Towards a Transdisciplinary Approach to Rural Electrification Planning for Universal Access in India

by

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B.S. Human Development, Cornell University, 2009

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ABSTRACT

Around 30% of India's roughly 1.2 billion people lack access to electricity, largely in rural areas. National and state rural electrification efforts are predominantly focused on grid extension, but interest in off-grid systems, like solar home systems and microgrids, for rural areas has been growing. Little policy or regulation dictates off-grid electrification and detailed data about customers' needs are hard to access, making it difficult for planners to determine the best electrification mode for a given area. New planning approaches are needed in the face of these challenges.

Technoeconomic planning methods typically dominate rural electrification planning, yet many obstacles face rural electrification planners that are not technoeconomic. This thesis posits that combining the best aspects of technocratic and communicative planning into a transdisciplinary planning methodology will allow planners in India to incorporate technoeconomic, socioeconomic, sociotechnical, social, political, and regulatory factors that influence rural electrification into a single comprehensive approach to regional rural electrification planning in India.

I propose and demonstrate three elements of this overarching methodology. First, I attempt to elicit planners' perspectives on rural electrification planning priorities in India through semi-structured interviews ($n = 6$) and a pilot survey ($n = 10$). Second, I discuss the importance of understanding consumer electricity needs and demonstrate how electricity demand is both a technoeconomic and non-technoeconomic factor that influences rural electrification. Third, I show how a technoeconomic electrification planning model, called the Reference Electrification Model (REM), can illuminate the consequences of different assumptions about electricity demand on technology decisions for Vaishali District in the state of Bihar.

This research emphasizes the variety of perspectives and dynamics that influence rural electrification planning and reflects on the challenges of developing a truly transdisciplinary rural electrification planning methodology for India.

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I came to MIT wanting to study electricity access and I am forever indebted to Professor Ignacio Pérez-Arriaga for taking a chance on a non-engineer. I know that supervising a DUSPer has not been straightforward, but your patience, persistence, and creativity have helped me to do my best to make a contribution to this problem and your research team. I could not have gained as much from my time here, and from the process of writing this thesis, without your guidance and commitment to this topic.

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GLOSSARY

BERC = Bihar Electricity Regulatory Commission

CEA = Central Electricity Authority

CMD = Chairman and Managing Director

CNSE = Cost of non-served energy

DDG = Decentralized Distributed Generation

GDP = Gross Domestic Product

GIS = Geographic Information System

kV = Kilovolt

kW = Kilowatt

kWh = Kilowatt hour

LCOE = Levelized cost of electricity

LV = Low voltage

MAUP = Modifiable areal unit problem

MNRE = Ministry of New and Renewable Energy

MoP = Ministry of Power

MST = Minimum spanning tree

MV = Medium voltage

MW = Megawatt

NBPDCL = North Bihar Power Distribution Company Ltd.

NGO = Non-governmental Organization

PV = Photovoltaic

REC = Rural Electrification Corporation

RGGVY = Rajiv Gandhi Grameen Vidyutikaran Yojana

SERC = State Electricity Regulatory Commission

SMAA = Stochastic Multicriteria Acceptability Analysis

Wh = Watt-hour

Wp = Watt peak

WRI = World Resources Institute

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1. INTRODUCTION

1.1 ELECTRIFICATION IN INDIA

More than a billion people worldwide lack access to electricity. This statistic is almost a chant within the literature on energy poverty and electrification. The problem is particularly concentrated in India, which accounts for 17% of the world's population and 40% of the world's energy poor (Kale 2014). Approximately 30% of India's roughly 1.2 billion people lack access to electricity (IEA Energy Access Database). In fact, there is reason to believe the problem is substantially worse due to vagary about what constitutes access according to international standards (IEA Energy Access Database, World Bank 2013) and what constitutes "electrification" according to Indian standards (Ministry of Power).[1]

Nearly every paper, book, and report about energy poverty and electricity access in India or elsewhere starts with some version of these figures. It seems repetitive, but it is difficult to avoid because the numbers themselves appear to justify the research. After all, access to electricity is seen as an important indicator and enabler of development (IEA 2014, UN 2014). The Indian government has acknowledged this priority for decades — Sunila Kale (2014) opens her book about Indian electrification with a quote from former Prime Minister Jawaharlal Nehru whose term began after Independence:

> Electricity is perhaps the most necessary and the most revolutionary thing which you can take into the rural areas. The moment you take electricity, all kinds of things begin to move…(1)

Yet despite the continual manifestation of this priority in the form of electrification targets and a major national focus on grid extension, India has failed to connect all of its citizens. Even where the grid exists, the electricity supply is highly unreliable (National Electricity Act of 2003, Ministry of Power 2006, Santhakumar 2008).

The inadequacy of the electricity sector may seem perplexing to outsiders who imagine India to be a high-tech emerging super power, and predictable for those who see it as a teeming mass of poverty and struggle. Both are partially true. That is because some say there are two Indias (Ramesh 2006, Toyama 2012). Bharath Jairaj, a Senior Associate at the World Resources Institute, (interviewed as part

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[1] The Ministry of Power considers households in a village electrified if the village meets the following standard: "The number of households electrified should be minimum 10% for villages which are unelectrified, before the village is declared electrified."

of this project) explained the otherwise mind-boggling dichotomies that exist within the very same country this way:

> I think given what we refer to as the two Indias, there is one India where you're talking about basic services and so you need a strategy just to address that. And there is the second India where you talk about scaling infrastructure and making sure Indian companies are globally competitive and so on. Your energy needs are very different in terms of scale and so on. I think what tends to grab the headlines is what is happening in that second world. And the conversations around rural electrification and so on, one doesn't see that much as yet. [2]

The implications of this infrastructure challenge undoubtedly have ripple effects on India's economy and the welfare of citizens at nearly all socioeconomic levels (Kale 2014). Though in general, the electricity access gap probably serves to expand the space between the so-called haves — predominantly in urban, southwestern regions — and the have-nots who overwhelmingly live throughout northeastern rural India. About 70% of India's population lives in rural areas where limited access to employment and other resources, like electricity, can make life particularly grueling (Census of India 2011).

Though there may still be ample technical potential for grid extension in both urban and rural parts of India, people who currently have a grid connection experience sporadic service due to frequent grid failures or curtailment due to generation shortages. Most often, the finger of blame is pointed at electricity generation capacity, but in February 2014 available supply (128 GW) fell short of peak demand (132 GW) by more than 3.3%, despite the fact that India currently has about 260 GW of generating capacity (Central Electricity Authority (CEA) 2014, CEA 2015), indicating other culprits such as losses in transmission and distribution, inadequate infrastructure maintenance, the structure of fuel supply contracts, and others. According to the World Bank (2015), the power sector's total accumulated financial losses in 2013 were as much as 2.88 trillion INR ($44.9 billion), amounting to about 3% of GDP.

In fact, many people live under or near grid lines, but still lack a household connection. In total, the subpar performance of the Indian electricity sector is linked to a complex history of social, political, and institutional issues that predate Indian independence in 1948. In the next section, that history, as well as the underpinnings for the massive electrification challenge that India faces today, will be explained.

1.1.1 HISTORY

In post-independence India, Kale (2014) writes that electricity has been a “conduit” and a “symbol of modernization.” The primary catalyst, the Electricity (Supply) Act of 1948, created state-owned, vertically integrated corporations called State Electricity Boards (SEBs), marking the official transition from colonial private electricity utilities to a nationalized electricity sector. This transition granted the central government responsibility for allocating finances, gave states substantial control over electricity, including generation, transmission, and distribution, and nominally gave the SEBs autonomy.

This balance between state, national, and utility responsibilities is an important theme in India’s electricity story. Over many years, several amendments to the Act progressively attempted to increase state governments’ control over SEBs, allowing them to determine tariffs and make management and personnel decisions. Frequently, states appointed the state’s minister of energy to the position of SEB managing director (Santhakumar 2008). According to Kale (2014) the states’ motivation to assert stricter control over the SEBs was the ability to influence the electricity pricing structure. Under the SEBs, rural customers were charged higher prices based on the fact that it was more expensive to serve them, even though the goal of the Act was to expand access to this consumer base. Industry, on the other hand, was paying less than the cost of production, even though this sector consumed a large share of electricity. States wanted to shift SEBs towards the opposite tariff structure: below-cost tariffs for rural people and high, cross-subsidizing tariffs for industrial consumers. Both structures enabled the slow decline of India’s SEBs, which, by the 1960s, were not recouping costs through tariffs and wound up in a situation in which most did not have the revenue to finance expansion to remote, rural areas.

By 1964, the central government decided to get more involved in the tariff debate. The Venkataraman Committee, appointed by the central government to review the SEBs’ financial situation, recommended the Electricity Act of 1948 be amended to require SEBs to generate a three percent return on the value of its fixed assets and to put an end to low, subsidized rates for industrial consumers. The appointment of the Venkataraman committee reflected a revived interest in rural electrification amongst central government planners frustrated by their limited influence over electricity as compared to the state (Kale 2014).

