, solar panels 5 hours, diesel generators 25 hours, and the AC/DC converter and charge controller 2 hours per year. The three variants on this base case are as follows:

1. Reduce cost per hour of labor to $0.50/hr
2. Reduce required hours of labor (fixed cost) by half for all components.
3. Raise cost per hour of labor to $2/hr.

The results of this comparison are more or less inconclusive. They do not suggest that O&M costs have a large impact on the electrification mode chosen, at least not within the range tested. Within the range of labor costs tested (0.50, 0.93, and 2 $/hr) there is no strong trend. Quadrupling the labor cost from $0.5 to $2/hr results in a 0.5% increase in costs per customer for microgrid systems, and a 1.3% increase in the total cost of the electrification plan for the whole region. Only 0.08% of customers are assigned to a different electrification mode between the high and the low scenario.

The comparison of the reduction in fixed labor costs with the base case is difficult to do, however, because the base case seems to be a dramatic outlier in this set of four cases. It is possible that this difference is due to the stochastic variation discussed above. Indeed, the differences are consistent with the variations seen in the test of inter-run variability - most parameters change a modest amount, but the average size of the battery in a microgrid changes from 45 kWh in the base case to 5.0 kWh in the reduced labor hours scenario. In scenarios 1 and 3, average battery sizes are also significantly smaller, at 4.6 and 4.9 kWh per microgrid. Microgrid size is not a good explanation for this change, as the average size between the base case and scenario 2 differs only by 6.05%.

While these results are somewhat puzzling and support further investigation, they do suggest convincingly that generation O&M costs do not have a dramatic effect on

[1]Future versions of REM will incorporate some economy of scale into these fixed costs, recognizing that the time to service a generator and a PV panel at the same microgrid takes less time than servicing an equivalent generator and PV panel at different sites.

Case	Description	Peak demand / household (kW)	Average daily demand / household (kWh)
Lowest	Only two lights are possible, and the option to use a TV at night is eliminated.	0.153	0.255
Lower	Four lights are possible, and nighttime TV is eliminated.	0.183	0.405
Base	2 lights are considered critical, with an additional 4 noncritical. Fan, TV also included. (See Appendix A)	0.266	0.623
Higher	Same as base case, but with more customers (75%) assigned a fan.	0.266	0.795

Table 4.3: Description of cases run for demand level sensitivity

REM's outcome.

Demand Level To test the importance of demand level on the output of REM, we ran two cases with lower demand than the base case, and one case with demand higher than the base case. For a full description of the demand inputs, see Appendix A. The three cases are described in Table 4.3.

At the lowest level of demand, no customers are connected to the grid. This conclusion is striking, as the demand levels used (two lights, with a possibility of a fan and a small amount of TV usage) would be very typical for below-poverty-line households in India, though even then the TV is likely out of reach. At the lower and base levels of demand, approximately 90% of the customers are assigned to microgrids; 79% for the higher demand case. The level of demand does affect the levelized cost of energy and the generation chosen for microgrids, but not in a monotonic way. Figure 4-7 shows these impacts; isolated systems unequivocally become cheaper with higher demand, but for microgrids and grid extension it seems costs rise with increasing demand, before hitting some sort of economy of scale and falling again.

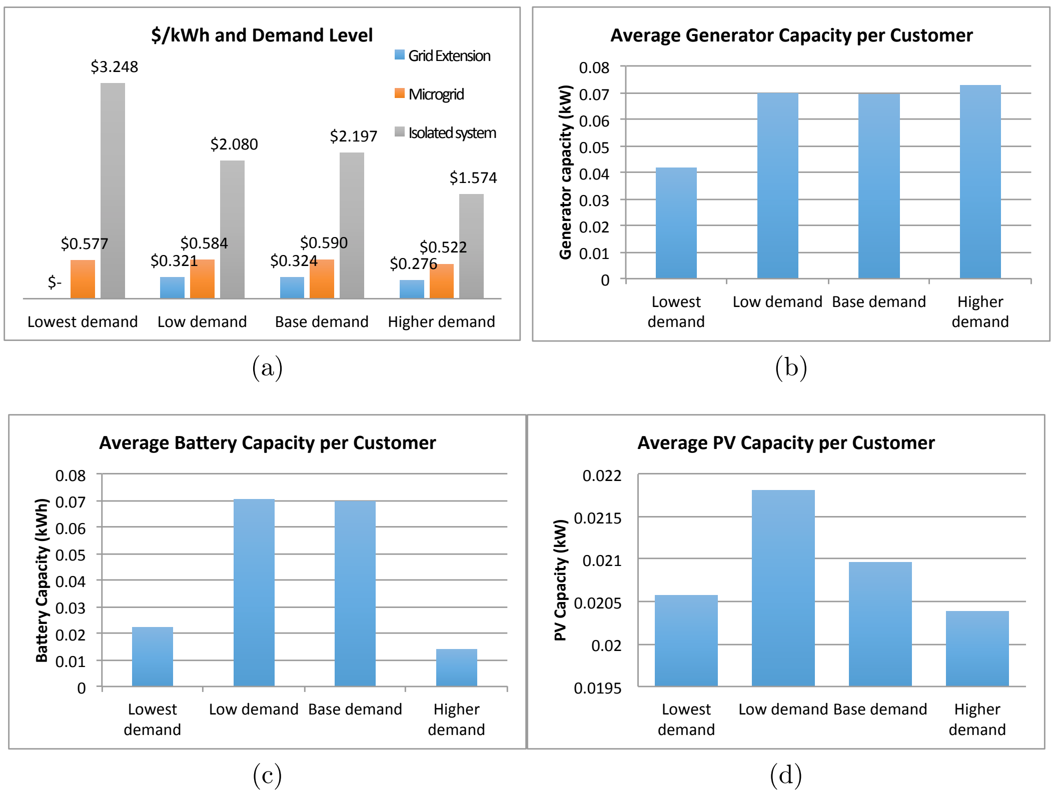


Figure 4-7: Impacts of demand on the cost per kWh and the generation options chosen for microgrids.

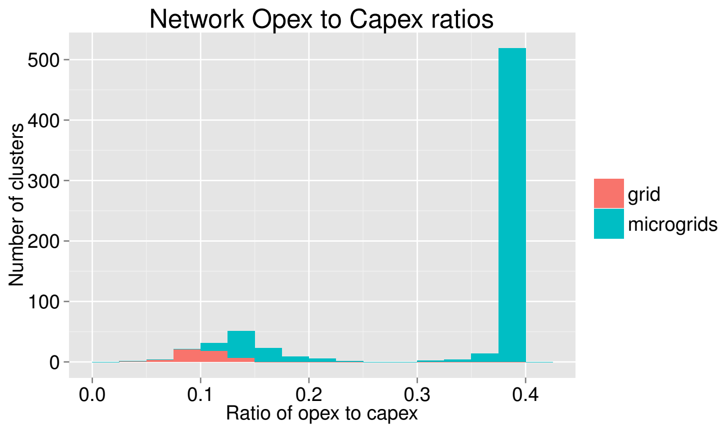


Figure 4-8: Histogram of average network operations and maintenance costs as a fraction of upfront installation, for each cluster

4.1.2 Other Model Result Observations

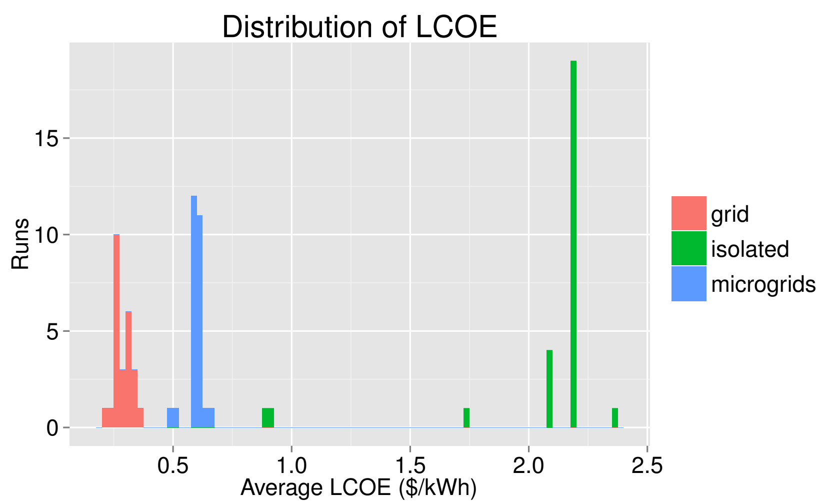
Bimodal Network Opex Costs As shown in Figure 4-8, the cost of operations and maintenance (opex) for the network has a bimodal distribution. For many systems, the ratio of the average annual network opex cost to the upfront cost for installing the network (capex) is well below 30%, but for many systems, all microgrids, the cost is almost 40%. These high opex costs are found generally in smaller microgrids; ratios less than 20% are found only for microgrids that are more than 1000 households. The reason for this bi-modality is unclear, and has to do with the way in which the Reference Network Model (described in Section 2.3.2) calculates operations and maintenance.

Cost per kWh The literature has several estimates of what the cost per kWh for a solar or diesel-powered microgrid should be. [14] reports a total LCOE of $0.446 to $0.569 per kWh, depending on the generation technology used, with higher values for diesel-based grids, assuming a microgrid size of 270 (the average village size in Gujarat). [13] estimates LCOEs for solar-and-battery microgrids ranging from under

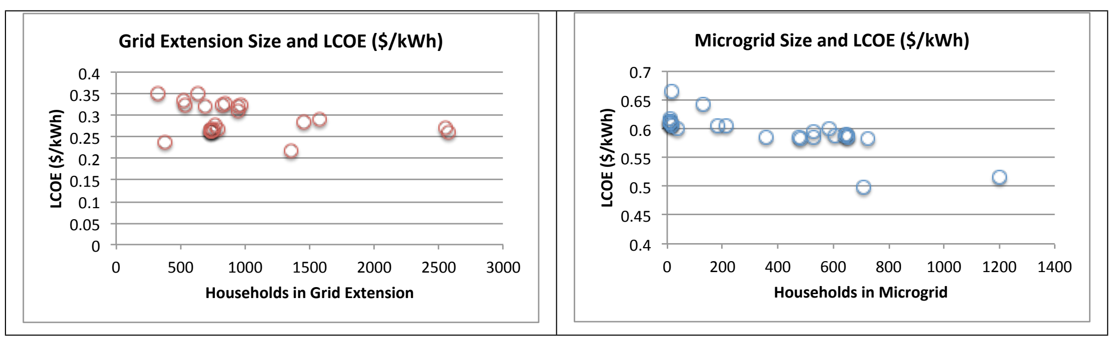
$1/kWh to as high as $23/kWh for very small systems, though for scenarios where peak demand was at least 45W per customer, the range was under $1 to roughly $3.5/kWh (See Figure 27 in [13]). In the runs examined, every customer is assumed to have at least 2 lightbulbs of 15W each which are considered critical load, and 4 additional optional lights. So these runs would be assumed to be in the lower range of [13]'s estimates.

The range of costs predicted by REM appears to be in line with what we would expect from [14] and [13]. Across the range of runs done for this sensitivity analysis, the average LCOE for microgrids was $0.595/kWh, only slightly higher than what [14] predicts and well within the range expected by [13]. Isolated systems tend to have an LCOE around $2/kWh. Extension of the grid, meanwhile, clocks in with an average LCOE of $0.29/kWh. The range of these values is illustrated in Figure 4-9a.

Fraction of Demand Served The fraction of demand served in microgrids appears to be very closely related to the number of customers in a microgrid and the size of the diesel generator. Without any diesel, microgrids in the base case tend to achieve a reliability of around 40%. After the microgrids grow larger than about 25 people, diesel generators begin to be economical and reliability quickly improves. While the exact numbers vary between cases, the behavior (with a low base reliability, increasing to high levels once some minimum economy of scale is achieved) is relatively similar. See Figure 4-10 regarding the relationship between the fraction of demand served and the number of customers in a microgrid, and the relationship between number of customers and generator size. In Figure 4-10a there are microgrids with similar number of customers that have significantly different levels of fraction of demand served; in particular, the fraction of demand served seems to increase rapidly, save for a few outliers. It is not clear why REM found these outlier solutions optimal, but these systems seem to have significantly smaller diesel generators than comparably

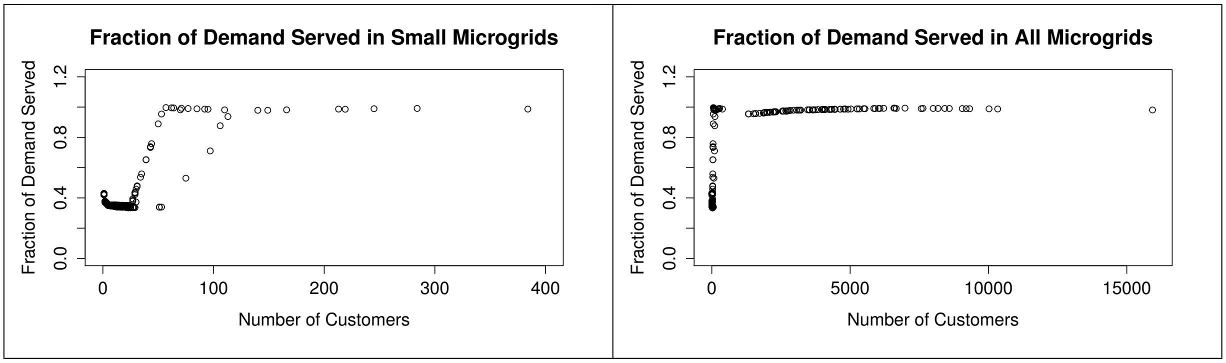


(a) Distribution of LCOE across all the runs of REM conducted for the sensitivity analysis

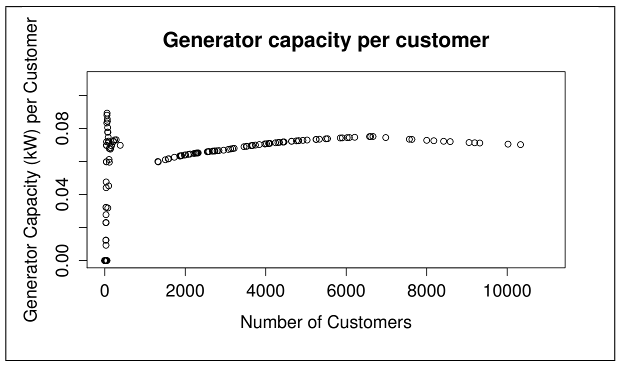


(b) The average size of a grid extension or microgrid does not have a strong effect on the LCOE, although there is a small correlation for microgrids.

Figure 4-9



(a) The fraction of demand served changes rapidly as microgrid size increases, until it hits a saturation point



(b) The installed capacity of diesel generation per customer increases rapidly at first, and then saturates and declines slightly.

Figure 4-10: Microgrid reliability is closely related to the number of customers and the size of the diesel generator.

sized systems.