The Green Revolution brought with it a change in the tenor of India’s interest in rural electrification. Instead of focusing on village electrification, the government focused on subsidizing electrification for agriculture — specifically, irrigation. In 1969, India set up the Rural Electrification Corporation (REC) to take responsibility for financing the SEBs expansion of rural access to electricity for agriculture. In exchange for rural electrification funds, the REC also required electrification of villages that were home to members of India’s lowest castes (Kale 2014).

By the early 1970s, the push for more centralized control over electricity was gaining supporters, both inside and outside India. One of those supporters was the World Bank, which is interesting given the Bank's advocacy for privatization just a couple of decades later. Kale (2014) argues that the degradation of autonomy amongst the SEBs and increased support for agricultural electrification created opportunities for political and electoral issues — like farmers' movements demanding free electricity — to have larger influence on tariff setting and thus, the spatial distribution of electrification. In many states, farmers successfully leveraged government support to secure electricity subsidies. Many SEBs also stopped metering agricultural consumers to mask transmission and distribution losses. Ultimately, these movements served to further politicize electrification.

In response to this shift towards agricultural electrification, SEBs began charging industrial consumers more to cover the lost agricultural revenue. But by the late 1980s, the massive expansion to rural agricultural consumers paying low or no tariff did not include more infrastructure investment and grid quality and reliability declined. This cross-subsidy scheme in favor of agricultural consumers, in particular, is charged with creating a vicious cycle of underinvestment in the centralized grid that has made grid extension to rural areas very difficult and the reliability of the grid, even in urban areas, very poor. In the mid-1990's, those rural people that did have a grid connection (less than 50% of households, nationwide) paid about 58% of the average cost per kilowatt-hour (kWh) and farmers paid about 12%, on average (Santhakumar 2008). Meanwhile, industrial consumers were paying more for less reliable electricity. In response to the economic opportunities lost to this inefficiency, the latter group began purchasing diesel generators, first for backup then as a primary source of electricity. SEBs lost some industrial customers altogether. With fewer high paying industrial consumers, political pressure to provide free electricity to farmers, and ever-present corruption, the SEBs were financially trapped (Kale 2014).

As was the case in many countries, the 1990s brought market reforms to the electricity sector and national attention shifted to privatizing electricity distribution. In 1991, the central government amended the Electricity Act of 1948 by opening generation to private investment. In 1996 and 1998, the central government amended the Electricity Act of 1948 again in order to unbundle the SEBs, allow open access to transmission and distribution networks, as well as to create independent state regulators (Kumar & Chatterjee 2012).

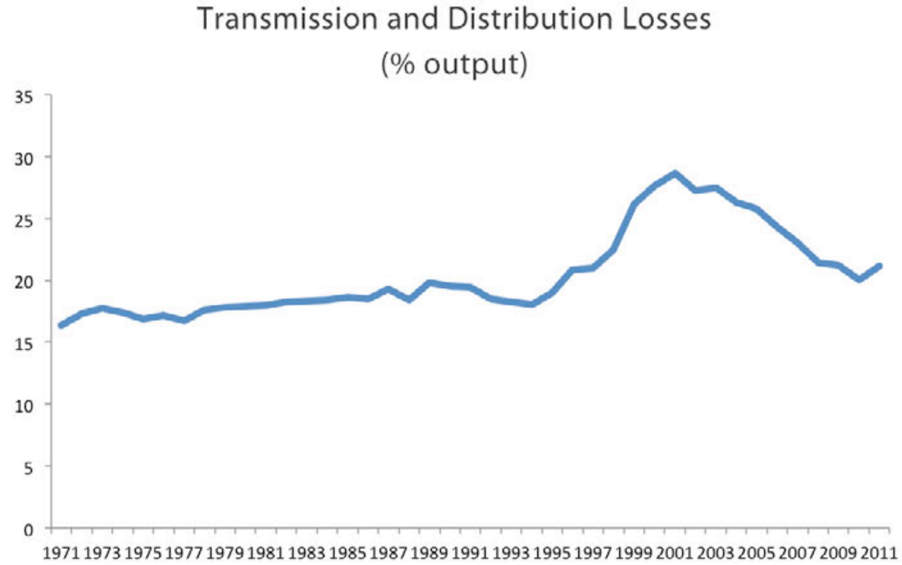
The amendments were motivated by World Bank recommendations that imagined these reforms would incentivize independent power producers to enter the market for generation and limit political influence over the tariff structure. States varied in the speed and extent to which they adopted these reforms, if they adopted them at all. For example, state regulators, the State Electricity Regulatory Commissions (SERCs), were intended to be independent to circumvent political interference, however, most regulators were previous government bureaucrats, casting doubt on whether consumers had as loud a voice as utilities when regulators were evaluating the rate case. Furthermore, the SERCs also had limited control since state governments could still influence or co-opt tariff-setting (Kumar & Chatterjee 2012, Santhakumar 2008).

According to Kale (2014), the efficacy of the SERCs varied substantially by state depending on the level of resources available and the level of autonomy afforded to them. The 1998 amendment to the 1948 Act also included the appointment of a national regulatory body called the Central Electricity Regulatory Commission (CERC). This body, however, largely serves to make recommendations to the SERCs who may choose to adopt or ignore those recommendations.

In 2003, the national government replaced the Electricity Act of 1948 with the National Electricity Act of 2003, which was more focused on creating opportunities for private investment in the sector, rather than on universal electrification (Kale 2014). The 2003 Act effectively formalized the 1990s market reforms and made the creation of an independent state regulator mandatory. Although the Act set expectations for the process of unbundling the SEBs, only a couple of states (e.g., Orissa (Odisha) and Delhi) fully carried this out. Orissa had done so before the Act was passed (Kumar & Chatterjee 2012). Some states have unbundled their SEBs and formed state-owned distribution corporations, while others continue to have vertically integrated state-owned corporations (Santhakumar 2008). In addition, neither privatizing generation nor introducing open access plans has proceeded according to schedule. For example, few generation capacity contracts have proceeded past the litigation stage (Prayas 2015).

Santhakumar (2008) and Kale (2014) both acknowledge that the 2003 Act had some positive outcomes, such as reductions in losses, expansion of metering, and increased electrification. For example, Kale (2014) writes that following the privatization of generation, the inclusion of independent power producers demanded more monitoring of SEB performance. Suddenly, SEBs were reporting drastically higher losses because they had been effectively hiding their losses, especially those from theft, through inaccurate or ineffective reporting of data. Through the mid-1990s losses were often as high as 40-50% (Santhakumar 2008). Figure 1.1 shows the World Bank’s record of India’s transmission and distribution losses. They might be slightly lower than Santhakumar’s (2008) figures depending on whether losses due to theft are counted.

FIGURE 1.1 Electric Power Transmission and Distribution Losses in India (1971-2011), World Bank Development Indictors



The 2003 Act did, however, provide for two policies relevant to rural electrification – the National Electricity Policy (NEP 2005) and the Rural Electrification Policy (2006). The NEP spelled out a framework for ensuring electricity access for all households within five years, which included mandates to minimize or eliminate generation shortages, and provide for a minimum of one unit of electricity per household per day by 2012 (Kumar & Chatterjee 2012). Ironically, the mandates to provide free, lifeline electricity and to reduce generation shortages work against each other. Though these goals have not been achieved, the NEP also marked the third key shift in the critical target of electrification, from the village, beginning in the 1940s, to irrigation pumps during the Green Revolution, and ultimately to residential household. Today, electrification targets and accomplishments are still primarily defined in terms of number of households electrified (Census of India 2011), though the other metrics are still important.

Despite amendments in 2004 and 2007, Kumar & Chatterjee (2012) argue that the 2003 Act is in need of a second round of reforms since the unbundling of the SEBs has not proceeded at the pace originally intended and regulators have been too weak in managing tariffs to mitigate the continued financial crisis the utilities experience. One report estimates that, on average, utilities serving poor, rural consumers lose about 4 INR ($0.06)/kWh (Prayas 2015). These failures to fully institute power sector reforms mean that India's efforts to achieve universal electricity access have so far fallen short.

The National Electricity Act of 2003 is currently under review for further amendment (PRS India 2014). The Electricity (Amendment) Bill 2014 promises to have important implications on the rural electrification landscape in India. The major proposals in the amendment include, the removal of limits to open access to distribution for suppliers smaller than 1 MW, stricter mandates on tariff determination and renewable energy generation, more disciplined grid management in anticipation of a growing number of suppliers, as well as a larger role for the Central Electricity Regulatory Commission in carrying out these national goals (Prayas 2015). This amendment is still under consideration by the Indian government.

Meanwhile, the country is still far from its 2012 target of universal access for all (Kale 2014). According to Prayas (2015), so-called last mile connections increased just 3% between 2001 and 2011, even after adjusting for the increase in number of households. As mentioned earlier, access to electricity is highly dependent on location. Some states, like Karnataka (90.6%), have official rates of electrification above 80%, while states like Bihar (16.4%) have rates of electrification well below 50% (Census of India 2011). Kale (2014) argues that this spatial disparity has a lot to do with the social and political variation between states, which have chosen to govern electrification in different ways. These political and social differences between states manifest in different electrification decisions that alter the degree to which the cross-subsidizing tariff scheme, massive generation shortages, high network losses, and corruption influence each state's electrification efforts (Kale 2014, Santhakumar 2008).

1.1.2 THE SHIFT TO OFF-GRID ELECTRIFICATION

In reaction to the ongoing challenges faced by India's electric power sector, there has been a growing shift in focus (first among entrepreneurs, and now among government officials) to off-grid generation and distribution of electricity in unelectrified areas. In its optimistic "Energy Access for All" scenario, the International Energy Agency estimates that 70% of rural people worldwide will get access to electricity through off-grid electrification and 65% of those people will gain access via a microgrid (WEO 2013). India is home to a substantial proportion of those people.

A variety of technologies have emerged to serve this electricity demand. Diesel generators are common throughout India, both as a form of backup for homes and businesses that have an unreliable grid connection, as well as a primary source of electricity (Kumar et al 2009). Solar home systems are individually-owned units that consist of a roof-top solar photovoltaic (PV) panel, a battery, a charge controller, and a means of connecting an appliance to the electricity supply (SELCO). Solar home systems can vary in the size of the PV panel and the size of the battery and thus, can range in cost. Microgrids are isolated distribution networks that connect as few as two, but potentially many more to a shared source of generation.[2] In India, that source of generation is most frequently solar PV

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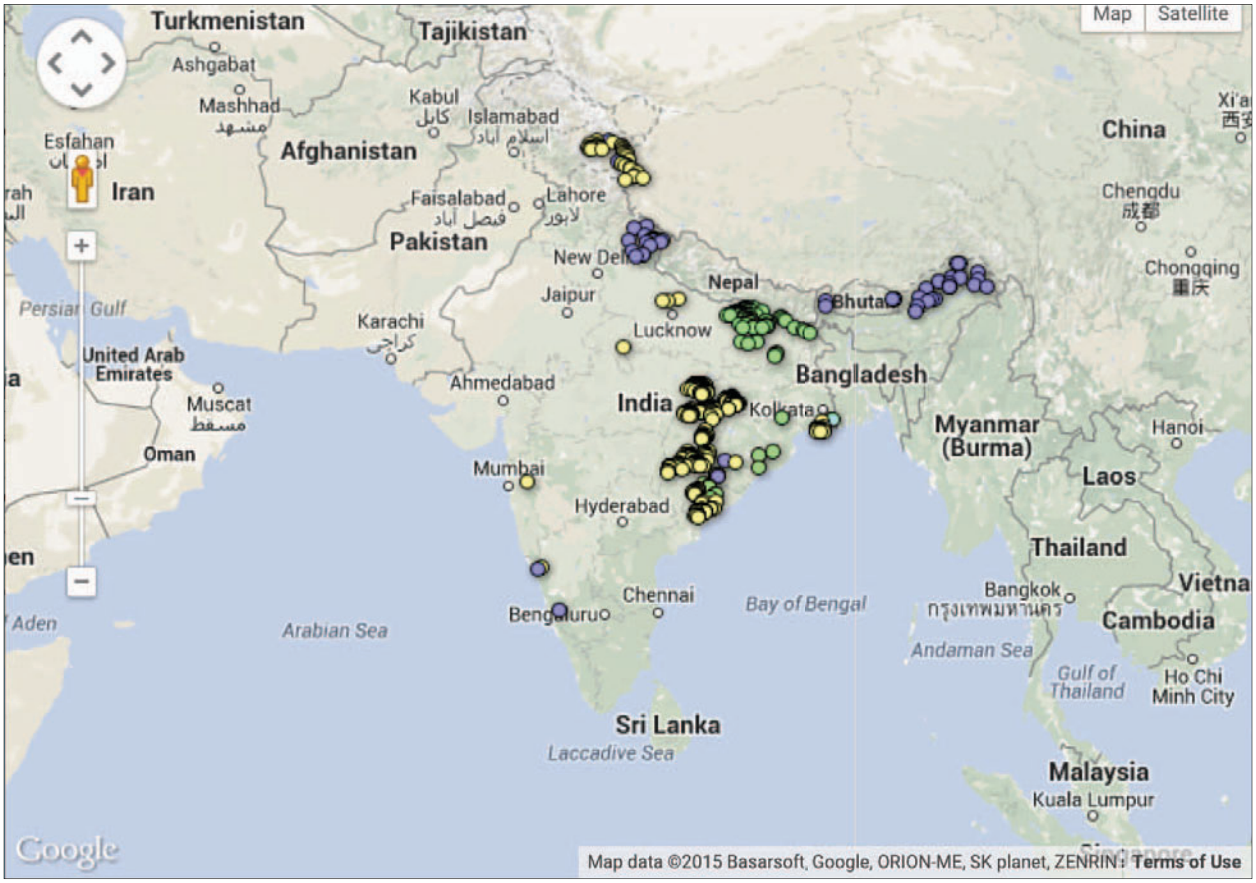
[2] There continues to be debate about the precise definition of microgrid versus minigrid, and the distinction between the two. For the purposes of this thesis, those terms will be used interchangeably and can refer to any size system that has the basic properties described in the text.

panels, a biomass generator, a diesel generator or some hybrid. It is also possible to have wind-powered turbines, though that is far less common.

Though solar home systems are more established in India,[3] there is significant excitement from domestic entrepreneurs, NGOs, and international governmental institutions about extending access to electricity to India's poorest via microgrids. For example, in response to the growing number of off-grid entrepreneurs, the World Resources Institute (WRI) and New Ventures India (NVI) have used data from the Census of 2011 to identify districts in India that might be viable markets for off-grid electricity solutions (New Ventures India). Prayas Energy Group (2014) has produced an incomplete, but telling map (Figure 1.2) of existing microgrids in India built by 22 providers, to provide a sense of microgrid proliferation.

FIGURE 1.2 Map of several existing microgrids in India (Prayas 2014)



But, in India, where the grid electricity tariff for rural consumers is heavily subsidized (or free), the per unit tariff for off-grid electricity tends to be more expensive (depending somewhat on the business model). This leads to a situation in which off-grid consumers are paying much more for electricity than

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[3] For example, SELCO, a solar home system company in Karnataka has been in business for about two decades.

those connected to the grid. Although a comparison of unsubsidized costs might yield a different conclusion, the cost differential between subsidized grid electricity and unsubsidized electricity supplied by a microgrid or a solar home system highlight important questions about who will bear the costs of off-grid solutions and whether such technologies will really constitute a major part of the solution to energy poverty, as the IEA predicts.

Although the emergence of off-grid electrification in India has not occurred in the absence of any rural electrification policy, there is little that directly regulates how private companies that sell off-grid systems must behave in terms of standards of service and interactions with the local utility. As discussed earlier, state regulators are responsible for regulating utilities, but the strength of these institutions varies by state. The National Electricity Act of 2003, as mentioned above, lays out India's universal electrification priorities at the national, state, and local levels. The Ministry of Power (MoP), along with the Rural Electrification Corporation (REC), are primarily focused on ensuring that state utilities extend the grid to unelectrified villages and approving proposed projects within each state through the Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY) program.[4] The REC supports this effort by identifying unelectrified villages that the state-run utilities must connect within the next five years, though the method by which these villages are selected is not transparent (Ministry of Power).

Beyond the grid, the MoP as well as the Ministry of New and Renewable Energy (MNRE) administer four major rural electrification programs: RGGVY (this program also has an off-grid component), the Decentralized Distributed Generation (DDG) program, (parts of) the Jawaharlal Nehru National Solar Mission, and the Remote Village Electrification program. Under each of these programs, states are expected to distribute various subsidies to independent off-grid electricity distribution companies and monitor the state-run utilities' adherence to the elements of these programs (Bhattacharyya 2006). These subsidies — some targeted at project developers and some targeted at consumers — are intended to alleviate the tariff disparity between subsidized grid and off-grid electricity.

According to Bhattacharyya (2006), the high and frequently changing demands on states to oversee these immense electrification projects have not been easy to manage, particularly given the generally weak governance structures that exist in states with the lowest electrification rates. National mandates offer little in the way of prioritization or structure, providing leeway for state and local officials to influence electrification decisions in ways that suit their politics, such as where utilities will extend the grid and where subsidies are disbursed for off-grid projects. Companies report that procuring the subsidy money under these programs can be a daunting, if not harmful process to their business

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[4] This program was very recently subsumed by Deendayal Upadhyaya Gram Jyoti Yojana, according to the Ministry of Power website and the former RGGVY portal (www.rggvy.gov/in), just as this document was being prepared for publication.

outcomes [1, 16], though there have been some reported improvements over the course of this research [1].