4.2 Scenario Results

Recall from Section 3 that the three main scenarios in question are:

1. Mixed approach to electrification, utilizing grid compatible microgrids
    (a) Low grid reliability (75%)
    (b) High grid reliability (95%)
2. Mixed approach to electrification, utilizing non-grid-compatible microgrids
3. All grid extension.

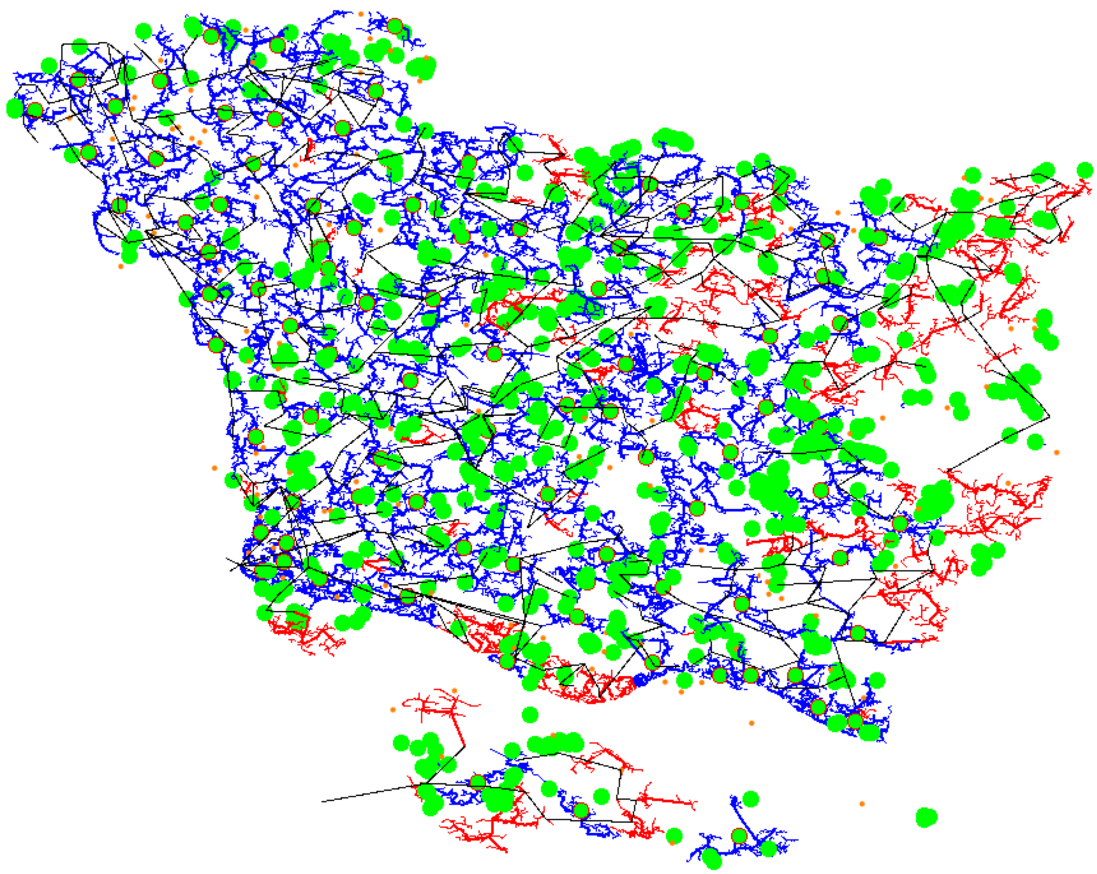


Figure 4-11: Map of the output from the Scenario 1a. Grid extension network lines are in red, microgrids in blue. Green circles represent microgrid generation sites; those with a red border are connected to a medium voltage network. Thick network lines represent medium voltage, thin lines represent low voltage. Small orange dots represent isolated systems. The black lines represent existing medium voltage grid lines

REM's default approach is in line with scenario 1. For scenario 1, we examine a situation from each side of the grid reliability threshold: one with 75% grid reliability and more microgrids, one with 95% grid reliability and fewer microgrids. Note that 75% grid reliability is still higher than what we have observed in agricultural feeders in Vaishali, based on historical log books. The map of the low-reliability scenario is shown in Figure 4-11. It is interesting to note that in the dense urban areas in the lower left, microgrids are preferred, while grid extension is preferred in the less-dense areas on the right side.

To simulate scenario 2, we wished to replicate the cheap, DC microgrids used by companies like Mera Gao, which supply a few hours of evening light to their customers. However, attempts to adjust REM's parameters to simulate a DC system within the AC architecture of the Reference Network Model used to design the network were unsuccessful.

Instead, cheap microgrids were simulated by lowering the cost of nonserved energy for low-priority and high-priority demand to $0.4 and $0.8, respectively, such that low-priority demand would rarely be met by a microgrid, but high-priority demand (2 light bulbs at night) would often be. As well, the discount rate was raised and the lifetime was lowered for these systems, to replicate the high risk environment of these projects. These settings resulted in many microgrids that met only a small fraction of load. However, the efficiency of these microgrids is likely still vastly overestimated in this scenario, since some of the microgrids are much larger than would be expected from a DC grid.

For scenario 3, the generation costs available were raised to very high levels. Solar panels were priced at $10000 (instead of $225 and $50 for the different sizes). Diesel cost was raised to $2/liter. Even under these high cost scenarios, 2 microgrids and 3 isolated systems powered by solar PV and a battery were found to be cost-effective, but the rest of the consumers were placed on grid extensions.

For scenarios 1a, 1b, and 2, each run was done twice; once assuming that the microgrids are managed by private entrepreneurs with costs of capital and management costs the same as the base case, and again assuming that the microgrids are managed by the utility with the same cost of capital and no economy of scale in management costs. The effect of the change was negligible, with the relevant output variables changing by less than 2%. As a result, this section presents those figures derived from the scenarios run with the assumption that microgrids are owned by private companies, for clarity.

The high-level results of these runs are laid out in Table 4.4.

For the all-grid scenario, the government could reduce the subsidy required by 45% if it were willing to raise the tariff only for customers above the poverty line to 340 rupees per month, which is twice the current rate. Below-the-poverty-line customers make up 35% of the customers in rural Bihar, and arguably their rates should be kept low. However, adjusting the tariff for those above the poverty line to be more reflective of the cost of service would significantly reduce the subsidy needed.

A doubling in microgrid tariffs, from 100 Rs/mo to 200 Rs/mo, does not have an enormous impact on the government subsidy required, even for the scenario 1(a) run in which 88.5% of customers are on microgrids. This indicates how little of the cost of the microgrid customers might pay. Indeed, few if any of the microgrids in this scenario are able to cover the ongoing costs O&M and equipment replacement costs of the microgrid, ignoring the upfront investment costs.

It is worth noting that for scenario 1a the number of households per microgrid has a bit of a bimodal distribution. There are many microgrids with fewer than 350 households, and many with 1300-1600 households, but none in between. Future work should investigate the reason for this bimodality.

Metric	Scenario 1a: Compatible microgrids, Low grid reliability	Scenario 1b: Compatible microgrids, High grid reliability	Scenario 2: Cheap Microgrids Low grid reliability	Scenario 3: All-Grid Low grid reliability
Annualized financial cost ($ million / yr)	$35.64	$20.64	$19.00	$16.98
Total cost including nonserved energy ($ million/ yr)	$39.46	$25.41	$32.42	$39.91
Annualized financial cost per customer per year	$77.47	$44.86	$41.3	$36.9
Customer assignment, microgrid	88.51%	0.62%	1.57%	0.00217% (10 houses)
Customer assignment, grid extension	11.47%	99.37%	98.40%	99.99%
Customer assignment, isolated systems	0.025%	0.013%	0.022%	0.0007% (3 houses)
Average microgrid size (customers)	517	9.3	1247	5 customers
Average $/kWh, microgrid	$0.630 / kWh	$0.669 / kWh	$0.737 / kWh	$9.132 / kWh
Average $/kWh, grid extension	$0.314 / kWh	$0.278 / kWh	$0.294 / kWh	$0.383 / kWh
Average $/kWh, isolated system	$2.077 / kWh	$2.079 / kWh	$2.080 / kWh	$18.62 / kWh
Percent of demand met by off-grid systems	97.44%	37.19%	38.48%	38.48%
Percent of demand met	94.83%	94.63%	74.41%	75%
Subsidy cost to government, NPV. ($ million)	$453.0 - $504.4	$130.7 - $131.0	$256.1 - $257.0	$56.20
Subsidy cost, amortized over 20 yrs ($ million)	$22.88 - $25.47	$6.6 - $6.62	$12.93 - $12.98	$2.84

Table 4.4: Results from the two runs examined in Scenarios 1-3. The annualized financial cost represents the sum of the annual costs incurred by the microgrid, and the annuity of the capital costs. The annuity represents the value that could be paid yearly so that the net present value of those payments is the same as the actual costs incurred; this value is a way of distributing the infrequent capital costs over the lifetime of the project. The range in subsidy projection is based on a range of microgrid tariffs from 100 Rs/mo to 200 Rs/mo, and a project lifetime of 20 years. The subsidy calculation assumes a lifetime of 20 years and a discount rate of 9.5%.

4.3 Comparison

4.3.1 Savings from a mixed on/off-grid approach

The results from the scenarios above show a modest savings available through the use of a mixed approach over an all-grid plan. These savings would likely be considerably higher if the cost of upstream reinforcements in the transmission and distribution infrastructure were considered, as this would drive up the costs of grid extension significantly. The magnitude of the additional load attached to the grid would necessitate considerable grids in in Bihar's already-overburdened infrastructure.

The use of solar/battery powered microgrids even when panel prices are $10000/panel in scenario 4 clearly indicates that for the furthest consumers, off-grid systems can be eminently cost-competitive with the extension of the grid. The difference between the all-grid scenario (3) and the low-cost microgrid scenario (1(a)) shifts just 1.57% of customers off of the grid and onto relatively low-quality microgrids. However, this scenario could enable societal cost savings of at least $7 million per year; this number is certainly an underestimate, as our cost of nonserved energy estimates are likely to be underestimated, and the reliability of the grid in real-life can be much poorer than 75% in many rural areas - and likely would be so in other rural areas that have yet to be electrified. This difference is illustrated in Figure 4-12a.

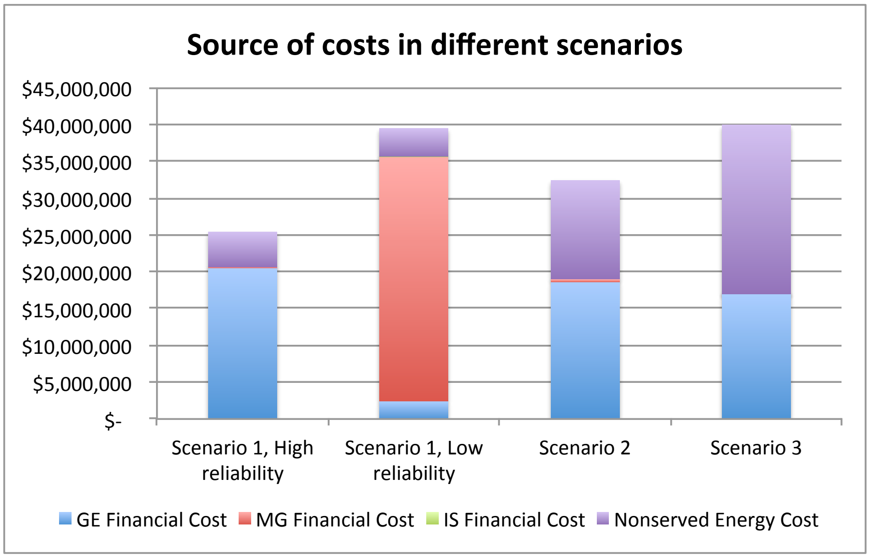
When the costs of not supplying electricity to consumers and businesses are factored in through the cost of non-served energy, it is clear that solutions involving more microgrids are vastly more favorable. The poor reliability of the grid in India results in huge losses for consumers who are connected to the grid but receive only very poor service. Whether these costs are sufficient to motivate additional investment in and subsidy for microgrids depends on the resources and perspective of the planner. The total costs are almost the same between scenario 3 (all grid) and scenario 1a (grid-compatible microgrids); however in the former there are very high costs of nonserved energy, while in the latter there are very high microgrid costs. Figure 4-12b shows the high level of government subsidy that would be required to sustain those microgrids and make them viable. These figures would be even higher if the microgrid is require to charge a tariff consistent with on-grid rates; Uttar Pradesh, for example, has suggested a tariff of Rs 60/mo, half the level that is used in these calculations.

Looking ahead, if the government is able to raise grid tariffs for above-poverty-line (APL) households, it would in fact have a considerable impact on the subsidy required. A doubling of the APL tariff, considering that 65% of rural households in Bihar are APL, could reduce the total subsidy required for the grid by 45%.

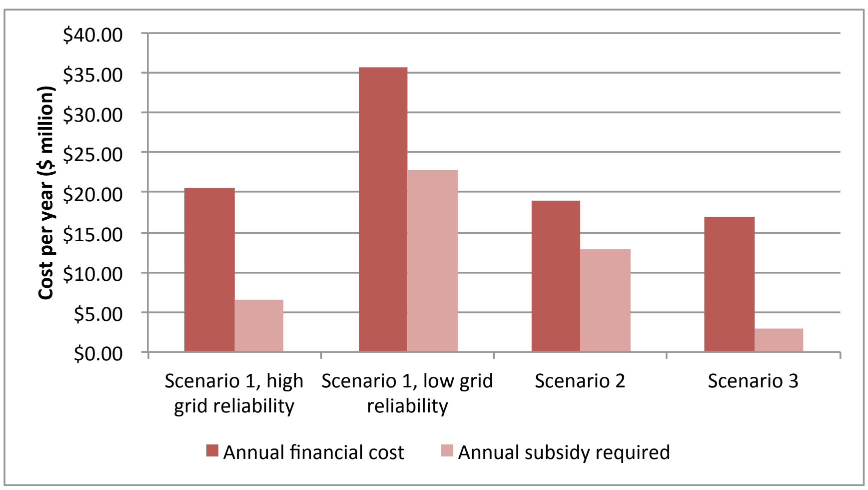
These numbers make a strong case for microgrids as a way to reduce the societal burden of non-served electricity demand, though not as effective way to reduce the cost borne by the government. It is very likely that the subsidy costs borne by the government would in reality be somewhat lower, as these simulations do not account for any non-residential load; commercial load would likely use more power and likely could pay a higher price, making the microgrids more viable. (Though it is important to note that abuse of these cross-subsidies from commercial to residential customers could drive commercial customers to seek their own generation source if they are abused.) Even a small number of microgrids, as in scenario 1b and scenario 2 increases the subsidy cost borne by the government considerably over scenario 3.