The National Electricity Act of 2003 merely notes that any distributor seeking to provide electricity in a rural area is not required to possess a license (Article 14):

> Provided also that where a person intends to generate and distribute electricity in a rural area to be notified by the State Government, such person shall not require any license for such generation and distribution of electricity…

The only other stipulations regarding off-grid systems have to do with safety and supply (Section 53). Oversight from state regulators and energy departments appears to be minimal or nonexistent. At the same time, data necessary to inform decisions about where grid extensions are expected and where microgrids may be viable is limited, even though state planners responsible for planning rural electrification are mandated to promote grid extension and oversee electrification subsidy programs. While it may seem as though off-grid entrepreneurs have nearly free reign to serve an enormous market of rural electricity consumers, companies report that the lack of regulation can lead to difficulty effectively targeting customers, particularly the poorest. They cite a variety of reasons, including limited data about where poor, unelectrified villages are, local attitudes about the quality of solar technologies, and limited affordability among consumers to pay for electricity services [1, 3, 19, 22, 24, 25].

To be clear, these problems have not gone unnoticed. The Central Electricity Regulatory Commission has been advocating a regulatory framework for off-grid distribution since 2012 (Forum of Regulators/ABPS Infra 2012). Furthermore, in the two years since this research began India has experienced a massive political shift as the Indian National Congress party left office and Narendra Modi, of the Bharatiya Janata Party, claimed the office of prime minister in mid-2014. Modi has made electrification a major priority of his early agenda and his ascent to power has inspired rising expectations of improvements to the centralized grid that will allow 24/7 power for all. This could have important implications for off-grid electrification, though it is far too early to tell (NDTVProfit 2015, [1, 2]).

This confluence of socioeconomic, regulatory, political, and other factors has created a challenge in which decisions about which electrification method is best suited to meet the needs of a given area are difficult to make and assess. In this context, understanding where opportunities exist to expand electrification through off-grid solutions like microgrids and individual home systems requires planning by both public and private actors and participation from the many stakeholders involved in addressing this challenge.

Approaches to planning can exist on a spectrum, some start at the individual community level, such as a microgrid built by Greenpeace International (2012) in Bihar, while other approaches focus on making decisions at the regional level, such as models that plan generation capacity expansions and grid extension (Bazilian et al 2012, Levin & Thomas 2012). Models intended for large-scale comprehensive electrification planning have the potential to be extremely useful for quickly determining appropriate applications of different electrification technologies for entire regions based on technoeconomic factors. They can also be used to rapidly design electrification interventions since they attempt to operate at a scale commensurate with the size of the energy poverty challenge. These models, however, tend to focus predominantly on the technological and economic factors that inform system specification and design. They are typically not suited to consider the sorts of socioeconomic, regulatory, and political factors that can complicate these plans during the implementation process.

It may seem obvious that greater coordination between the public and private sector is critical to the effective and equitable functioning of a sociotechnical system as massive as India's electricity sector (Kale 2014), and that planning models could help enable that coordination, but such an approach has yet to be clearly articulated. The work presented here contributes to our understanding of how technology choices in the electricity sector are subject to non-technical influences and offers a means by which information asymmetries that hamper decision making at various levels could be addressed to achieve universal access to electricity in India.

1.2 INSTITUTIONAL CONTEXT

This section will briefly describe the context for and role of this thesis at the Massachusetts Institute of Technology. I describe the broad questions that motivated this work, then present the questions that this thesis addresses specifically.

1.2.1 INSTITUTIONAL BACKGROUND

The impetus for this work was a somewhat impromptu research proposal submitted in 2013 to a very new research center at MIT called the Tata Center for Technology and Design.[5] The Tata Center is funded by the foundational branch of the Indian Tata family to develop low-cost technology solutions for application in India. The initial proposal envisioned the development of an expandable grid architecture that could bring technologically advanced low-cost electricity solutions to Indians lacking access to electricity. The project required a student to conduct the market research for such a product, which led to the funding of this research.

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[5] http://tatacenter.mit.edu/

At the same time, one of the principal investigators on this proposal had a separate but related interest in using optimization models to address electricity access challenges in the developing world. As the early stages of this project developed, it became clear there was interest from both MIT and Indian counterparts in developing these types of models to facilitate electrification planning in India, as well as in several other countries. Out of this realization, the Universal Energy Access Research Group has informally, but rapidly taken shape. While several of the students, including me, are funded through this initial proposal to the Tata Center, several are funded by other sources, as well, including the ENEL Foundation (Italy) and Iberdrola, a Spanish utility, respectively. The goal of the research group is to develop a comprehensive suite of planning models modified for developing world contexts to aid governments and market actors making technology and policy decisions, similar to how tools are used in the developed world.

1.3 MOTIVATION

While the broad motivation to do research in the field of energy access is driven by the staggering numbers mentioned in the previous section, there is a more specific motivation for this thesis. Over the course of several field research trips in India, a common theme emerged: many of our Indian counterparts believed that the electrification challenge was not a technology problem, but a human problem. I interpret that to mean that they believe existing technology is sufficient to meet the scale of the electrification problem, but human problems, or in other words, social, political, regulatory, and similar issues constitute the major obstacle to universal electricity access. For an aspiring social scientist, this conception of the problem is seductive because it is a call to research and action, but to an aspiring transdisciplinary thinker this framing is too simplistic. While technical problems may exist in relative isolation (e.g., can a particular technical functionality be invented?), technology problems and human problems are not mutually exclusive. This thesis seeks to contribute to the understanding of the complex nature of electrification through this lens by providing a methodological framework that holds the technoeconomic questions about how to efficiently expand electricity access to be as important as the sociological questions about how to meet diverse needs through the provision of electricity. At a fundamental level, this thesis seeks to contribute to the argument that universal electrification cannot be achieved without a serious consideration of this complex relationship.

1.3.1 MOTIVATING QUESTIONS

Both the Tata Center's and the Universal Energy Access Research Group's efforts are driven by shared, broad questions about the role of electricity in development.

How do societies change as they gain access to electricity? In what ways is electrification a technical problem and in what ways is it a social or economic one? In some developing countries, why has electric grid infrastructure been so difficult to build, operate, and maintain equitably, while in others, like Brazil and China, electricity infrastructure has successfully reached nearly all citizens? Is the centralized grid the best means of expanding access to electricity or is there an economically and socially justifiable long-term role for decentralized, off-grid modes of electrification? How does the answer to this question depend on future technological innovations? How could the trade-offs, also both economic and social, between different strategies be better understood to inform policy?

1.3.2 THESIS QUESTION

Although this work will not answer all of the questions above, it is inspired by the same spirit of inquiry. This thesis will explore the interplay of technoeconomic factors and socioeconomic, political, and regulatory factors in the electricity sector that influence electrification technology decisions.

Specifically, it seeks to explore a method by which both technoeconomic considerations and social, political, and regulatory considerations can be usefully combined to create a regional electrification planning tool that supports a comprehensive approach to rural electrification planning.

1.4 PREVIEW

In Chapter 2, I review literature on two broad schools of planning theory that inform the techno-economic and the non-technoeconomic aspects of the planning methodology proposed in this thesis. In Chapter 3, I describe the technoeconomic model, called the Reference Electrification Model (REM), including the data inputs necessary to run the model and the major assumptions implicit in the approach. Much of this work is informed by collaborative research that will also be documented in great detail by another master's student on my research team. I refer you to his master's thesis when appropriate. The second half of Chapter 3 will include an explanation of the interview and survey-based methods used to develop a focused list of critically important non-technoeconomic factors as well as the insight necessary to understand how these factors influence off-grid electrification projects. I present the analysis in two parts: first, the analysis of the survey results and a discussion of the critical factors in the context of a social acceptance framework; second, a scenario analysis of three demand scenarios run using REM and a discussion of how other non-technoeconomic variables can be studied with this method of analysis, even when those factors are hard to account for within the model. Finally, in Chapter 5, I conclude with a discussion of how this planning approach can be used to inform electricity regulations and policies geared to universal electricity access in India with some reflection on the goal of developing a transdisciplinary planning methodology.

2. LITERATURE

2.1 TYPES OF PLANNING

As I mentioned in the introduction, most papers about rural electrification start off in a similar way (I essentially did the same): state the number of people without access to energy, and electricity services in particular (the size of the problem), then describe the motivation to bring electricity to those people (the need). But that somewhat linear construction is not the only one that results in the realization that more electricity access is a solution to a problem. Another construction involves determining the needs of the poorest, most marginalized people and recognizing that electricity could help meet a subset of those needs. These two constructions are emblematic of two broad types of planning approaches: technocratic planning and communicative planning, respectively. As Fainstein (2003) puts it:

> Differences among the types reflect the enduring tension within planning thought between a focus on the planning process and an emphasis on desirable outcomes. (174)

This literature review will describe these two general approaches, explain their shortcomings in the context of rural electrification, and discuss the applications of those approaches to this thesis in the context of multiple disciplinary research.

2.1.1 “TECHNOCRATIC” APPROACHES

Technocratic approaches to planning are rooted in the rational comprehensive tradition and, in general, consist of four broad components: “goal-setting, identification of policy alternatives, evaluation of means against ends, and implementation of decisions” (Hudson et al 1979). Rational comprehensive planning (Hudson et al also call it synoptic planning) takes a systems viewpoint. When it comes to service delivery, Pritchett and Woolcock (2002) describe the practical technocratic approach in three steps: “define the goal as a ‘need’,” “find the least-cost supply solution to the need,” and “implement this solution nationally via the public sector and thus by funding.”

Rational or technocratic planning has several relatively well-known weaknesses, which Hudson et al (1979) summarize, including “its reductionist epistemology,” its “a priori goal-setting,” its “presumption of a general public interest rather than pluralist interests,” and “its bias towards central control — in the definition of problems and solutions, in the evaluation of alternatives, and in the implementation of decisions,” among others.

Importantly, this “standard organizational algorithm” has largely worked for all kinds of service delivery challenges, including electrification, in developed countries, yet “mimicking” this process has not worked in developing countries (Pritchett and Woolcock 2002). Harrison (2013) cites Miraftab (2009) who argues that planning theory and practice should “understand them [the Global South] by their own rules of the game rather than by planning descriptions and fantasies of the west.” One of those so-called rules of the game is the degree of informality that is common in many developing countries, including India, which adds different dynamics to the system (Roy 2009). It may also be that in understanding these context-dependent rules, the nature of the problem in many countries of the Global South is revealed to be substantially different and far more complex than the service delivery challenges solved using the technocratic approach to planning. To the extent that certain service delivery challenges, such as universal electricity access, are just a component of a broader poverty problem, they may be “wicked” problems that evade the hunt for an optimal solution (Rittel & Webber 1973).

Furthermore, this approach to planning is not merely biased toward centralized action, it generally overlooks “interactions between citizens, the state, and providers” (Pritchett and Woolcock 2002). This orientation leads to biases with regard to which types of information are considered knowledge, pushing planners towards information from those doing the service delivery, not information from those who need the service — in this case, electricity. As Flyvbjerg (2003) notes:

> Power determines what counts as knowledge, what kind of interpretation attains authority as the dominant interpretation. Power procures the knowledge which supports its purposes, while it ignores or suppresses that knowledge which does not serve it. (319)

Kumar et al (2009) propose a diagram that describes a highly rational off-grid project planning process (see Figure 2.1), which serves as a useful example here.

FIGURE 2.1 Diagram of the off-grid electrification project planning process according to Kumar et al (2009)

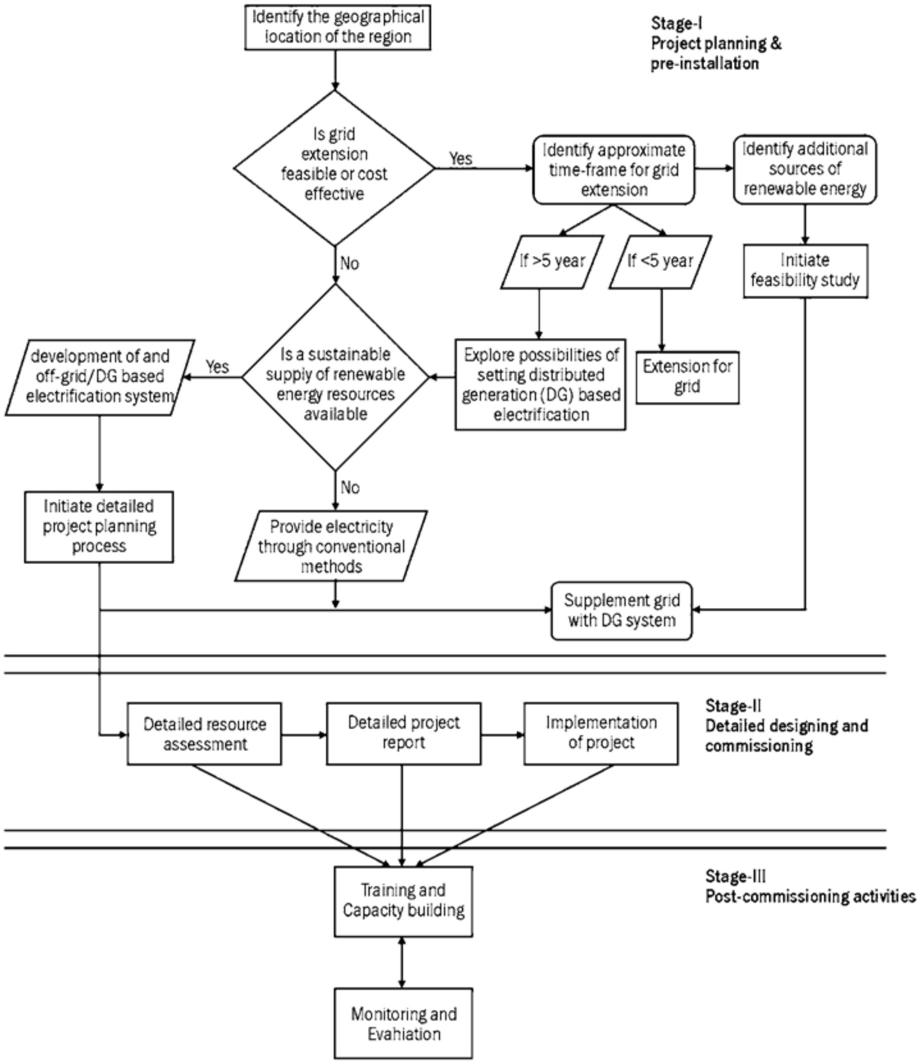


Fig. 2. Planning and formulation of off-grid electrification projects.

Upon closer review of the diagram, the only type of knowledge prioritized, particularly in the pre-installation phase, is knowledge that can be obtained through government data and electric utilities (e.g., resource availability, expected time for grid extension, etc.). At no point in the pre-installation phase (Stage I) do Kumar et al (2009) include a step that involves gathering information from different categories of actors involved in the process.

In general, but particularly in a data constrained environment, several types of knowledge must be taken seriously in order to understand a problem and plan relevant solutions. There are so many different levels of stakeholders that can influence the rural electrification process (not to mention, each other) that the rational instinct to focus on the least-cost supply solution, *a priori*, risks pushing a planner to overlook telling dynamics between actors that could alter the so-called optimal solution.

2.1.2 "COMMUNICATIVE" APPROACHES

Communicative approaches result from the converse perspective that "one size does not fit all." In other words, the standard technocratic set of steps to service delivery are not necessarily implementable when you take local idiosyncrasies into account. Where technocratic approaches are biased towards the centralized, participatory approaches tend to be more decentralized in nature. Pritchett and Woolcock (2002) describe two basic, agreed upon tenets of participatory approaches:

> (a) they will embody something like what is conveyed by terms such as "empowerment", "participation", "accountability", "transparency", or "good governance"; and (b) how the principles are actually embodied in concrete organizational forms will involve a great deal of institutional heterogeneity—one size clearly will not fit all in countries as different as Canada, Chad, China, and Costa Rica.

These tenets are not nearly as prescriptive as the three steps that constitute the technocratic approach, thus a wide array of communicative approaches have been proposed, though there is little agreement on which are best in any given situation. This disagreement has created a new type of public service delivery problem (Pritchett and Woolcock 2002). Harrison (2013) argues that one problem may be that planning theory is difficult to relate to practice, leading to confusion amongst planners about how to implement theoretical ideas about participation.

Hudson et al's (1979) description of "Transactive" planning is focused on determining citizen's needs and making plans based on lessons learned from studying people's lived experiences. Anderson and Doig (2000) recommend a consultation process that includes developing a planning manual to help villagers learn about their technology options and make technology decisions. While Arnstein (1969) would likely argue that these sorts of "consultation" approaches constitute a "degree of tokenism," as opposed to a "degree of citizens power," both may be necessary steps away from purely rational, least-cost approaches, particularly in the realm of electrification planning (see Figure 2.2).

FIGURE 2.2 Arnstein's (1969) Ladder of Participation

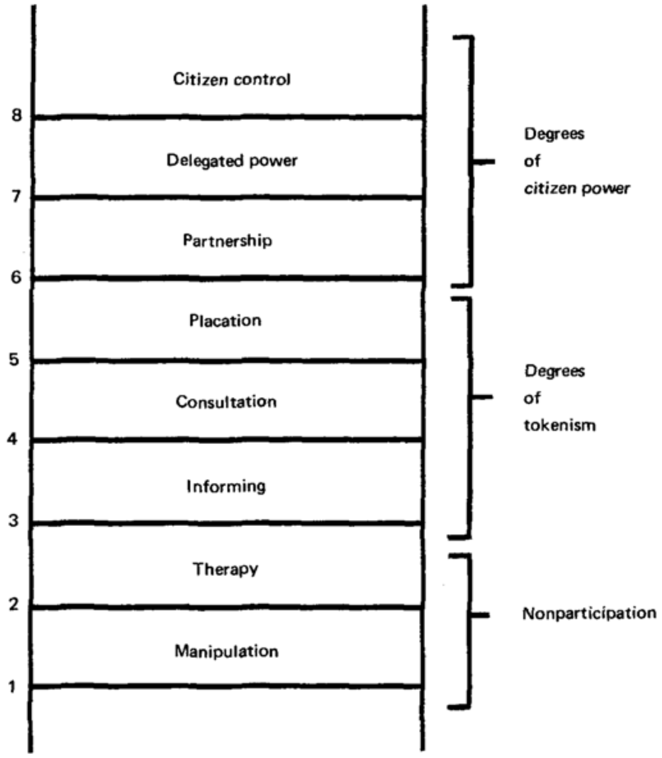


FIGURE 2 *Eight Rungs on a Ladder of Citizen Participation*

For example, according to Schnitzer et al (2014), there are seven critical factors that must be considered in rural electrification planning — tariff design, tariff collection mechanism, maintenance and contractor performance, theft management, demand growth, load limits, and local training and institution building — some, if not all, of which apply to those planning from the public or private sector perspective, but none of which are factors that reflect the citizen or consumer perspective. Training and institution building may help consumers adjust to the specifications of a new technology, but the ability to execute those steps may be hampered without previous community engagement to enable communication about needs. Parshall et al (2009) highlight four planning pathways originally described by Munasinghe (1988) that encompass planning strategies in the developing world: integrated rural development, area coverage, grid extension, and intensification. These are broad strategies that seem to have as their focus a push for speed and scale with an assumed solution, rather than an embedded process of solution determination that seeks to understand the preferences of the population to be served. Either public or private actors could adopt most of these approaches in pursuing the goal of universal electrification, since it is not evident that they are always mutually exclusive, yet none of these strategies appear to hail from the communicative paradigm.