4.3.2 Value of grid-compatible microgrids

As discussed above, scenario 2 is a very rough approximation of a solution involving cheap DC microgrids, which makes a comparison between non-grid-compatible microgrids and grid-compatible microgrids difficult. A more useful simulation of the non-compatible approach would contain less grid extension and more and smaller microgrids, and could certainly be produced in future research. Although the cost per customer for a microgrid should be much lower in scenario 2 than the other scenarios, it is not significantly lower than the costs per customer seen in any other scenarios where a small fraction of customers are connected to microgrids. However, based



(a) Breakdown of scenario costs between actual financial costs for the different system types (MG = microgrid, GE = grid extension, IS = isolated system), and the costs of nonserved demand. These costs are the yearly annuity that covers upfront and intermittent capital expenditures in addition to ongoing costs. The scenarios referenced are described in section 4.2 and 3.



(b) Estimation of the annual value of subsidy costs that would need to be paid by the government, over a lifetime of 20 years, as compared to the annuity cost of the microgrid. The scenarios referenced are described in section 4.2 and 3.

Figure 4-12

on the limited data available, we can draw some first-order conclusions about what grid compatible microgrids and their accompanying regulation need to accomplish in order to make them a good investment.

An attractive theory for grid compatible microgrids is the idea that these businesses will bear the costs of the network and generation, covering them with tariffs and perhaps some subsidies, and pave the way for the future expansion of the grid; once the grid arrives, the theory goes, its costs will be greatly reduced because it will not need to build a significant amount of network infrastructure. These results question that theory, given the tremendous cost of building the microgrids in the first place; it is almost double the cost of extending the grid initially. Of course, some of those costs are generation, which would reduce the operating costs of the utility. However, it is unlikely that diesel generators would be economical to run in the presence of grid power, and diesel makes up a sizable fraction of the generation capacity in the scenarios examined. As the majority of the microgrids built in the scenarios showing a high penetration of microgrids have a significant amount of their generation from diesel, the contribution of that generation to reducing the operating costs of the utility might be limited. This is certainly a question for further research.

A comparison of scenario 3 with scenario 1a shows that the financial costs of providing electricity service to most consumers through high-quality microgrids are more than double that of providing electricity service through the extension of the grid alone. Accounting for the costs of nonserved energy, however, reveals that the two scenarios are almost the same cost, with the grid extension scenario being slightly more expensive. Which one is preferable in this situation is dependent on the values of the planner and how much weight they place on the cost of nonserved energy.

Considering that the costs of nonserved energy are likely an underestimate and the reliability of the grid is likely an overestimate, these financial costs should be considered strongly as in reality they are probably much higher than what is simulated here. An important unaddressed aspect is the cost of reinforcing the existing network as it is extended to more customers. Doing so would be incredibly necessary as line capacity limits are already constraining in some rural areas. Accounting for this cost would raise the cost of scenario 3 significantly. An additional consideration is the impact of distributed generation on the transmission and distribution costs incurred when the microgrids are connected to the grid. It is possible that local generation could reduce the transmission capacity needed, resulting in lower costs overall. However, the cumulative impact of local generation on transmission and distribution expenses is highly dependent on the actual situation present, the timing of generation and demand, and the intermittency of supply. Future studies should certainly take this into account.

4.3.3 Need for ongoing subsidy of grid-compatible microgrids

The results of these scenarios point towards the need for ongoing subsidy to support grid compatible microgrids. The average annual cash-flow shortfall for microgrids in scenario 1a was $4,503 per customer per year, indicating that a subsidy of a similar magnitude would be needed to make the project break even. This figure assumes a tariff of 120 rupees per month per customer, and excludes upfront costs. Figure 4-13 shows the close relationship between the number of customers in a microgrid and the average subsidy need per customer. The economies of scale start to saturate around 100 to 200 households in these scenarios, indicating that governments should encourage microgrids that will be at least this big for the most efficiency.

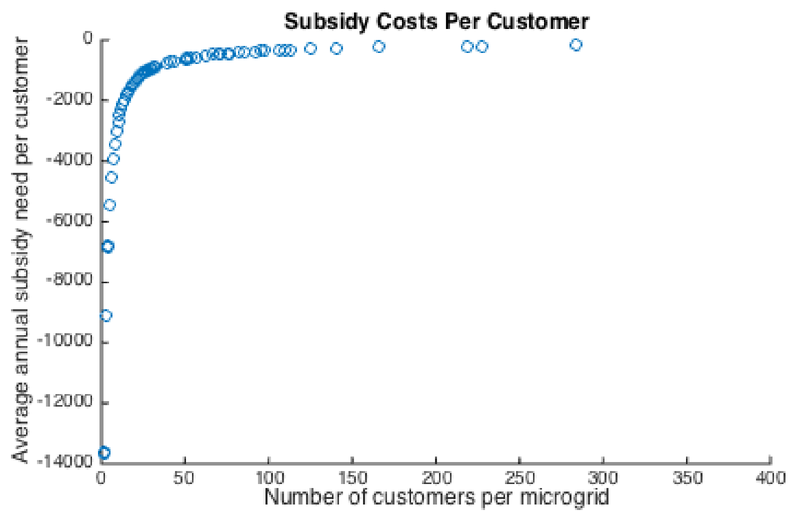


Figure 4-13: Average annual ongoing subsidy needs (as expressed in cash-flow shortfall) per customer in scenario 1a, for microgrids below 400 customers each. Note that there are a significant number of microgrids with more than 1300 households, but the same trend continues for these larger microgrids; subsidy costs decrease with number of households. There are no microgrids with 400-1300 houesholds

Chapter 5

Regulatory Assessment

5.1 Regulatory requirements

Tenenbaum et al (2014) makes the astute observation that many countries have a "two-pronged approach" to electrification: grid extension for most people and microgrids for remote areas, but for this approach to work countries must have a set of regulations for when the two meet [54]. Bad regulation that leaves microgrid investors feeling that they may be treated unfairly when the central grid arrives is just as bad as no regulation at all, if not worse. India has started to develop regulations governing off-grid, grid-compatible microgrids, and how these businesses should be dealt with and regulated once the grid arrives. This chapter reviews those emerging regulations and assesses how they might be improved to ensure their success.

Cost is an important dimension of grid-compatible microgrids, and regulatory structure is a key driver of these costs. Regulation must ensure the reliable and equitable supply of electricity while allowing investors to recover their costs and minimizing risk [60]. Regulation for off-grid systems must also be light-weight and quick. If it involves a lot of paperwork, red tape, and delay it can act as a significant barrier to entry for off-grid operators. Since these businesses often operate with slim profit margins, regulation that is time-consuming and costly to comply with could make an off-grid electricity business unprofitable [54]. As well, light-weight regulation can reduce the burden on state electricity regulators, who are often already underfunded for the work they have to do [30]. The key is to have just enough regulation to ensure the fair and equitable provision of electricity, and no more: not an easy balance to strike. In order to strike this balance, regulators should seek to minimize the number of times the business is required to interact with the regulator and the amount of information that must be provided, and they should standardize and publicize documents and processes.

Before determining how to implement regulation for off-grid systems, regulators must determine the broad frameworks and requirements. There are several proposals in the literature for what these frameworks might be. One example comes from Tenenbaum et al (2014), which notes four main options for the relationship between grid-connected microgrid and utility, and suggests that all should be available options for a microgrid developer [54].

1. "Small power distributor," (SPD) in which the microgrid effectively becomes a small distribution company, buys electricity wholesale (or from the distribution company) and sells at retail to customers. The generator is no longer used. This model has been used in Nepal, Bangladesh, Vietnam and Cambodia.
2. "Small power producer," (SPP) in which the microgrid sells electricity to the national grid but does not sell to customers, and may receive a feed-in-tariff. The utility can take over network operations. This option is most similar to what has been proposed as a model for Indian grid-compatible microgrids by ABPS Infrastructure and the Shakti Foundation, and endorsed by the Indian Forum of Regulators [1].
3. Combined option: in which the microgrid buys wholesale electricity and also maintains generation assets that it may use to sell power back to the main grid.
4. Buyout: the central utility buys out the microgrid owner at whatever is

determined to be a fair value. Book value (the depreciated value of the physical assets) is a common way to determine this value.

The first and third of these options are most similar to the existing franchisee structures in India, described below. [21] also provides a useful taxonomy of the possible ways in which an existing microgrid and an encroaching central grid could interact, shown in Figure 5-1, which encapsulates and extends the options offered by Tenenbaum with intuitive graphics.

5.2 Current status of regulation in India

The Electricity Act of 2003, and its subsequent amendments, remains the most prominent piece of legislation concerning the electricity industry in India, as discussed in Section 4.2. The Act gives distribution companies (discoms) a ‘universal service obligation,’ compelling them to provide service to everyone living in their service area. However, discoms have been unable to meet this obligation due to their generally poor financial situation, and due to its in-feasibility, as discussed in Section 1.1.3.2 regulators do not enforce it. The Indian central government announced the UDAY (Ujwal DISCOM Assurance Yojana) scheme in early 2016, which is aimed at improving the failing finances of the state distribution companies. The effect of this policy may enable distribution companies to meet their obligations more effectively but it is too early to tell. (see Section 1.1.3 for more details.)

5.2.1 Status of off-grid regulation

Meanwhile, policies have enabled other electricity businesses to grow in India in several ways. The Electricity Act of 2003 allows the distribution of electricity in rural parts of India without a license. This provision is how many small microgrids

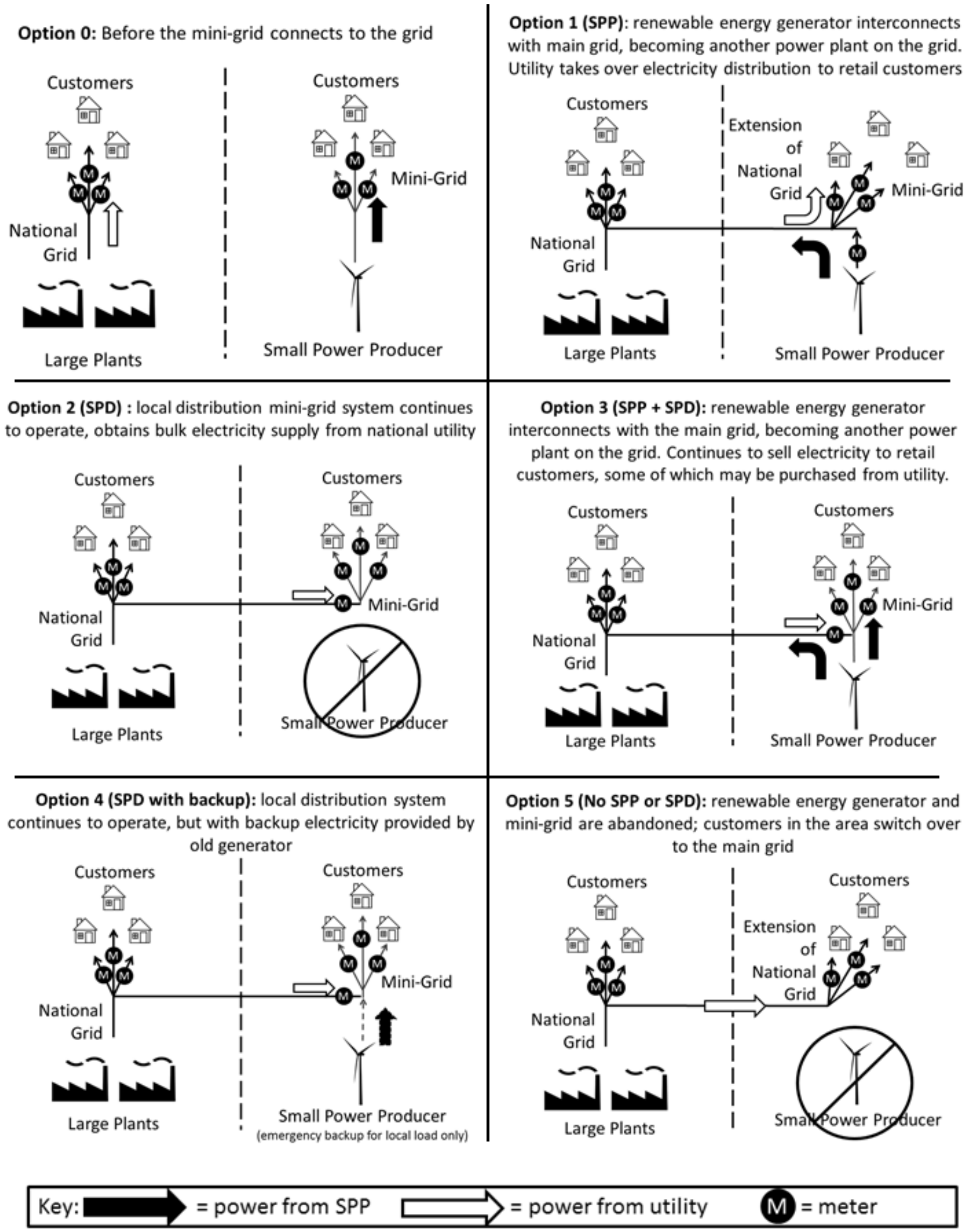


Figure S1. Options for interconnection of mini-grid with main grid.

Figure 5-1: This figure taken from [21] illustrates the complete range of options for the interaction of a central grid and a minigrid operate in India. In justifying the lack of license or tariff regulation, the Government of India cited the idea that a low cost of entry could provide sufficient threat of competition to keep tariffs reasonable for consumer [54]. However, it is highly unlikely that a competitor would consider building another microgrid in a location where one already exists; the barrier to entry is already quite high due the the magnitude of the initial investment requirements. Thus, this justification for the lack of tariff regulation is not a very good one.

Currently, microgrid operators have no recourse when the central grid arrives to their area of service; they will most likely go out of business as they lose customers to the heavily-subsidized central utility service. Recent amendments to the Electricity Act of 2003, discussed below, require state regulators to provide a more formal path for isolated microgrids to interact and connect with the central grid.

5.2.2 Existing franchisee regulation

India does have regulations allowing for licensed franchisees that are somewhat similar to the SPD model described above, though they are meant for on-grid businesses. [37] estimates that in 2012 there were 37,000 franchisees covering 216,000 villages in India, however recent conversations with stakeholders in the sector have suggested that this model has not proved to be as attractive or popular as hoped, and it has faced opposition from states and state-owned distribution companies who do not want their business infringed upon by franchisees [1]. This animosity is important to keep in mind when assessing proposed new regulations.

The Ministry of Power, through the RGGVY program (now subsumed under DDUGJY), has specified six models for a more formal franchisee setup [1, 3]:

- Collection-Based Revenue franchisee: The franchisee is responsible for billing, collections, and facilitating connection of new consumers. They are given a

[1] Meeting with Akanksha Chaurey, July 2015; Meeting with Sanjay Prakash Jan 2015; Meeting with Amol Gupta (World Bank) July 2015

share of the fees collected, and are given a revenue collection target each month.