The emphasis on scale and speed in the factors and strategies that Schnitzer et al (2014) and Parshall et al (2009) highlight are indicative of a key criticism levied at communicative approaches: essentially, they are too slow. When it comes to electrification, many argue that focusing on scale and speed leads to solutions that attract investors because electricity service providers can more easily drive down costs and recoup investments. The question a planner in the communicative paradigm might ask in response is: scale and speed, for whom? Or as Nieusma & Riley (2010) put it in a critique of engineering development projects: "countering the privileging of outcomes over process demands a focus on local decision-making about technology, enabling processes in which local control takes precedence over concerns around technical functionality." This tension is embodied in Fainstein's quote at the start of this chapter.

When it comes to rural electrification, though, where economies of scale have real benefits to consumers in terms of cost, but where off-grid technology deployment may not be able to achieve the optimal level of speed and scale, it is not clear where the balance lies between these two planning paradigms.

2.2 MODELING APPROACHES FOR ELECTRIFICATION PLANNING

Modeling is a key tool for the technocratic step of evaluating means versus ends or, in other words, determining an optimal, least-cost solution to the problem of electrification (Barclay 1979). Models can be used by planners to carry out any of the rural electrification planning strategies mentioned by Schnitzer et al (2014) and Parshall et al (2009). With particular relevance to this thesis, models can be used to evaluate which combination of electrification options might be most appropriate to a given context from a technical and economic perspective and can facilitate strategic decision making, whether the electrification goal is area coverage or intensification. More specifically, modeling can be used to design electrification systems, inform site identification for off-grid projects, and/or compare different electrification options to determine the so-called optimal electrification solution. For example, at the national level, India's electrification programs and policies are focused on grid extension (see Chapter 1) but grid extension may not always be the most cost effective choice. Modeling different technology decisions and their associated costs could help make a case for policy reform.

The enormous scale of the Indian electrification challenge and persistent rural poverty, not to mention the constant churn of the political cycle, enhances the perceived urgency of the problem and places planners and entrepreneurs under pressure to make hasty decisions. To address this conundrum, many researchers have recommended and proposed the use of various modeling tools that can allow rapid assessment of the cost-effectiveness of various electrification modes over large regions (Parshall

2009, Szabo 2011, Rahman 2013, Village Infrastructure, Kemausauor et al 2014). These tools, described below, tend to fall into three broad categories of models that can facilitate electrification: those that emphasize assessing the scope of the electrification landscape or the market for a particular type of technology, those that emphasize optimal system design, and those that support long-term strategic planning in the context of broader economic goals. In a developing country context, modeling capabilities are significantly limited by data scarcity, however, as the discussion below indicates, these approaches attempt to generate the most useful plans possible in the absence of ideal information. For a broader description of energy modeling for decentralized electrification see Hiremath et al (2007).

2.2.1 MARKET/LANDSCAPE SCOPE

Various spatial models for the evaluation of the most cost-effective generation and electrification mode have been proposed. Most of these models rely on a least-cost technoeconomic assessment, with little consideration of consumer ability to pay or other sociocultural considerations. Parshall et al (2009) developed a spatial electricity planning model for Kenya that uses regional data on electricity demand and costs, estimates of population density, a poverty index, and spatial location of the medium voltage (MV) distribution grid to understand how settlement patterns and income information can help prioritize viable locations for grid extension. The researchers use a combinatorial optimization method called a Minimum Spanning Tree (MST) to evaluate the cost of extending the MV grid versus electrifying an area with a decentralized technology (either a diesel-powered microgrid or solar home system). While the model tries to account for population distribution, ability to pay for electricity, and electricity consumption at the residential, household, and institutional levels, the data (in the Kenya case) are aggregated at the sub-location level (on average 15 km^2). The poverty index is similarly low resolution, differentiating settlements as high or low income, but not based on ability to pay for a given solution. Furthermore, the model does not account for grid reliability in its grid extension decision making, which can play an important role in electrification decisions in rural areas.

Szabo et al (2011) proposed a spatial cash flow model to compare the application of solar photovoltaic (PV) technologies for rural electrification in Africa to the use of a diesel generator or to grid extension. Later, Szabo et al (2013) expanded their least-cost model to compare the viability of grid extension to a wider variety of distributed generation options. This model, however, is purely focused on the tradeoffs between generation costs and grid extension, not a complete comparison of decentralized system costs.

Rahman et al (2013) propose a multi-factorial decision making approach that first assesses whether an area is a candidate for grid extension or off-grid electrification on the basis of levelized cost of electricity (LCOE), then uses Stochastic Multicriteria Acceptability Analysis (SMAA) to evaluate off-grid options on the basis of 24 criteria values. This method weights and ranks the various criteria on five dimensions: technical, economic, social, environmental, and policy or regulatory. These criteria were selected based on the researchers intent to account for more qualitative, sociocultural factors that influence off grid electrification, not just financial and technical factors. Importantly, this model is used in the paper to make decisions about choosing decentralized generation technologies and focuses on specific regions, like a village, though it may be possible to apply it to a broader regional assessment or site identification.

Market or landscape assessment models are powerful in that they address the need for rapid evaluation of a region for various electrification options. They can efficiently focus planning and development efforts on regions most suitable to particular interventions or business models. Furthermore, they can improve the effectiveness of the other types of models briefly described below. Given their broad regional scope, however, they must often rely on highly aggregated data and limited information about the extent and reliability of the central distribution grid. They also give no consideration as to how the results fit with the needs of the people the model plans for.

2.2.2 SYSTEM DESIGN

System design models for rural electrification are particularly useful once a site has already been targeted for an intervention, though they can also be used to inform more general design decisions when applied to larger regions. Some models treat system design problems as MST optimization problems (Zvoloff et al 2009, Levin & Thomas 2012). Other models, such as the National Renewable Energy Laboratory's HOMER software, do more detailed system design, employing a variety of optimization methods to facilitate optimal generation planning, as well as network component and design decisions.

System design models are useful for detailed technological decision making, but they typically do not consider local economic and sociocultural dynamics. While a more detailed review of existing system design tools is outside the scope of this literature review, there is significant potential to integrate these types of models with the market or landscape assessment models described above.

2.2.3 NATIONAL STRATEGIC PLANNING

In India, both regional and local energy planning are inextricably linked to national planning priorities due to budget, resource, and regulatory constraints. Furthermore, achieving higher levels of electricity access could have ripple effects on the national economy. National strategic planning models can be used to estimate the broader potential economic outcomes of implementing recommendations suggested by the system design and market/landscape assessment-style models or to evaluate the unexpected consequences of electrification options at scale.

Models designed to facilitate national energy planning can range in complexity. Levin & Thomas (2012) use an electricity grid expansion model (MST algorithm) to find the shortest centralized transmission network, then use a least-cost methodology to determine how to serve 150 different countries with both centralized and decentralized electrification. While the application of this model is intended to assist with national grid planning, the authors note that it could be used at a more localized level. Importantly, this method does not take national budget or policy priorities into account.

The MARKAL/TIMES family of energy models are bottom-up partial equilibrium optimization models which model the outcomes of energy processes and seek to minimize the cost of supply over time and maximize total discounted social welfare for an entire energy system (Alvaro 2014). The MASTER model, that builds on the MARKAL/TIMES philosophy, is a static optimization model that is intended to represent a complete national energy system (Alvaro 2014). Research being conducted by my colleagues seeks to adapt this model for application to the developing world.

2.2.4 GIS APPLICATIONS

Geographic Information Systems (GIS) can be a useful tool in the planning process to organize information, build spatial models, and visualize the output in order to better target electrification efforts. GIS has broad application to both government planners and private sector electricity project developers who can benefit from a better understanding of where people are and how their characteristics, resources, and activities are spatially distributed. Many of the technoeconomic factors that are most critical to effective electrification planning vary according to spatial location, including population density, distance from the centralized grid, electricity demand, load factor, cost of fuel, availability of energy resources, etc. (Nouni et al 2008, Parshall et al 2009). Importantly, socioeconomic, social, cultural, and political characteristics that may influence electrification may also vary by location (Kale 2014).

Kemausauor et al (2014) developed a web-based decision support mapping tool called The Network Planner that is intended to allow planners to construct scenarios based on technoeconomic factors to evaluate least-cost technology options for areas that lack access to electricity. The web tool is based on the work described above by Parshall et al (2009).

In addition to government and private sector planning, GIS can be used for sharing and easily communicating information to stakeholders. A recent USAID report (2014) identified a need for a networked information hub for electrification solutions in India. A GIS and GIS-based analysis could be a critical component of making such an effort useful to entrepreneurs and others in the sector. Village Infrastructure, a small sustainable energy development organization, has developed a tool in this spirit called UNMapper, which is intended to help planners visualize a variety of global data pertinent to electrification goals. The tool is not really intended for analysis, but is helpful for surveying large or obscure datasets.

GIS can be used to enhance various types of electrification models by storing and structuring data in a way that can be easily transmitted. This research focuses directly on the development of a model whose results can be visualized spatially to provide insight into the market for off-grid electrification in India by assessing the rural electrification landscape and identifying suitable sites for grid extension, microgrids, and individual home systems.

As was noted earlier, substantial precedent for GIS-based rural electrification market and landscape assessment tools exists (see Parshall et al 2009, Szabo et al 2011, Kemausauor et al 2014). Although they employ different methods, these examples all tend to adopt LCOE as the central metric informing decisions about where to extend the grid, where to site microgrids, and where to deploy individual home systems. Optimization methods, such as MST (Parshall et al 2009) and Pimm's algorithm (Levin & Thomas 2012) are common approaches. Other modeling approaches include multi-criteria decision making methods such as weighted sum or weighted product overlays, preference ranking, and multi-objective optimization (Pohekar & Ramachandran 2004).

Critical technoeconomic and socioeconomic inputs to electrification decision making that have a spatial component and can be quantified include distance from the grid, average village load, peak village load, load factor, number of households, average number of people per household, energy resources, fuel costs, terrain, ability to pay (income/monthly consumer expenditure), and others (Nouni et al 2008). Many models account for most of these inputs and can provide useful and necessary cost assessments.

2.2.5 WEAKNESSES

While modeling enables cost estimates that are useful for policymakers and private entrepreneurs, cost by itself does not capture other influential variables, such as access to financing, access to local community development organizations, technology attitudes, and other sociocultural and political influences. While building least-cost systems is a worthy goal, previous research identifies the limits of analyses that only take into account technical and cost considerations and ignore sociocultural dynamics and long-term sustainability (Kobayakawa & Kandpal 2013, Szabo 2011, Kumar et al 2009).

Another major pitfall of using modeling to inform electrification plans is that it is vulnerable to what Pritchett and Woolcock (2002) call 'skipping straight to Weber,' a phrase they use to refer to a practice of finding the most efficient way to reach particular service delivery goals in developing countries without consideration of idiosyncrasies of the locality in which they are planning. These models illuminate expected costs for the planner, but do a poor job highlighting the costs, often abstract transaction costs, that might accrue to the village in need of electricity. This goes back to the question mentioned earlier in this chapter about scale and speed: *for whom?*

The third major pitfall of the models discussed above involves design. Verbeek (2006) argues that technology influences the way users perceive the world as well as the decisions they make, thus raising ethical and moral questions about the design process. This conundrum applies to modeling, too. While most of the models above were probably designed to help a planner or service provider do a better job delivering electricity service to an end user, they are generally not designed with intensive participation from the ultimate electricity consumers. Arguably, this makes sense since model developers most likely imagine that their work enables a planner to do a better, faster job serving end consumers. After all, the explicit goal of modeling is to automate planning and the implicit goal is to minimize participation, since participation brings with it transaction costs that make work in an already resource constrained environment more time consuming. As Arnstein (1969) points out, participation is not obviously compatible with least-cost planning. That may be true, but what is not clear is how to account for the factors that influence electrification, but cannot be evaluated automatically. Or, as Verbeek (2006) might argue, how to ensure that the design of the model does not enforce or produce unintended biases in the planning process, a risk that Nieusma & Riley (2010) highlight, as well.

2.3 A NOTE ON MULTIPLE DISCIPLINARY APPROACHES

Rural electrification is a complex, probably "wicked" problem. As I will discuss throughout this thesis, extending electricity access in India touches on a multitude of issues that are not easily accounted for by a linear approach to problem solving (Buchanan 1992, Rittel & Webber 1973). This thesis is really just the beginning of an effort to bring multiple planning approaches together in the hopes that the best elements of each approach could be drawn on to address rural electrification challenges in India. As Buchanan (1992) points out, systems engineers, such as power system planners, and urban planners both focus on planning from different aspects of an integrated system. The efforts of one should not preclude the efforts of the other, "with no priority given to any single one."

The literature on multiple disciplinary approaches to planning is growing, however, it is somewhat dispersed, probably because it seems as though there is a good deal of confusion about terminology i.e., whether to label research multidisciplinary, interdisciplinary, or transdisciplinary (Lang et al 2012, Choi et al 2006, Aboelela et al 2007). Aboelela et al 2007 propose definitions for each of these three types of multiple disciplinary approaches based on a review of health-related literature.

FIGURE 2.3 Aboelela et al's (2007) proposed categorization of multiple disciplinary approaches to research

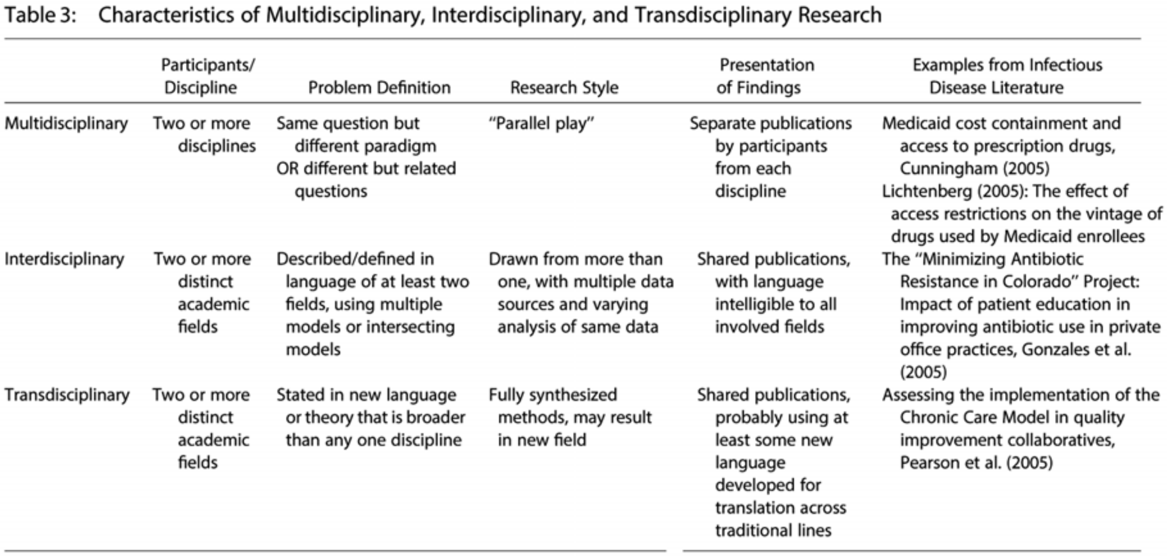


Table 3: Characteristics of Multidisciplinary, Interdisciplinary, and Transdisciplinary Research

	Participants/ Discipline	Problem Definition	Research Style	Presentation of Findings	Examples from Infectious Disease Literature
Multidisciplinary	Two or more disciplines	Same question but different paradigm OR different but related questions	"Parallel play"	Separate publications by participants from each discipline	Medicaid cost containment and access to prescription drugs, Cunningham (2005) Lichtenberg (2005): The effect of access restrictions on the vintage of drugs used by Medicaid enrollees
Interdisciplinary	Two or more distinct academic fields	Described/defined in language of at least two fields, using multiple models or intersecting models	Drawn from more than one, with multiple data sources and varying analysis of same data	Shared publications, with language intelligible to all involved fields	The "Minimizing Antibiotic Resistance in Colorado" Project: Impact of patient education in improving antibiotic use in private office practices, Gonzales et al. (2005)
Transdisciplinary	Two or more distinct academic fields	Stated in new language or theory that is broader than any one discipline	Fully synthesized methods, may result in new field	Shared publications, probably using at least some new language developed for translation across traditional lines	Assessing the implementation of the Chronic Care Model in quality improvement collaboratives, Pearson et al. (2005)

Although my focus is not health research, the table is useful in providing a sense of the degree to which different planning approaches can be brought together in a research effort. Notably, one of the key differences between interdisciplinarity and transdisciplinarity is the use of language. Where interdisciplinarity uses language from each of the fields involved in the project, as I currently do, transdisciplinarity adopts "new language or theory that is broader than any one discipline" (Aboelela et al 2007). The use of language from different fields or the need to develop new language is easier said than done. For example, in exploring the two bodies of planning theory that inform this research, confusion about the term "bottom-up" arises. Frequently, the two dominant schools of planning thought are categorized as either "top-down" (i.e., central planning) or "bottom-up" (i.e., grassroots planning). From the perspective of those on the team developing the electrification planning model, though, "bottom-up" refers instead to the way in which the technology decision is made or the level at which the decision is being modeled — they consider our model to be "bottom up" because the model makes decisions at the level of the individual household. In the descriptions above, I chose to use the words "technocratic" and "communicative" as umbrella terms in order to avoid confusion over the "top-down/bottom-up" binary, though my ultimate goal would be to create a transdisciplinary term that obviates the need for either.