- Input-Based Revenue franchisee: The franchisee is responsible for revenue collections as in the collection based franchisee, but the target for collection is based on the amount of electricity that the utility measures going into the franchisee's area. This setup creates incentives for loss reduction.
- Input Based franchisee: This franchisee buys electricity from the utility at a predetermined rate, and must cover those costs with the revenue it collects. This creates incentives for loss reduction and efficiency.
- Operation and Maintenance Franchisee: This franchisee has all the rights and responsibilities of the Input Based franchisee, with the added obligation of conducting operations and maintenance work on the medium and low-voltage lines. In return they are able to purchase electricity at a cheaper rate.
- Rural Electric Cooperative Society: In this arrangement, the community owns, operates, and manages the infrastructure and collects payments, buying power from the utility.
- Electric Cooperative Society: This arrangement is similar to the above, but the community may decide to contract out the operation of the grid to a private company.

With regards to the cooperative arrangements (the last two bullets), [19] states "It is unclear if these franchise concepts were ever enacted. It does not appear that any [Ministry of Power] supported ownership co-ops were initiated in recent years." .

5.2.3 Recent developments in off-grid policy

India itself recently enacted new regulations in an amendment to the Electricity Act that directed state electricity regulators to create regulations for microgrids to connect to the grid and receive payment from the central utility [20].

The recent tariff policy amendment, passed Jan 28, 2016, acknowledges the risk to investors of the grid reaching the microgrid, and specifies that the State Electricity Regulatory Commissions (SERC) create regulations addressing the following:

> "Micro-grids supplying renewable energy are being set up in such areas where the grid has not reached or where adequate power is not available in the grid. Investment involved in setting up of such microgrids is substantial. One of the risks of investment is grid reaching the area before the completion of the project life and thereby making power from micro grids costly and unviable. In order to mitigate such risk and incentivize investment in microgrids, there is a need to put in place an appropriate regulatory framework to mandate compulsory purchase of power into the grid from such micro grids at a tariff to be determined under section 62 of the Act considering depreciated cost of investments and keeping in view industry benchmark and with a cap if necessary, as approved by the Appropriate Commission. The Appropriate Commission shall notify necessary regulations in this regard within six months."[2]

The details of this regulation have yet to be worked out by State Regulatory Commissions; Uttar Pradesh was the first to release draft regulations, in early 2016.

Suggestions for this policy are found in ABPS's report "Final Report On Policy and Regulatory Interventions to Support Community Level Off-Grid Projects," written in conjunction with the Shakti foundation, and in the draft regulations promulgated by the Indian Forum of Regulators, which build off of these suggestions [1, 2]. These suggestions are discussed in more depth below. The advantages and disadvantages will be discussed after reviewing best practices from around the world.

[2] http://powermin.nic.in/upload/pdf/Tariff_Policy-Resolution_Dated_28012016.pdf Accessed March 28, 2016

5.3 Lessons learned in other countries

There are several existing examples of similar regulation of independent small generators and microgrids to draw on in considering a new regulatory structure. Rwanda has proposed a system in which "private operators can own and operate decentralized grids while selling the power to the state-owned utility that retails the electricity using existing prepaid electricity systems and distribution channels" [60]. Several countries, including Cambodia, and Tanzania have implemented similar "small power producer" (SPP) regulations [60, 54]. Some of their experiences are briefly detailed below, offering useful lessons in what to do and what to avoid.

One item that stands out in reviews of these programs is the idea that light-handed or no tariff regulation can promote a lively rural micro-grid sector. Tenenbaum et al. [54] notes, "most successful decentralized rural electrification schemes for isolated mini-grids have involved little or no price regulation." This observation supports India's decision to allow rural microgrids to operate without a license and charge whatever tariffs their consumers will agree to. The arrangement certainly lowers the barriers to entry by removing red tape. However, it is important to note that while this lack of regulation may be beneficial for the market in the short term, in the long term it may not encourage the most equitable or effective electricity provision. Some tariff regulation and minimum quality standards is recommendable to ensure that consumers are adequately protected, as a local microgrid does not experience sufficient competition to prevent it from exerting monopolistic power.

5.3.1 Cambodia

In Cambodia, Small Power Producers (SPPs) sprang up without regulation, determining tariffs through an agreement between the entrepreneur and the community. Later, a national regulator came into existence, provided licenses to the so-called 'rural electrification enterprises,' and regulated their tariffs. Cambodia has no uniform national tariff; tariffs are generally higher in rural areas than urban areas, for example. The regulators found they had to allow the SPPs to adjust the tariff based on fluctuating diesel costs to allow them to remain profitable [54].

Many of Cambodia's isolated mini-grids converted to small power distributors when the main grid arrived, selling their diesel generators and buying electricity wholesale from the utility. They were required to get a new license from the regulator to covert to a small power distributor; 82 had done so by 2013. Utilities benefit from this arrangement because they do not have to deal with a proliferation of low-demand customers, and the micro-grid owner benefits by being able to stay in the business. The regulators ensure their financial viability by setting a sufficient margin between the wholesale power tariff and the retail power tariff. The certainty provided by this regulation encourages microgrid investors to invest in their systems, and to ensure their facilities meet sufficient technical standards [54].

5.3.2 Tanzania

In Tanzania, Tanzania Electric Supply Company (TANESCO) owns and operates both the main grids and some existing microgrids, and they allow independent power producers (IPPs) to feed into both. The IPPs receive regulated feed in tariffs, but these are based on avoided cost and are thus around three times higher for microgrids than for the main grid [54]. When the main grid connects to the microgrid, the tariff will drop down to the main grid tariff. For small power producers receiving a feed-in tariff the date of arrival of the main grid could add significant uncertainty to the expected lifetime profitability. The low grid feed-in tariffs, moreover, mean that only rather inexpensive generation, like hydro or biomass, will be competitive for supplying the main grid [54].

Independently operated microgrids also exist in Tanzania. Small Power Producers (<1 MW) do not need a license in Tanzania, just a registration with the regulator, which does not require their approval. For producers < 100 kW, the regulator does not even need to review the proposed retail tariffs, though they reserve the right to review if there are significant consumer complaints [54].

5.3.3 Mali

Mali has successfully promoted a large number of isolated microgrids. They offer a substantial capital subsidy for every consumer connected, but no operating subsidies. In Mali, microgrids are allowed to charge tariffs substantially higher than the main grid's, sometimes two to three times higher, though there is regulatory oversight of tariff and revenue levels. The capital subsidy grant comes with minimum service requirements as well as maximum tariff specifications. The flexibility of this regime has its risks; Tenenbaum et al. (2014) notes that some villages have reported that they were not adequately consulted before the government granted the license to the microgrid operator; requiring an agreement between the developer and the villagers may prevent this sense of disenfranchisement [54].

In areas where the microgrids are close to the designated concession areas of the national utility, this creates some tariff envy. In response to this envy, the regulator ordered seven isolated microgrids located close to the main grid to be connected to the grid in 2011 [54]. The authors of [54] note that at the time of writing Mali was actively considering what rules might govern the handoff of the microgrid assets to the central grid. [3]

[3] We have not been able to locate any evidence of these regulations.

5.3.4 Sri Lanka

In Sri Lanka, the government promoted the creation of 'Village Electricity Consumer Societies,' which created small mini-hydro microgrids owned by the community. When the central grid has expanded into the areas served by these microgrids, consumers have typically switched over, and the microgrid goes out of business. Sri Lanka also has many small power producers, typically micro-hydro, which sell wholesale to the national grid [54].

5.4 Assessment of India's Proposed Regulation

The amendments to India's Electricity Act of 2003 require state regulators to propose regulations for buying power generated by microgrids when they are connected to the main grid. This description does not capture the whole story, however, as the costs of the network and other non-generation components of the microgrid are also significant investments requiring some compensation. These aspects are addressed in the Forum of Regulators' model regulation in this area.

5.4.1 Forum of Regulators Recommendations

ABPS Report

The ABPS report which served as a basis for the Forum of Regulators' model regulations recommends an "off-grid distributed generation based distribution franchise model" (ODGBDF) over other methods including distribution franchisees, relying on renewable energy certificates (RECs) for revenue, and generation-based subsidies. This scheme is most similar to the Input-based Revenue Franchisee, as described above, and like that model it would be approved under the RGGVY guidelines.

Under this scheme, the microgrid developer will be a franchisee of the discom, collect a regulated tariff from its customers, and receive a feed-in-tariff from the distribution company to cover the viability gap. The feed in tariff would be determined by state regulators, and the Forum of Regulators is to define guidelines for how it should be calculated. The franchisee will receive the feed in tariff from the discom, minus the revenue collected from customers. The report also makes a passing mention that the state regulators could choose to include a franchisee fee paid to the franchisee by the discom. As well the Government of India could determine that it wishes to provide subsidies through the existing rural electrification support programs (DDUGJY).

Once the microgrid is connected to the grid, the franchisee would purchase power from the utility, but beyond this the recommendations are quite vague. It seems that the feed-in-tariff might continue after grid connection, and the Central Electricity Authority would need to provide guidelines for grid interconnection. The nature of the relationship between the microgrid and the discom upon interconnection, however, is left to state regulators to determine. The SERCs would specify the tariff at which the franchise would purchase power from the utility, as well as most of the specifics of the regulation governing the incorporation of the microgrid into the grid. The SERC's decision regarding what price the franchisee would have to pay to purchase power from the central grid (once it is connected to the grid, if it remains a franchisee) is a significant choice. The margin between the power purchase price and the tariff collected by the franchise is a key determinant of the viability of the microgrid once it is connected to the grid.

Forum of Regulators Recommendations

The Indian Forum of Electricity Regulators has set forth a set of draft model regulations which build off of the ABPS report (and were developed in conjunction with ABPS) to guide state regulators in setting up proper regulations for the connection of microgrids to the central grid [2]. The arrangement described in this regulation follows the suggestions for the ODGBDF. Once the central grid reaches the franchisee, the discom is to buy out the franchisee's network assets at book value. The franchisee will continue to own the generation and will continue to sell generated power to the grid at the pre-determined feed-in-tariff.

The model regulations set forth a framework in which a microgrid would operate as the franchisee of a utility, with a license and an exclusive right to provide service within their geographical area. The microgrid would be required to charge tariffs that are no higher than the grid's tariffs, which would certainly be below the costs of supply. To reimburse this viability gap, the costs of generation would be subsidized through a Feed in Tariff agreed upon in a Power Purchase Agreement with the utility and the rest through franchisee fees. Before receiving their license, the microgrid would be required to obtain the consent of the local governing body, after presenting them with a comprehensive plan.

The State Electricity Regulatory Commission would be required to determine the amount of the Feed in Tariff for each renewable generation technology recognized by the Ministry of New and Renewable Energy. The determination of the Feed in Tariff would be through a cost-plus methodology, in which the tariff is set to cover the expected costs of operation plus a rate of return on capital investments, and would thus require only infrequent re-examination. Microgrid operators could request a revision in this tariff if they felt it was unfair. The other costs of distribution and management would be subsidized through a franchisee fee paid by the discom to the microgrid operator, determined by mutual agreement of the discom and the microgrid. The discom would also be expected to assist the microgrid in applying for state and central subsidies as relevant.

Upon arrival of the central grid, the microgrid business would retain ownership of the generation assets and would continue selling power to the discom at the feed in tariff agreed on in the power purchase agreement. The rest of the assets of the microgrid (the network etc.) would be purchased by the discom at their depreciated book value.

This arrangement has many positive aspects. The requirement for local consent avoids the disenfranchisement felt by some customers in Mali, as noted above, who were upset when the government granted distribution monopolies without their consent. This process also promotes village 'buy-in' to a microgrid, which is often critical to a project's success by promoting adherence to tariff payments and discouraging theft. Also noteworthy is the maintenance of the same feed in tariff for reimbursing generation both on- and off-grid avoids the revenue risk faced by microgrids in Tanzania, and provides long-term certainty regarding the value of generation assets. However, there are areas requiring some careful examination and improvement.

Recommendation 1: Require a grid expansion plan

The franchisee model has been somewhat unsuccessful in India partly due to the animosity of the incumbent utilities, who are loath to see some of their service area passed off to a competing business, as discussed above. Regulation should be designed considering that the discoms may have an incentive to hinder the development of off-grid franchisees. In this respect, there are a few worrying parts to the Forum's proposed regulations.

The regulations provide that "Within one month of receipt of application from the Rural System Operator, the Distribution Licensee shall process application and confirm acceptance / rejection of the application. Provided that the Distribution Licensee can reject application only on the grounds of violation of norms of design of the system, or plan to extend electricity grid within two years," [2]. While this aspect of the regulation does limit the discom's ability to deny microgrid's franchisee applications out of malice, the provision for rejection in case of the extension of the grid is a loophole that could be easily abused.

In almost all of the conversations that our team had with the distribution company in Northern Bihar over the last two and a half years, a common refrain has been that all of Bihar would be connected to the grid within two years. This claim appears to be based on political promises, and those who work outside of the discom will freely opine over the implausibility of this promise. The history of electrification in India is littered with ambitious goals and unmet promises. If these common and untrustworthy promises are sufficient grounds for rejecting a microgrid's application, then the discom could have sufficient ground to deny a great deal of applications. This escape clause for the distribution company only makes sense in the presence of a realistic grid expansion plan, produced by the discom and approved by the regulators. Such a plan does not exist in Bihar or in many other states.

The regulation should allow the discom to deny a microgrid's application only in the presence of a grid expansion plan vetted by the regulators which indicates that the area will be electrified in the next two years. This requirement would prevent abuse of power by the discom. It would have the added benefit of providing a significant amount of useful information to microgrid entrepreneurs who are trying to figure out where the best areas to set up a business would be.

Recommendation 2: Provision of subsidy to microgrid franchisees by a third party

The Forum's draft regulations specify two ways in which the viability gap will be covered for microgrid franchisees: the feed in tariff and franchisee fees. Both of these revenue streams will be paid by the distribution company. This arrangement raises the issue both of the discom's ability to provide those payments and of their willingness to do so. The distribution companies do not have enough revenue to cover their own costs, let alone pay the expensive subsidies that will be required for grid-compatible microgrids. As the discoms have an incentive to raise barriers to entry to these potential competitors, they may find reasons for payments to be delayed or underestimated. Investors may well feel uncomfortable if the viability of their business depends on the benevolence and solvency of the distribution company, which the current form of the regulations would suggest.

These subsidies should ultimately be covered by state or central government funds, since the distribution companies are unlikely to be have the extra revenue to cover them. In light of the worries about payment by the discom, it would be wise to have these subsidy streams delivered in total or in substantial part by an entity other than the distribution company. Possible candidates for this third entity are the state government, central government, or a contracted private party that manages government money. In the future, India may have developed more sophisticated financial infrastructure which facilitates the delivery of subsidies directly to the consumer. It could be undesirable to place the risk of subsidy provision on the poorest consumers who can least bear that risk, especially if the subsidy remains somewhat uncertain. However, there is reason to believe that the political clout of all those customers would make the payment of such subsidies a priority.

Recommendation 3: Provide option to continue as grid-connected franchisee

Under the proposed regulations, the off-grid franchisee has one choice when the grid arrives - sell the network assets at book value, and retain the generation assets, which will receive the feed in tariff. This arrangement ignores the benefits that could come from the discom leveraging the existing relationship with the community that the off-grid franchisee has developed. They may be better positioned to effectively collect tariffs and prevent theft than the discom, which has no personal relationship with the customers.

Cambodia, for example, has effectively employed an arrangement in which existing microgrids can become a franchisee of the distribution company, purchasing electricity wholesale from the distribution company and reselling it to the local customers [54]. The off-grid franchisee should have the option of converting to what might be called an Operations and Maintenance Franchisee as described in the taxonomy in Section 5.2.2, while retaining ownership of the generation and receiving a feed-in-tariff.

Recommendation 4: Allow islanded operation of microgrid with feed in tariff

Although the generation assets of the microgrid are guaranteed the same feed in tariff once they are connected to grid, they may still experience a significant drop in revenue if the grid is unreliable. The generator cannot sell power on to the grid while the grid is down, and for all of these hours they will lose revenue. One flawed option for addressing this gap would be to force the discom to pay a penalty to the generation owner when outages force the owner to lose revenue.

A more useful option would be to provide regulations allowing the islanded operation of the microgrid even when the main grid is blacked out. This arrangement would also offer more flexibility to the franchisee to provide service even when the main grid is not providing power. Such an arrangement could result in a much higher quality of supply in areas where the grid is unreliable. The discom would still have to pay the generation owner the feed-in-tariff for their generation in this time, lessening the loss imposed by the grid outage.

Of course, more infrastructure is required to operate in islanded mode than to simply sell onto the grid. The proper controls must be in place to disconnect and reconnect from the grid safely, and to govern power consumption during the blackout. (These requirements are described in greater length in Section 1.2.)

Recommendation 5: Allow limited flexibility in tariffs For equity reasons, the tariffs charged by microgrids should not be very different from those charged by the discom. Allowing different tariffs on different systems would be sure to cause political discontent, and could make the microgrid businesses' relationship with the community somewhat tense. Situations where customers who are located close to each other, but are connected to different electricity sources and are paying significantly different rates, could create political discontent, as evidenced in Mali (discussed above). Any attempt to pick a dividing line between lower and higher tariffs will result in some perceived unfairness.

However, given that the grid's tariffs are known to be dramatically unsustainable and should be revised, and given the known unreliability and difficult of obtaining government subsidy in India, some flexibility may be beneficial. As long as subsidies are viewed as not sufficient or sufficiently reliable to make up the viability gap between the grid tariffs and the cost of service, regulators should provide for a limited and monitored flexibility in tariff rates. Without this flexibility, microgrid companies will have difficulty making sufficient profits, ultimately resulting in fewer viable businesses and thus more consumers without electricity access. For example, the cheap or even free rates provided to agricultural customers require significant subsidies to maintain, yet even the state-owned discoms do not always receive the state reimbursement for these subsidies in a timely manner [30]. A microgrid operator, with less connection and political clout, cannot be expected to fare better in receiving the prompt payment of subsidy. Even if subsidies are ultimately provided, if the timing is unreliable the microgrid business cannot trust it to support their cash flow.

Of course, the first-best solution would be to provide subsidies in a more consistent and reliable way, as described in Recommendation 2. However, the issue of subsidy unreliability is rooted in serious systemic, bureaucratic, and often political issues. Regulators must be realistic about the rate of reform, if they are serious about promoting electricity access as soon as possible.

In light of this situation, regulators may wish to offer an exemption from adherence to the grid tariffs, especially for microgrids that are not very large. This exemption should still set maximum tariffs that can be charged. The maximum could be based on the cost of service that would be incurred by the distribution company in the local area (i.e. the tariff that they would charge if their tariffs were rational), or it could be based on estimations of the efficient cost of service for a microgrid. The proper level allowed will depend on the local economic conditions and the costs of generation (which could decline with improving technology). Of course, in setting this maximum regulators should still maintain carve-outs for below-poverty-line populations and other vulnerable customer groups; ensuring timely supply of subsidies to enable cheap supply to these people should be the utmost priority.

The requirement for the consent of the local governing body to the terms of service would serve to validate the reasonableness of a proposed tariff schedule in a village. As well, there should be a formal process for villagers to appeal to the regulator if they feel that the microgrid is charging tariffs that are unreasonable.

Recommendation 6: Ensure Feed in Tariff accounts for time-of-service

The proposed subsidy structure accounts for the costs of generation through the feed-in-tariff, and the costs of the network and operations through the franchisee fee prior to the arrival of the microgrid. However, this structure does not account for the value of time-of-delivery. The Feed-in-Tariff incentivizes total production, not production at useful hours. Given that a large amount of off-grid generation in India is solar PV, which does not produce during the peak morning and evening hours, this time-of-use aspect is crucial.

In particular, most renewables-powered off-grid systems (and the regulations have a heavy bias towards renewable generation) will address this need through the purchase of a large battery, which is expensive and must be replaced every 3-5 years. While it could be possible to include the cost of the battery in the franchisee fee, this does not address the issue of how to ensure the value of the battery is not lost if and when the central grid arrives; the ongoing feed-in-tariff would not cover it, and the discom's purchase of the network assets is unlikely to include it.

Time-of-use pricing is not typically proposed for rural microgrids due to the cost of smart meters for each consumer. However, the cost of a single smart meter to observe the production from the generator is a significantly more manageable cost, especially if it allows the microgrid to be properly reimbursed for their battery costs. Regulators can incentivize electricity service at useful hours by paying a higher feed-in-tariff to solar-powered microgrids for peak hours that do not coincide with solar production. The difference between the daytime feed in tariff and the nighttime feed in tariff should be set to account for the cost of the battery, including financing, operations, and depreciation costs.

This arrangement would be useful for properly reimbursing the microgrids for providing a useful peak-hours service during off-grid operation, and it could serve to address the central grid's peak-hour supply deficit once connected to the main grid. (The regulator may wish to adjust the hours of 'peak tariff' to account for possibly different hours in which the generation is most valuable to the central grid.)

Recommendation 7: Allow less-rigorous grid standards for microgrids

In order to be connected to the main grid, the microgrids are required to meet the same electrical and safety standards required for the central grid. However, these requirements can be overkill in rural areas. Brazil, for example, has significantly reduced the costs of its rural electrification by establishing standards for rural electrification which maintain system safety but are less onerous and less costly than those in urban areas [11]. While it is important that safety and the integrity of the electrical system be maintained, regulators should specify the least onerous way that this can be accomplished in rural settings.

5.4.2 Uttar Pradesh microgrid regulation

Uttar Pradesh released, in early 2016, regulations for microgrids that provide for their connection to the central grid [56]. It offers two options for microgrid owners to 'exit' when the grid arrives: a total buyout of the microgrid including the generation assets, or a buyout of the network only, allowing the owner to remain as a power producer selling to the central grid. As noted above, this addition of allowing the microgrid business to remain as a franchisee could have benefits.

The policy offers a 30% upfront subsidy to microgrids, but only under several onerous requirements. The first of these is that the microgrids eligible for this policy must meet the standards of the central grid, a requirement which could be improved by modifying, as recommended above. Second, these microgrids must charge Rs 60/month for customers whose peak power draw is <50 watts, and must supply for 8h per day (3h in the morning, 5h in the evening) for all domestic customers. These rates are quite low, lower than what we have observed in many off-grid arrangements for a lower level of service. Under these conditions, microgrids may not be able to break even, especially given the added costs of network compliance. Indeed, the microgrids modeled using REM rarely break even with tariffs that are twice as high.

Finally, the regulations require all the solar-powered microgrids to not use any fossil-based generation in addition, with an exception for limited use of a genset to charge the battery. The restriction to renewable sources is not inherently problematic, but requiring the back-up generator to operate only through charging the battery is misguided. It would be much more efficient for the generator to deliver that power directly to the grid, because charging and discharging the battery results in a non-negligible amount of electricity losses.

The regulation does allow other microgrids that do not receive the subsidy (and thus do not need to meet the tariff limits) but meet the grid standards to have access to the two grid connection 'exit' strategies: the total buyout, or buyout of network only. So, despite the shortcomings outlined above, this policy still leaves room for the development of other grid-compatible business models, which is a great leap in and of itself. Although there is room for improvement, both this policy and the Forum of Regulators suggestions are significant improvements over the previous status quo.

5.4.3 Conclusions

Indian policy makers, especially in the central government, are certainly aware of the challenges facing distribution companies and microgrid companies in rural India. The recent history of policy and regulation show that significant strides are being made towards addressing the major risks facing off-grid investors and the challenges facing the distribution companies. The UDAY scheme (discussed in Section 1.1.3.2) is the first to require that states off-take the distribution company's debt on an ongoing, creating an alignment of incentives which may spur much-needed tariff reforms. The recent Electricity Act amendments acknowledging the significant risk to microgrids from the expansion of the grid and requiring regulation are merely the capstone of a significant body of work and thought regarding these issues in India. While there are important issues to be addressed in the proposed regulation, they are an admirable start. The next few years in India will tell how successful they are.

Chapter 6

Discussion and Conclusions

6.1 Utility of REM

REM remains under active development, and the version used here is by no means the final version. However, even in its intermediate stage, REM shows its usefulness in the analysis presented in this thesis. The flaws identified in the sensitivity analysis are worth investigating, yet they do not give us significant reason to doubt the relative conclusions reached in the results. The model largely behaves as anticipated under a variety of conditions.

The most significant added value of REM could be its ability to showcase the relative importance of different factors to electrification plans. While planners, policymakers and academics may all know that a set of factors are important, they may not be able to determine which are more important than the others. REM allows us to see which factors are more influential.

For example, both diesel price and the efficiency of managing a microgrid are important factors in the ongoing costs of a microgrid. There are more than a few papers devoted to discussing possible business models for microgrids and how they can be more efficient ([3] is one example). Although both appear significant, REM's sensitivity analysis reveals that the diesel price can be much more influential on the final suggestions than the efficiency of management, or the economy of scale in management costs. Knowing the relative importance of these factors will help planners focus their efforts on constraining and improving the most important issues.

Still, REM is only useful within a comprehensive understanding of the underlying social, political, and regulatory context. [12] offers an in-depth exploration of many of these factors. The importance of non-technical factors is evident in the motivation for grid compatible microgrids themselves; the uncertainty of grid expansion cannot be captured adequately within REM, yet it is a key factor in thinking about the relative value of grid compatible microgrids.

6.2 Potential for Grid Compatible Microgrids

A key motivation for this analysis was to determine what the potential is for grid-compatible microgrids to enable societal cost savings, and in what circumstances the higher upfront costs of a grid compatible microgrid could be outweighed by the benefits. The results show that there is significant room for grid compatible microgrids to create value for society, but they are unlikely to be profitable on their own, and that value is significantly dependent on the value assigned to non-served energy.

Although REM's analysis shows that ongoing subsidies will likely be needed to make these businesses profitable, the necessity of subsidies does not mean that they cannot create societal value. In the case of subsidies for the poor, the government has clearly made the choice that it is more valuable to society to provide these people with a basic level of access. As well, the value to society of greater electricity access (which would be reflected in the government's willingness to subsidize it) includes values that may not factor into individual decision making and individual willingness to pay; these values could include the returns of future commercial growth, and improvements in health, safety, and education. These are exactly the type of values that are captured in the cost of non-served energy within REM[1].

The all-grid electricity provision plan is more expensive when taking into account the costs of non-served energy. Under this scenario more of the costs are borne by individuals, who incur costs and forgo significant opportunities due to their lack of electricity access. As well, none of the costs are borne by private parties. In the mixed approach, in which both grid expansion and microgrids are used, the costs are borne less by individuals and more by the government and private investors. The financial costs borne by the government in this scenario are likely to be higher due to the high levels of subsidy that might be required. However, the total societal costs will decrease due to the reduction in the cost of non-served energy, and in the long run the government and society at large will benefit from the economic improvement which typically follows energy access.

Not only is an all-grid electricity provision plan more expensive when taking into account the costs of non-served energy, but it also presents the possibility for more significant delays in electricity access. The expansion of the central grid in India has been hampered by a lack of funds, political manipulation of the electricity sector, and extensive bureaucracy. As a result, the costs of nonserved energy shown in Figure 4-12a on page 96 for the all grid scenario are likely an underestimate, as there would be significant unmet demand as the grid expanded slowly. Under the right set of regulations, the expansion of microgrids could be much more rapid.

There are five other key assumptions present in the analysis conducted which would have the impact of underestimating the value of microgrids relative to grid extension. The first is the assumption of only household demand for all customers, which neglects the significant number of businesses, schools, health centers, and other users who would have a significantly different usage profile and ability to pay than the household customers we have simulated. Including these customers in our analysis would likely

[1] It is worth noting that in future versions of REM, we expect the cost of non-served energy to represent only the costs associated with intermittency of electricity service - not the costs of not having it in the first place. In lieu of including those costs in the cost of non-served energy, we expect to have a more robust implementation of a minimum service threshold within REM.

improve the financial viability of microgrids, as these customers tend to buy more power at hours when it can be cheaply provided by solar and are willing to pay more for it. TaraUrja, a microgrid developer in India, has told us in conversation that they try to only build microgrids in villages with a significant number of commercial entities, as these locations are the ones where they will be able to create a sustainable business. Granted, these customers would have a similar effect on the viability of grid extension. However, commercial load which typically operates in the daytime (as opposed to the morning and evening peaks for households) can make an even bigger difference on a microgrid powered by solar than on the grid, since solar-powered microgrid power is abundant during the day but more scarce and costly to deliver in the evening.

Next is the influence of grid reliability, and the upstream reinforcements of the central grid which would be required to maintain and improve that level of reliability when more customers are added. The line capacities are already insufficient for peak demand in many rural areas of Bihar, according to the system operators. When more consumers are added, the distribution company will either need to invest in significant upstream upgrades, or else provide power to an even smaller fraction of their customers than before. Both of these options have the impact of significantly raising the cost of any grid-based approach. Third, the grid reliability used for the 'low grid reliability' scenario is 75%, which is consistently higher than what we observed in rural feeder data in Bihar, so these cost of nonserved energy estimates are significantly underestimated, especially given that reliability in a given hour seems to be anti-correlated with demand in that hour [17].

Fourth, the wiring costs modeled for microgrids could be significantly reduced, since these values currently are based on the same standards as used for urban grid lines. These high standards are not necessary in rural areas to maintain safety and effectiveness; reducing them could have a significant impact on costs for microgrids.

Finally, the costs of nonserved energy used in this assessment are likely to be underestimates, as discussed at length in Appendix B. A higher cost of nonserved energy would bias the result against a grid that is unreliable, or even a reliable grid that is slow to expand. The sum of all of these assumptions is a reduction in the cost of an all-grid approach and an increase in the costs of a microgrid-based approach.

The determination of the value of a grid-compatible microgrid over lower-quality microgrids was hampered by the failure of the attempt to simulate DC microgrids within the REM framework. Although scenario 2 featured a set of microgrids under a set of lower penalties for non-served energy costs, with higher discount rates and lower lifetimes to simulate increased risk, these systems are not a good proxy for existing DC microgrids, in part because hey were very large, with an average size of 1257 households per microgrid. As a result, a direct cost comparison is not useful. As well, it was not a useful proxy for determining the value of the investment that would be lost if and when the grid expanded into the domain of a DC microgrid.

We were expecting to see a larger effect from higher discount rates on the attractiveness of grid-compatible microgrids, representing the reduction in risk occurring from better regulation. However, the effect of the discount rate in the range tested (9%-14%) appeared to be small. Perhaps a wider range would have given more informative results, given that investors are known to avoid this sector entirely due to the risks of grid expansion [14]. This effect might have been captured with a higher discount rate or shorter lifetimes. Whatever the mechanism, the risk of grid extension has a much larger effect in real life than captured in the REM simulations. It could be useful to think of the benefits of making microgrids grid-compatible not just in terms of decreased financing costs, but also in terms of the value of non-served energy that arises from the deterrence of investment in this area.

There is some room for non-grid-compatible microgrids to be a cost-effective interim solution, especially if their costs are very low relative to the costs of a grid-compatible microgrid and if the grid is slow to expand. If the loss of the depreciated book value of the remaining microgrid assets at the time of grid expansion is considered as a cost to society like cost of nonserved energy, and if that depreciated book value lost is less than the cost of nonserved energy that would have been incurred, we can say that it would be preferable to have a non-grid-compatible microgrid servicing critical electricity demand in the interim.

6.3 Regulatory conclusions

The takeaways from the analysis with REM, and the assessment of the literature and best practices highlight the need for regulation that reduces the economic risk imposed by grid expansion. They suggest that containing costs through efficient regulation and well-designed subsidies is key to ensuring the financial survival of microgrid businesses.

As shown by [14], the threat of grid extension is a key risk that is preventing significant investment in microgrids, and all the business innovation that comes with it. There are two main ways that regulators can combat that risk. The first is by forcing a discom to publish and abide by a reasonable grid expansion plan, which would show potential entrepreneurs where their projects would remain unmolested by the central grid. The second is to reduce the financial losses suffered by the microgrid when the central grid does arrive, through specifications for making microgrids grid-compatible, and regulations governing the ways that the two entities can interact and the process for determining payments from the discom to the microgrid.

These two approaches for mitigating grid expansion risk are highly complementary. A grid compatible microgrid will be able to plan its investments more prudently if it knows the date at which it will connect to the main grid. Of course, both are easier said than done. The animosity of discoms towards microgrids who may be viewed as competitors requires smart regulations and empowered regulators to ensure that such regulations are useful in practice, and not simply another source of uncertainty.

A highlight from the REM analysis is the significant need for ongoing subsidies to support grid compatible microgrids. These subsidies may not be as high in real life as they are in this idealized analysis, once accounting for commercial customers and potentially lower network costs. However, they are likely to still be necessary. Regulators should ensure that their grid compatible microgrid scheme accounts for this need, without encouraging inefficiency on the part of the microgrid business.

India is well on its way to promoting this type of regulation. The proposal from the Forum of Regulators discussed in Chapter 5 provides for on-going subsidies and provides for a more certain end-game for the microgrid when the grid arrives. However, these suggestions might not be taken up. The Uttar Pradesh microgrid regulations provide for no ongoing subsidy, and they require the microgrid's tariff to be quite cheap, which appears to be a recipe for insolvent microgrids. There are additional federally-funded subsidy schemes, through DDUGJY for rural electricity access and the Jawaharlal Nehru National Solar Mission, which could potentially help make up this deficit, but they both only provide upfront grants, still leaving a significant gap in ongoing funding.

Regulators must also directly confront the issue of the discoms being a suspect partner in implementing pro-microgrid regulations. Discoms are not, at the moment, very trustworthy sources of subsidy due to their poor financial situation. The perceived competition from microgrids may make them even less helpful, as they may seek to avoid handing over parts of their established territory to a competitor. Future regulations might consider addressing this latter issue through actually enforcing the universal service obligation with real financial penalties, and making microgrids a way to avoid these penalties.

6.4 Future work

There is a significant body of work that could build off of the initial analyses presented in this thesis. Investigating and rectifying the shortcomings and inconsistencies noted in the sensitivity analysis and results presented in Chapter 4 is the first order of business. Indeed, improvements to REM have been ongoing during the writing of this thesis and will continue afterwards. It could even be worthwhile to conduct the exact same scenario analysis with the improved version of REM in order to understand how better clustering methodologies, the inclusion of topography, and upstream network reinforcement costs affect the outcomes. As well, Vaishali is just one case study, representing a fairly homogenous and flat area. We do not know how different the results might be for a region with different geography and significantly different settlement patterns.

The capability to model the costs of upstream network improvements, which is being actively developed for REM, suggests the possibility of assessing the impact that the presence of distributed generation will have on the need for network reinforcement. The impact of DG on these costs may affect regulator's assessment of the value of storage, to meet peak demand hours. Such an analysis could help establish the levels of incentive (for example, through a time-variable feed in tariff) that regulators would wish to provide. As well, the capability of predicting network improvement needs is one that was explicitly requested by the managing director of the North Bihar Power Distrbution Company to us in meetings.

Demand is notoriously difficult to predict, especially for customers who do not yet use electricity. As well, the omission of non-residential loads from this analysis probably had a significant impact on the calculated viability of different electrification options. Future work should consider in more detail the impact of having multiple demand types.

Finally, there is room for a more thorough assessment of the adequacy of proposed and future grid-compatible microgrid regulations to bring certainty to investors. It is difficult to know from afar how reassuring these regulations are, and to what degree they are expected to be abused and manipulated to the detriment of microgrid entrepreneurs. Semi-structured interviews with investors and other stakeholders in India and other countries with similar regulations would elucidate thse questions. The answers are important, because they can help guide regulators' efforts in improving future regulation.

6.5 Conclusions

The regulatory and economic context for grid compatible microgrids is changing rapidly in India and elsewhere. Over the coming years, the recent amendments to India's Electricity Act of 2003 will be implemented in the form of state-level regulations governing the connection of microgrids to the main grid. This activity will generate significant interest and development in the relevant regulatory ideas, and create the opportunity for new ideas and approaches to enter an often-conservative industry. Of course, there is room for pessimism alongside optimism; these systems operate in retrenched bureaucracies that are often tied up in politics. The strength of the resulting regulations will be tested by this challenging environment. In either case, it will provide ample fodder for studying and learning from the success and failure of the different regulations implemented in each state.

The technology available to off-grid systems is also undergoing rapid innovation. The drop in solar panel costs is well known and its impacts will continue to be felt in the increasing attractiveness of off-grid solar-powered solutions. As well, innovation in communications, power electronics and meters, and the development of these products explicitly for a cost-conscious, developing-world context is enabling more complex and interesting billing methods and business models. This business model innovation can create new opportunities for microgrids to be profitable businesses.

Finally, this regulatory, technological, and business model innovation is occurring at a time of growing awareness of the climate impacts of electricity generation, and the need to reduce emissions growth in the developing world as well as the developed world. Although expanding access to electricity accounted for just 3-4% of India's carbon emissions increases in the last three decades, reducing the carbon intensity of the energy supply is an imperative that cannot be overlooked [42]. Electricity use in India accounted for 11-25% of the increase in carbon emission since 1981, and reducing the carbon intensity of generation should be a priority [42]. While a basic level of electricity access should not be sacrificed in the name of carbon emissions, as the emissions are small and the human dignity implications are large, it is increasingly possible that this is a false tradeoff. It is possible to expand electricity access while using low-carbon generation methods, as evidenced by the proliferation of solar-powered microgrids and home systems in India and Africa, and the significant regulatory and financial support from India's government for renewable-powered on- and off-grid generation. Incorporating that off-grid generation into the central grid as it expands will not only do a favor for microgrid investors, but also for the climate.

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Appendix A

Inputs for REM: Definition and Values Used

The most interesting of these inputs are also covered in Chapter 3. This appendix contains a full explanation of the definition of the vast majority of the inputs to REM, and the values used in the Vaishali case study.

A.1 Discount rates

Definition

These figures (along with the lifetime of the investment) are used to calculate the annuity (i.e. the cost per year) from the upfront costs. They are critical inputs because the annuity is the basis on which REM compares different options. There is one for grid extension, for microgrid, and for isolated systems. They represent the time value of money for the relevant actor; typically this would come from the financing terms (i.e. debt or equity) that they receive, but more generally it reflects the opportunity cost of putting this money towards the system in question, rather than investing it elsewhere (for example to purchase other equipment that could be used to start a business, or to purchase medicine or food). Thus, the actor who is providing the money to build the electricity infrastructure influences what the discount rate is, because they will have different opportunity costs for their money depending on who they are. For example, for a bank, that opportunity cost may be not investing in stocks or other projects, and for an individual consumer it may be not purchasing medicine, food, or other necessities; clearly for these two actors the opportunity costs, and hence the discount rates, would be different. The discount rate would also be expected to vary based on government regulation, business model, and financing arrangements.

The annuity value is what is used to compare different options of network and generation. The annuity is the sum of annual costs (like O&M costs, and non-served energy costs) and the annualized upfront capital cost. The discount rate is used to calculate the annuity with the following equation (where r = discount rate and L = lifetime of upfront capital cost):

$$Annuity = \frac{Upfront\ capital\ cost * r}{\left(1-(1+r)^{-L}\right)}$$

The discount rate depends significantly on the regulatory and business scenario we are considering. What discount rate we use depends on who will be funding the various modes of electrification and what the overall goals of the planner are. The discount rate encapsulates two main ideas; first is the opportunity cost of capital, and second is the risk associated with waiting. The opportunity cost reflects the returns that one could get from putting that capital towards something else; what that cost is depends closely on what opportunities are available to the agent holding the capital. For a poor rural family, those opportunities may include buying medicine, a new piece of farming machinery, or sending a child to school; for an investor who might fund a microgrid, they may be comparing the microgrid to opportunities like investing in the stock market, or in a different local business.

The risk portion of the discount rate refers to the idea that the future is unpredictable; there is uncertainty about market conditions, about the opportunities that might be available in several years, and about the likelihood of an investment to yield the expected returns. Different businesses have very different levels of risk; a utility may be relative low-risk, since it has a regulated rate of return, while a microgrid could be significantly more risky, contending with issues like local acceptance, maintenance quality, demand growth, and the arrival of the central grid, among others.

The Capital Asset Pricing Model (CAPM), which is commonly used to determine the rate of return that investors should require from a project, exemplifies the dual nature of the discount rate. (Note that discount rate and interest rates/rates of return can be two sides of the same coin.) CAPM calculates the rate of return as the sum of the 'risk free' rate of investing, plus an added rate to account for the risk inherent in the specific project and the returns that are expected above 'risk free' returns.

Whose discount rate? The resources used to purchase electricity and build infrastructure have different opportunity costs depending on whose wallet they are taken from, as well as the type of opportunity costs that are considered. For this reason, we have allowed REM to use a different discount rate for each mode of electrification; different sorts of actors may own them. The function of the discount rate is to incorporate the time value of money and risk into the cost comparisons made within REM. Who bears these costs and what types of costs we allow our analysis to consider both affect the discount rate the user should use in REM.

With regards to who bears the cost, the actor or actors who actually invest their money in electricity infrastructure have different opportunity costs and hence discount rates. Even if REM is run from a 'global social planner' point of view, where the user is interested in finding a design that maximizes overall societal welfare, it might need different discount rates for different types of systems. The ownership structure and risks of different business models are important because by choosing to invest resources in electricity infrastructure, the actor in question would be forgoing investment in other opportunities that could also create value for society. For example, if we consider that a solar home system may be owned by a single household, the discount rate used will be different than if we consider that the system is owned and leased by a larger company; in the latter scenario, we would use lower discount rates because they have less uncertainty and different alternative opportunities.

The perspective of the analysis we wish to conduct with REM also affects what types of opportunity costs we wish to incorporate. There may be opportunity costs than an individual actor may not consider but that a social planner (for example in the central government) would want to incorporate. Examples of these opportunity costs include the GDP, development, and/or political impact of other investments the government could make with the money needed to fund or subsidize an electrification project. A user of REM who is more socially-minded would want to incorporate these broader benefits, Conversely, a user of REM who is more market-driven (like the owner of a business who wants to see where it is most likely that their off-grid technology would be preferable to customers) would not want to include these social opportunity costs in their analysis.

It is likely that a user of REM would be interested in funding or subsidizing to an affordable level all modes of electrification; such users include government and international development banks. In this case, since the source of the capital would be the same across all modes of electrification, the opportunity costs would be the same. This perspective, then, would dictate that the opportunity cost portion of the discount rate be the same for all modes. However, different modes would still have different risks associated with them, so this user may still wish to differentiate between the modes slightly based on risk level.

Sensitivity to discount rate Discount rates typically vary within a rather tight window, and small changes in the rate can have significant impacts on the annuity calculated for different modes and, hence, the ultimate recommendation on electrification mode from REM. The sensitivity to discount rate also hinges significantly on the lifetime used for computing the annuity (which varies between components to reflect their different useful lifetimes). The longer the lifetime, the more sensitive the annuity is to the discount rate used. For high values of the discount rate, e.g. above 15%, extending the lifetime does not have a significant impact.

Values used for Vaishali

- Grid extension: 13.3% for NBPCDL
- Microgrid: 10% at minimum
- Isolated system: 14% based on SELCO financing rates

Grid: For the extension of the grid, we could use 10% in the absence of other data. This number is based on a paper from Climate Policy Initiative "Solving India's Renewable Energy Financing Challenge" [50] which bases their discount rate on the government cost of borrowing (7.83% at the time of writing, 7.77% on Jan '16, based on Indian 10 year bonds), plus a risk premium of 2%. This risk premium is meant for large-scale renewable energy, so it may not be representative for a utility. Indeed, this number may be too low as evidenced by regulatory documents in India.

The regulatory documents for the North Bihar Power Distribution Company Ltd (NBPDCL) for Fiscal Year 2015-2016 from the Bihar Electricity Regulatory Commission (BERC) grant NBPDCL a rate of return on their equity of 14%, and an interest rate on their loans of 13%[1]. The rate of return on equity is established by Regulation 73 (2) (c) of the Bihar Electricity Regulatory Commission regulations of 2007. These regulatory documents assume that the debt:equity ratio for capital investments will be 70:30, which gives us a weighted average cost of capital of 13.3% [2]

Microgrids: This number will vary based on the regulatory context that we consider. The risk premium will be lower if we consider a regulatory structure that accounts for grid-compatible microgrids in a reliable and trustworthy way, but it will be higher

[1] Taken from Table 6.57 and Table 4.62, found at http://berg.co.in/media/Tariff-Order/Tariff%20Order%20NBPDCL%20FY%202015-16.pdf Accessed April 6, 2016

[2] However, these regulatory documents note that NBPDCL "has projected funding of capitalization through Grants at 94% and through Loans at 6%," meaning that the capital investments of NBPDCL could be more likely to be dictated by the preferences of the central government grant maker than by NBPDCL and their discount rate.

if the regulation does not provide investors with sufficient reassurance that their investment will be properly valued and compensated when they connect to the main grid. The risk premium will again be higher when we consider non-grid-compatible microgrids, as the companies planning these will lose their whole investment when the grid arrives; additionally, previous conversations with them have revealed that they typically look for a relatively short payback period (on the order of 5 years).

TaraUrja uses a discount rate of 10% in the calculations that they sent to us, and the World Bank cites 10.3% as the interest rate "that usually meets the short and medium-term financing needs of the private sector." In light of the justification for 10% as an appropriate interest rate for a utility or large project (in [50]), this rate does seem optimistic. [50] cites 12.3% as the commercial rate of interest applied to renewable projects in India, though it is meant for larger utility-scale generation installations, which could be perceived as lower risk than a microgrid. [3] and [23] use an interest rate of 12% for their calculations regarding solar microgrids (though neither specifies a source for this figure). It seems that 10% is a reasonable lower bound for microgrids. One would expect microgrids to have a higher discount rate than utilities as they are often riskier investments, so in that light a higher rate may be justified.

Individual home systems: Individual customers are known to have very high individual discount rates (on the order of 20+%), likely due to high uncertainty surrounding the future. [23] observes: "Ekholm et al. (2010) use discount rates of 62–74% for rural households and 53–70% for urban. Reddy and Reddy (1994) estimate an internal rate of return of 28% for a switch from kerosene lamps to electricity- which could be a lower bound on the discount rate". However, a lower discount rate would be appropriate when financing is available to households.

Grameen Shakti is a highly-successful social enterprise, which supplies solar home systems with financing through the microcredit scheme supported by the Grameen Bank in Bangladesh. Households wishing to purchase a system can have a 3-year loan with a 12% interest rate, 2 years for 10% interest, and 1 year for 9% interest .

In India, SELCO works to provide purchasers of solar home lighting with financing; they state interest rates ranging 5%-14% over 3 to 5 years with a 10-25% upfront deposit (25% is required by the Reserve Bank of India) [3].

Very high discount rates could make individual home systems very unattractive relative to other solutions within REM. The appropriate discount rate likely depends on a variety of factors, especially the availability of and access to financial institutions and the reliability of the household's income.

A.2 Cost of Nonserved Energy (CNSE)

Definition

This value refers to the penalty added to the cost of supply in REM when projected demand is not met, on a per kWh basis. Critical values are higher than normal values, and are used for loads that are higher-value to the consumer. For example, a few lights at night would be considered critical, while a fan probably would not be.

The basis of CNSE should be in the value placed (either by the purchaser or by society) on the supply of electricity and the services provided by it. The perspective used will depend on the motivations of the planner and the anticipated business model and subsidy structure. For example, if the model is used with the assumption that the government will subsidize access to and quality of electricity, it may be more appropriate to use a 'social' CNSE. This more global cost would capture values like lost health from kerosene pollution, reduced hours for businesses and students to work, and reduced economic growth.

If instead the planner anticipates that the government will not be providing significant support to such projects, it would be preferable for the user to use a CNSE that represents the value to the consumer themselves, as they will be the ones footing the

[3] http://www.selco-india.com/finance.html Accessed April 6, 2016

bill for higher microgrid or isolated system costs. I have assumed the latter situation in my calculations and have been choosing lower bounds when given the option, as a result.

Values used for Vaishali

- Critical: \$2, based on [59]. This is higher than estimates from substitution analysis and from the Power Corp. of India's Value of Lost Load assessment (discussed below), but these numbers are known to be left-skewed and to not capture important effects like the GDP impacts of lack of electricity access.
- Noncritical: \$0.51 is a lower bound, taken from the Power Corp. of India's Value of Lost Load assessment. [58]

There are several possible ways of calculating the Cost of Nonserved Energy, but none of them are likely to ever find the 'true' value. By examining several methods and taking into account what they miss, we can assess a reasonable estimate for the purposes of running REM.

Via substitution: See Appendix B for more detail on how to calculate CNSE by looking at substitutes for electric lighting. In summary, we use kerosene lighting costs as an estimate for CNSE based on the units of 'cost to provide the service of illuminating a house'. This is a reasonable basis for a CNSE because people's expenditure on kerosene is an indicator of the lower bound of the value they place on energy services – particularly on the service of lighting. Lighting is one of the highest value uses for electricity (with agricultural water pumps and cell phone charging the likely competitors), so a CNSE based on this use is likely to be 'a lower bound on the upper bound' of an individual's valuation of electricity services.

This method does not capture added benefits of using electric lighting over kerosene such as health, increased quality of light, and the social value to development and GDP of energy access. While an individual consumer may not take all these factors into account, a social planner who has the interests of the whole country in mind would wish to incorporate these values into a higher CNSE.

Via reported VOLL: Power companies regularly determine a 'Value of Lost Load' (VOLL), representing the cost of an outage, to guide their investment decisions. While the cost of an individual outage is likely to be lower than the cost of simply having no supply at all, this is still a useful yardstick[4]. A report by Wartsila India reports that the Power Grid Corporation of India estimates the VOLL in India as Rs.34/kWh to Rs.112/kWh, or \$0.51 - \$1.67/kWh [58]. The range is used because the cost of an outage is dependent on a variety of categories. Welle (2007) notes that customer type (industry, service sector, households), perceived reliability level, time of occurrence, duration, and advance warning can all affect the determination of the VOLL [59].

[59] notes that for developing countries the literature strongly suggests a range of VOLL that is 1-10 \$/kWh, and likely 2-5\$/kWh, higher than the Power Corp of India's suggestions ([59] notes their values are likely to be left-skewed). The VOLL for rural consumers in India would likely be on the low end for variation within consumer type, low end for perceived reliability level, and the high end for variation based on time of occurrence, duration, and advance warning. Without information on the relative magnitude of these effects, it is difficult to say how these customers are likely to compare to the average.

Summary: Substitution analysis suggests a minimum of \$0.37 to \$1.84/kWh (CFL vs Incandescent) for critical CNSE. VOLL studies from India suggest a range of \$0.51 - \$1.67/kWh and a literature review of VOLL studies in developing countries suggests a range of \$2 - \$5/kWh. All of these values come with the caveat that they are likely to be left-skewed (i.e. underestimates).

[4]In future version of REM, an improved minimum reliability requirement will eliminate the need for accounting for the cost of having no supply at all.

A.3 Diesel cost

Definition

This cost is used for assessing the costs of operating a diesel generator in a microgrid.

Values used for Vaishali

I will use a price of $0.82/liter. In July 2015, we were told that the price of diesel was $0.82/L (there is no longer any subsidy for diesel fuel in India). This is consistent with data on mypetrolprice.com. Added onto this figure is a transport cost as described below, taken from [53].

> "The transport costs ($/l), P_t, for diesel are estimated using the following equation:
>
> $P_t = 2P_d ct/V$
>
> where P_d ($/l) is the national market price for diesel; c (l/h) is the diesel consumption per hour; t (h) is the transport time, and V (l) is the volume of diesel transported. The factor 2 is due to the fact that the vehicle has to drive back to the origin point (assuming dedicated transport for the fuel in the generators). For the calculations, we assumed average values of V=300 l and c=12 l/h. These parameters assume the use of a standard small van of a carrying capacity of 300 l. The transport cost is calculated as 0.01 Euro per kWh one way [9,22], with 12 l consumption in 1 h (it can cover different distances during the same period assuming approximately the same consumption per hour depending on the roughness of the surface)." [53]

A.4 Network and component lifetimes

Definition

Each capital investment modeled by REM, from the network to the charge controller, has an associated lifetime, which allows us to calculate an amortized value (the yearly annuity) which we can use as a standard measure between options. The lifetime represents how long until the component in question needs to be replaced, or how long until the developer wishes to recoup their investment.

Values used for Vaishali

- Network: 40 years for grid, 20 years for grid-compatible microgrid.
  - For grid extension, 40 years is a common value used in utility regulation.
  - For a microgrid, a shorter period of time would be more appropriate as a project developer does not have the kind of assurances that a utility has regarding their long-term stability. TaraUrja, who builds non-grid-compatible microgrids, annualizes their costs over 10 years in financial data provided to us .
- Per customer investment: this represents the lifetime of the meter, switchboard, lightbulb, etc need to be replaced.
  - 20 years is used. Utilities may use a 40 year time horizon as they are relatively stable businesses, while a microgrid developer may be working on a 10-15 year time horizon. As a compromise, I have chosen 20 years; after this point, increases in the lifetime have a negligible effect on the annuity due to discounting.
- Generation components:
  - Battery: lifetime given as throughput, and converted into years within REM. Throughput is 103 kWh for the smallest (0.284 kWh) battery, and 845 kWh for the largest (1.38 kWh) battery
  - Generator: lifetime given in hours (35,000), and converted into years within

REM.

- Solar Panel: 20 years
- AC/DC Converter: 15 years
- Charge Controller: 15 years

A.5 Per customer costs

Definition

For each mode of electrification, we define the per customer costs as the cost of the meter or load limiters, if they are employed, any provided internal wiring, switchboards and lighting. It does not include labor costs for installing these components.

This value is not the same as the connection charge that is charged by the utility or microgrid provider. Sometimes the utility may inflate the connection charge in an attempt to balance their books, and the charge may also be used as a commitment mechanism to make customers invested in their new electricity infrastructure. Mera Gao, for example, reports that they charge a $2 connection fee as a commitment mechanism [13].

Values used for Vaishali

- Isolated System: No meter + home wiring = ~$10
- Microgrid: Cheap meter + home wiring = $10 + $12.50 = $25
- Grid Extension: Meter + home wiring = $25 + $12.50 = $35

Meter costs: Utility meters in Rwanda cost around $25[5]. Off-grid meters cost $20-30 [6] in Rwanda. According to Taraurja, meters are available at Rs 700 from Bentex, i.e.

[5]Source: email communication with Paul Rugambwa (employed at Rwanda's Ministry of infrastructure), March 2015

[6]Source: communication with Mobisol, Mesh Power, and 3E Power during workshop in Rwanda 2015. (All are energy service companies operating in Rwanda.)

USD $10.60 [7]. I will use the lower value from TaraUrja for off-grid meters, especially since this price is likely to fall with innovation in this sector. Isolated systems would probably not use a meter, as the user typically owns the whole thing, though there are certainly 'solar as a service' business models for which this is not true.

Other costs:

TaraUrja, a microgrid provider in India, charges a $15 (1000 Rs) connection fee covering the LED bulb, socket, switchboard, load limiter, and line leading to the house (this does not include a meter). For an isolated system, we would expect lower per household costs, since the load limiter and line are not necessary. I assume $10 for this value.

The labor cost of installing meters, switchboards and bulbs in houses is important to capture. The experience of another MIT research group (the uLink project) shows that the cost of installing in-house wiring for a basic Solar Home System in Jamshedpur, India, is $2.50/household.

A.6 Demand growth rate, years of demand growth, and k-factor

Definition

REM includes three factors that relate to the trajectory of demand growth and electrical losses growth over the duration of the project. These inputs are (1) the demand growth rate, (2) the final year to consider for generation and network design, and (3) the level of losses accounted for in the later year of the project, termed 'k-factor'.

The Demand Growth Rate is the rate of demand growth per year on an individual customer basis, and the Years of Demand Growth defines how many years of demand growth to consider in the design of the network and generation. If Demand Growth

[7] Source: Email Communication with Sreyashee Das, TaraUrja, Jan 27 2016

is 0%, the Years of Demand Growth does not affect the output.

Demand grows for the number of years specified by Years of Demand Growth; the demand in the last year of demand growth is the 'maximum demand.' The generation will be designed for the year of maximum demand, regardless of the path taken to get there (e.g. regardless of whether the level of demand is a result of 0% demand growth or 50% demand growth and a lower initial demand). The network will be designed so that line constraints are met in the year of maximum demand, and it will also take into account the net present value of losses over the whole lifetime of the network. The network will be sized to account for losses most effectively, and since losses are assumed to be quadratically proportional to demand growth, this rate may affect the network cost and hence network line choice.

For REM, the Years of Demand Growth is used in two ways: it is used as the 'years of demand growth' and also the 'years of losses growth'; the latter represents the period over which losses are expected to grow, given the demand growth rate specified. REM currently treats these two values as the same, though they are separate inputs to RNM. If the years of losses growth is longer than the years of demand growth, RNM would assume that the losses continued growing as if demand kept growing at the 'demand growth rate.' After this year, RNM assumes that the losses drop to a flat value for the rest of the lifetime of the network, simulating the event of further demand growth requiring reinforcement of the lines; that value of losses is determined by the k-factor. The value of the losses for the rest of the lifetime of the project will be the product of the initial losses and the k-factor. The years of losses growth and the k-factor control the weight that power losses in the later part of the network's life have in the NPV of a network.

Values used for Vaishali

Although the proper estimation of demand growth is an important issue for properly building sizing the generation for microgrids, this analysis is not concerned with its impact. I will assume that demand and losses are constant throughout the project's lifetime. As a result, I will leave the demand growth rate at 0% and the final year for network and generation design as year 1. The k-factor will be 1.

Minimum reliability threshold

Definition

This input defines the minimum percent of kWh demanded that the REM-proposed solution must provide. The percentage is calculated over the timeframe of the total period simulated by REM, which typically is three weeks. Its main function is to ensure that all customers are given some basic amount of electricity supply and to avoid recommendations in which consumers are not provided any electricity. Thus, its main function is not to enforce high-quality service, since it cannot differentiate between service in different time periods; it can be used to force higher-quality minimum provision of electricity, but it is a crude way of doing so. The fault of using a similar metric to assess quality of service (rather than presence of service) is illustrated in the case of Indian utilities that are required to provide 6-8 hours/day of service to villages in order to receive subsidy; the utilities may simply supply that electricity in off-peak hours like the middle of the night when it is not needed much.

The preference for useful provision of electricity is reflected instead in the demand profiles, the cost of non-served energy used for that demand, and which portions of that demand are assigned a 'critical' or 'non-critical' cost of non-served energy.

Values used for Vaishali

This metric is not currently useful for requiring a certain quality of electricity service, but rather for specifying that no households are left without a minimum supply of electricity in REM's design[8]. The quality of supply should be modified through the demand profiles and the cost of nonserved energy. Thus, the precise value of this threshold is not critical.

The Indian Government has made its subsidization of grid extension to rural villages contingent on them receiving at least 6-8h of service per day [23]. If demand is evenly spaced throughout the day, for example in an area with robust residential and commercial loads, this would suggest a value of 25%-33%. However, the study period over which this metric is calculated is on the order of several weeks, and we are looking a predominantly residential load that is clustered in the evening. This would argue for a higher threshold to use for specifying a bare minimum of service, so I use 33%.

A.7 Annual management costs

Definition

This category includes the definition of the number of customers in a 'small' and 'medium' microgrid (the number for a large microgrid is assumed to approach infinity), as well as the annual management costs for a small, medium, and large microgrid. These figures are used to define the costs in administration and revenue collection associated with each additional household (or building) added to a microgrid. The distinction between small/medium/large is used to simulate economies of scale, and these figures are used to fit a smooth exponential curve that is used to define costs for all sizes of microgrids.

The values used for the small microgrid are also used for the management costs for an isolated system. The costs for a 'large' microgrid are also used for grid extension.

[8]This parameter will be improved in future versions of REM, so that it will be more specific to the time of electricity service provision.

Values used for Vaishali

- Number of customers for small/medium microgrid: 1/100
- Annual Management cost small/medium/large microgrid per customer: $15/11/7 per year

Campanella's thesis reports the management costs and scale factors for Mera Gao; when operating at full capacity, management and collection costs are approximately $7/household/year [13]. This number is based on a regional office with a manager and fixed costs that coordinates 150 microgrids of 30 customers each, and 20 employees (10 technical maintenance staff, 10 collections agents) that each serve 15 microgrids. We can use that figure to define the low end of the cost, as Mera Gao operates very cheaply and this number assumes that the business has enough microgrids that they have reached full economies of scale.

It is worth noting that the economies of scale in Campanella's figures for Mera Gao come from having more microgrids of a fixed size, not larger microgrids, which is what this REM input is meant to represent. However, it remains the best and most detailed data I have found regarding the scaling of management costs. If the regional office is operating at half capacity, the management cost goes up to $11/household/year, which in the absence of better data is used as an estimate for the medium management cost.

TaraUrja reports to us[9] that the salary of one person s 6000-10,000 Rs/mo, or $100-150 USD. If one of these people were fully employed administering a medium microgrid (or 100 individual systems), the cost would be $15/household at the upper limit; this would be a very inefficient arrangement. I use this cost as the upper limit for management costs.

[9]Meeting, January 2016, New Delhi, India.

Grid electricity cost

Definition

This is the value used to calculate the costs of the electricity delivered through grid extensions.

Value Used for Vaishali

$0.09/kWh is used.

The Forum of Regulators report, "Report on Road Map for Reduction in Cross Subsidy", Chapter 6, Reports the cost of supply for domestic customers is 6 Rs/kWh ($0.09/kWh), for agricultural it is 9 Rs/kWh ($0.13/kWh) [19]. However these figures are all-India and do not seem to include losses. It also reports that total (technical and nontechnical) losses for Bihar are 24.54%.

The Forum of Regulators report "Strategy for Providing 24x7 Power Supply" [18], cites all-India Transmission and Distribution losses of 23.04% in 2012-2013. For Bihar this number is 49.42%, yet the Forum's 2015 report cites a substantially reduced rate (below), so improvement must have happened in the intervening years, though there is some discrepancy with the numbers provided by Bihar distribution company.

Financial Statements for the Financial Year 2013-2014 from the North Bihar Power Distribution Company[10] report an average power purchase cost of 4.2 Rs/kWh, and a distribution loss of 35%. Including distribution losses, this results in a power cost of ~6.5Rs/kWh, or USD$0.097/kWh, although these losses may included 'non-technical' losses like theft and non-collection. Based on this range of data, 9 cents/kWh is justifiable, based on rounding off the figures from NBPDCL as well as the Forum's figures for cost of supply.

[10] Acquired in hardcopy during a 2013 visit to Bihar.

A.8 Operations and maintenance (O&M) costs

Definition

REM breaks down O&M costs into 'fixed' and 'variable' components for each item. The fixed component is represented in terms of man-hours per year, while the variable component is represented as a fraction of capital cost. This breakdown captures the idea that there are some maintenance tasks that do not change regardless of system size, while others are highly dependent on system size. [11]

Values Used for Vaishali

The value used for cost of labor per hour could be a range of values; we have heard monthly salaries for technicians that range from $100 (from TaraUrja) to $2400 (from Mera Gao). I will use a figure of $0.90/hr, which is in line with TaraUrja's upper estimate of $150/month for their technicians, assuming a 40-hour workweek. The values used here are drawn from those used in [17].

Fixed costs (man hours per year)

- Battery: 5 hrs
- Generator: 25 hrs
- Solar Panel: 5 hrs
- AC/DC Converter: 2 hrs
- Charge controller: 2 hrs

Variable costs (fraction of capital cost)

- Battery: 1%
- Generator: 5%

[11] Future versions of REM will add an additional level of detail by describing the fixed component of the O&M as a per-system cost, allowing for economies of scale in maintaining several co-located generation resources and also more accurately capturing the expected travel time between systems for a technician. As the data-gathering for this variable has not yet been conducted, I will leave it to future users of REM.

- Solar Panel: 1%
- AC/DC Converter: 1%
- Charge Controller: 1%

A.9 Installation costs

Definition

Installation costs for per customer components (meters, internal wiring) are included in the cost of components. Installation costs for the network are included in the costs as well. However, for the generation components, installation cost is given separately. The values used here are drawn from those used in [17].

Values Used for Vaishali

- Battery: 20% of capital cost
- Generator: 80% of capital cost
- Solar Panel: 40% of capital cost for large (0.25 kW) panel, 20% for small (0.02kW) panel.
- AC/DC converter and Charge Controller: 0 (their costs are included in the cost of installing the solar panel)

A.10 Existing Network data

The location of the existing network and transformers was obtained directly from the North Bihar Power Distribution Company Ltd, which provided us with a physical map of the network in 2014. That physical map was geocoded (as described in [17]) with the help of Tata Consultancy. The location of MV/LV transformers was given to us in Jan 2016. This data was used to extrapolate the location of consumers who were already connected to the grid.

A.11 Demand & Customer Type

Definition The demand profiles used are the same as those described in Ellman's thesis, and much of this description is paraphrased from it - please see section 2.6 of [17] for a more detailed description. The profiles are constructed in a semi-random way based on a set of activities that the electricity might be used for and a set of parameters for each activity. These parameters are as follows:

- Whether the activity is 'critical' or 'noncritical', to assign the proper cost of nonserved energy
- The energy used by this activity.
- The hours of the day in which this activity might happen.
- Restrictions (such as temperature or sunset times) on the usage of this activity.
- Average daily duration of activity.
- Variability in daily duration of activity.

From these inputs, a set of demand profiles is generated for every hour of the year. Using a set of randomly generated demand profiles allows REM to account for benefits that arise from aggregating customers with peak demand at different times.

Values used All customers were assumed to be domestic customers. While REM is capable of handling more than one demand type, there is very little data regarding the location of commercial loads available. The possible load types that these domestic consumers used in the base case are as follows. The ownership probabilities are taken from a National Sample Survey of India, see [17] for more details).

Usage	Critical?	Avg. # used	Probability of ownership	Avg daily duration	Restrictions
Critical light	y	2	1	5	Irradiance less than 0.05
Extra light	n	2	1	5	Irradiance less than 0.05
Night light	n	2	1	5	Irradiance less than 0.05
Fan	n	1	0.26	-	Temp greater than 32.5 degrees C
TV - night	n	1	0.26	5	-
TV - day	n	1	0.26	1	-
TV - Standby	n	1	0.26	-	-

A.12 Network and Generation Catalog

An important input to REM is the equipment available for generation and distribution. The equipment used is based on that used in [17], and the reader should refer to section 2.5 for a complete description of the inputs and their sources. The network catalog has been modified somewhat since the publication of [17] by our collaborators at IIT Comillas. These modifications are as follows:

- Remove the LV single phase wires, because their costs were not coherent with the rest of the catalog.
- Adjust the costs of lines to be coherent with Indian values, and so that they were monotonically increasing with capacity.
- Adjust resistance of each line to be monotonic with capacity.

These modifications were necessary to prevent the clustering step from getting stuck at very small clusters.

Appendix B

Calculation of the Cost of Nonserved Energy

In calculating the CNSE, there are a few different methods available to us. Woo and Pupp (1992) identify three different methods - proxy-based, consumer surplus, and contingent valuation [62]. The last two have very high data requirements and high uncertainty.

- Consumer surplus methods involve obtaining a demand curve, which may be difficult, especially as the shape of the demand curve may depend on the timescale involved.
- Contingent valuation relies on surveys, which can be unreliable, as villagers are prone to overestimating their willingness to pay; additionally, their answers will be constrained by their available budget.

[23] uses a combination of proxy-based and consumer surplus methods to calculate a social cost of power interruptions. For the latter, they use cross-sectional data on electricity consumption as it varies with different levels of tariffs charged in different regions of India; from this data they construct a demand curve, which they use to calculate consumer surplus forgone due to restricted supply. They add to this lost consumer surplus the cost of the backup used (specifically, the costs that are in surplus

of what they would have spent for electricity), in this case kerosene for lighting.

In this analysis we use the proxy method to determine the cost of non-served energy, based on the cost of the alternative employed in the absence of electricity. The consumer demonstrates that their valuation of the electricity service is at least the cost of the alternative by spending money on an alternative source of a service. While this method is imperfect in many ways, the data requirement is not as high as the other options and the methodology more transparent, making it more tractable to and clearer to future users of REM.

This method can provide a reasonable basis for our CNSE estimates, but it is important to understand what it misses. This valuation will not reveal the full cost of non-served energy, because it cannot capture the additional value provided by the advantages of the electricity-based service over the alternative. In the case of lightbulbs vs. kerosene, this method misses advantages like better quality of light and reduced pollution. It also will not capture macroeconomic effects like impacts on GDP growth.

Here it is important to note that electricity itself is not a product - it is a way of providing a service. Typically, people place value on the service that electricity provides, not on the kWh themselves. Thus, determining the value of a non-served kWh requires converting that kWh into units of service, whether that service is hours of lighting, volume of processed agricultural goods, or water pumped. This conversion will inherently make our estimation dependent on the technology used to provide electricity-based services (just as the calculation of the cost of a kerosene backup depends on the efficiency of the lantern).

When electricity is provided to those who did not have it, lighting (and cell-phone charging) is often the first service used, indicating that it is the highest-value service provided by electricity[1]. We can identify a floor for the value of this electricity service (in $/kWh) by identifying (1) how much money people spend on kerosene to replace

[1] It is possible that other services are more valuable, but the equipment required also has a very high up-front cost and they are budget-constrained and/or cash-flow and debt-constrained.

Luminosity:	Incandescent Wattage	CFL Wattage	LED Wattage
415 Lumens	40W (10.4 l/W)	8W (can provide 376-500 lumens) (51.9 l/W)	~ 4.6 W (5W bulb is 450 l) (90 l/W)
710 Lumens	60W (11.9 l/W)	11 W-14 W (50.7 - 64.5 l/w)	~7.8 W (90 l/W)

Table B.1: Wattages of several types of bulbs

the lighting service and (2) how many kWh are needed to provide that service with electricity.

Cost of kerosene lighting

The cost of kerosene lighting can be calculated in a straightforward way with a few assumptions, laid out below and iin the calculations section.

Kerosene costs in India are subsidized, to Rs. 15/liter for the first 4 liters/month, above which it costs Rs. 25/liter (this is, of course, ignoring the existence of any black market, although we have been told that such a market is quite alive and well) [23].

Efficiency of electric lighting

Answering this question is fairly straightforward; we can observe the wattage of the bulbs used to provide light. However, as bulbs differ, our ultimate valuation of non-served energy will now depend on the technology employed. Many LED bulbs available have efficiencies of approximately 90 lumens/watt, and come in many wattages including 2W, 5W, 10W and above. Table B.1 compares the wattage by CFLs[2] and LEDs[3] needed to match a standard 40W or 60W incandescent bulb.

It is important to note that CFLs and, especially, LEDs may have too high an upfront cost to be desirable for many poor Indian families: incandescent commonly cost 10-

[2] CFL and incandescent data based on data from: CFL Bulbs and Fluorescent Tubes buying guide" by Bijili Bachao. https://www.bijlibachao.com/lights/cfl-bulbs-and-fluorescent-tubes-buying-guide.html

[3] LED data based on data from Phocos indoor LED lamps and products available on earth-LED.com

15 rupees, while CFLs and LEDs can be hundreds of rupees (though those costs are coming down rapidly)[57]. We will set aside the issue of upfront cost for now and focus on running costs, though they could prove an important consideration as the cash-flow limitations of poor Indians. Even though the more expensive bulbs have commensurately long lifetimes, the time-horizon of consumers' decision-making may be shorter than that lifetime (i.e. their discount rate is very high) due to their budget limitations.

Calculating CNSE

As mentioned above, what consumers care about is not the kWh purchased but the service provided. In order to use kerosene costs to value that service, we must decide on which units to value that service in. Two candidates are lumens and lighting hours. Since humans do not perceive lumens linearly (Home lighting is around 30-300 lumens/sq meter, while direct sunlight is around 100,000 lumens/sq meter [4]), lighting hours is a more reliable indicator. This method will miss the benefits from increased lighting quality and total output with an electric bulb, but more accurately reflects the metrics on which Indian consumers will be experiencing the world and making decisions. To calculate CNSE by using hours of lighting service, I use the following equation:

$$CNSE\left(\frac{\$}{kWh}\right) = \frac{1000\,Wh}{1\,kWh} * \frac{\$}{liter} * \frac{liters\,kerosene}{hr} * \frac{\#\,lamps\,used}{watts,\,light\,bulb}$$

Mills (2003) observes that kerosene lamps use anywhere from 0.005 – 0.42 liters/hr, and uses 0.01 liters/hr as a midpoint for his calculations. He observes that they produce 7.8 – 67 lumens, and uses 7.8 for his calculations [35]. The low end is what he observed with a lamp purchased in a rural market in Vietnam, the high end is from a hurricane lamp purchased in a US hardware store. I use both values to show the possible range.

Assuming a family uses two kerosene lamps for 4 hours per day each month, this

[4] Table 16.1 from Schubert, Fred E., "Light-Emitting Diodes" 2006. 2nd ed. https://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/Sample-Chapter.pdf Accessed March 25, 2016

Incandescent	CFL	LED
\$1.84	\$0.37	\$0.20

Table B.2: Calculated CNSE values

amounts to 2.4 liters/month, for 36 Rs/mo (\$0.54). The possible range using Mills' efficiencies of 0.005-0.42 liters/hr comes gives a range of 1.2 L/mo (Rs 18, \$0.27) up to 100.8 L/mo (Rs. 2460, \$37.05).

We have commonly heard that a family's expenditure on kerosene in India can be around 200 Rs/mo, so I use kerosene lamp efficiencies that result in that expenditure level. I also assume that 2 kerosene lamps are used in place of one light bulb, and that lighting is required for 5 hours/day. The level of efficiency which achieves that is 0.03 liters/hr, well within the range of common values observed by [35]. Table B.2 shows the resulting values of CNSE (\$/kWh), for each of the types of light bulb that might be used. In rupees, this is a range of 27.6-3.1 Rs/kWh. This is a very wide range and it does not account for the improved lighting quality provided by electric bulbs. For comparison, a household paying Rs120/mo for two CFLs which they use for 6h/day is paying an effective rate of 42 Rs/kWh (these numbers are similar to what we have heard for systems run by Mera Gao, without the cell phone charger).