Another notable characteristic that distinguishes the three types of multiple disciplinary approaches is the way in which the problem is defined (i.e., from what perspective is the question asked) under each paradigm. This observation harkens back to the beginning of this chapter when I pointed out that the way the problem is defined reveals the body of planning theory that informs the planner's notion of the situation. These sorts of linguistic decisions are indicative of the challenges and uncertainties of actually implementing research that draws on multiple disciplines, whether it is ultimately multi-disciplinary, interdisciplinary, or transdisciplinary. For example, many times throughout this thesis I refer to "technical factors" and "non-technical factors." Explicitly, I use these terms in the interest of brevity (listing out all of the different types of factors is undeniably cumbersome), but implicitly they communicate that this research was initially conceived by those more established in the technocratic paradigm, than the communicative one.

Regardless of the terminology, multiple disciplinary energy research is relatively rare, especially in the developing world. According to a study of three leading energy journals, just under 20% of papers published between 1993 and 2013 were authored by researchers affiliated with the social sciences (not including economics) and "[m]ost studies are the result of work under-taken at the bench or desk using computer models and experiments, rather than field research, interviews and surveys" (Sovacool 2014). Although my aspiration is to one day enable an approach to rural electrification planning that is transdisciplinary, for now, the nomenclature is less important than the immediate intent — which is to offer an early attempt at an approach to planning that pulls together the necessary technical methods along with social science techniques in a way that highlights new or overlooked insight that can lead to more equitable and sustainable solutions in the future.

3. METHODOLOGY

3.1 CONCEPTUAL APPROACH

On its face, determining locations where communities that lack electricity might benefit from off-grid electrification seems relatively straightforward. Eliminate all locations where utilities believe it is economically and technically feasible to extend the centralized electric grid and deploy off-grid systems in the remaining locations. In India, however, where population density is high, hundreds of millions are extremely poor, people are culturally diverse, and the centralized grid is highly unreliable (Kale 2014, Santhakumar 2008), technoeconomic cost comparisons, especially when considering the long term, are far more complicated than they appear. This thesis argues that an adaptive approach is needed that harnesses the computational power and scale enabled by a technoeconomic approach to electrification planning while evaluating and adjusting those plans in the context of factors that affect costs and efficacy in unexpected or inconsistent ways.

Studying the non-technical factors that influence rural electrification planning does not conform easily to any one methodology. Instead, our team's process of gathering and verifying data in the field has been circuitous. Certainties, as well as consistency, have sometimes been elusive. Isolating planning priorities that span socioeconomic and political issues can be complicated by the challenge of deducing whether a stakeholder's interests compromise his or her opinions. On more than one occasion, asking the same question different ways at different times elicited completely different answers from the same person. On other occasions, conversation felt like peeling an onion, with every repetition of a question or request for clarity revealing new layers of the situation. In India, where most government officials, NGO staff, and businessmen speak Hindi or Kannada as well as English quite fluently, it can be difficult to tell whether the discrepancy was the result of a language barrier or avoidance of particular questions. Turning these sorts of open-ended encounters into hard data was initially mystifying, but using them to provide more context to the facts that can be verified has created a much more colorful picture of the rural electrification challenge in India than is typically described in the somewhat limited technical literature on off-grid electrification in the country.

This research process has been further influenced by how rapidly India is changing. As mentioned in Chapter 1, politics have shifted drastically over the course of this project. The central government is now led by the Bharatiya Janata Party (BJP) and Prime Minister Narendra Modi, a leader who has raised expectations about aggressive policy reform (Economist 2014, Financial Times 2014, Wall Street Journal 2015). The shift has not only meant the announcement of new rural electrification and renewable energy goals (Brookings 2014, Guardian 2014), but also a massive shake up of government officials. Many of the contacts my team made on our first trip were no longer occupying the same government posts when we returned in July 2014 after the elections.

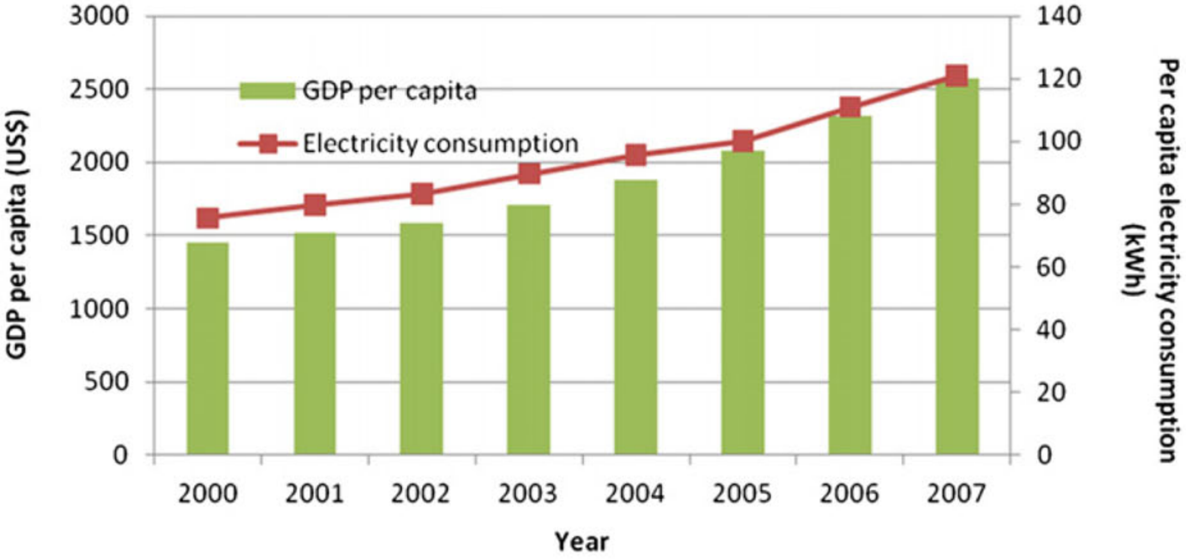
But all of these moving targets only serve to strengthen the conceptual approach to the thesis. A technoeconomic model cannot be expected to capture all of these subtleties, though it can help to illuminate them. This thesis architects one approach a rural electrification planner could take that combines technoeconomic insight with a qualitative assessment of the social, political, and regulatory issues in order to develop more effective policy and more sustainable projects.

3.2 DEVELOPING THE PLANNING APPROACH

Developing the approach to rural electrification planning that is proposed and demonstrated here has taken nearly two years of research, fieldwork, and debate. But before I describe the development process it is worth discussing a few key assumptions that have driven the types of questions being asked and the definition of the problem.

First, we assume that universal access to electricity is necessary for all Indians for two reasons: a) it will improve quality of life and b) it is essential, though not singularly causal, for economic development of India's poorest citizens. Though few would argue with these assumptions, it is fair to question to what degree these assumptions are rooted in fact or fiction. We base our argument on the link between access to electricity and human development indicators, including higher GDP (WEO 2004). Figure 3.1 shows the correlation between electricity consumption and GDP, specifically in India (Khandker et al 2012).

FIGURE 3.1 Relationship between electricity consumption and GDP (per capita) in India (Khandker et al 2012)



In addition, the link between access to electricity and improvements in quality of life is well-supported by the literature (Gaye 2008, Khandker 2012). On the other hand, while electricity may enable economic development, the precise mechanism by which electricity use enables these development outcomes remains poorly understood.

Second, we assume that scalability — reaching as many people as possible — must be the driving force behind electrification decisions. Specifically, the implicit assumption is that the selection of the "best" electrification mode must be made for groups of households and/or other types of load points rather than customized to each individual load point. It also holds as given that least-cost technologies are critical to achieving scale given that the target market is low income. This emphasis on scale necessarily subordinates the needs of the individual to the needs of a much larger group. This assumption is a central component behind the objective of minimizing cost and maximizing economies of scale in electricity generation, storage, and network design — a priority in techno-economic power sector planning.

While achieving scale may not be problematic in and of itself (I have rarely encountered anyone who would argue that planners should not aim to bring electricity to everyone), least-cost technology optimization need not constitute the central approach to electrification planning efforts. For example, Bharath Jairaj suggested that an alternative approach could focus on redefining what it means to achieve electricity access at scale:

> I think the definition of scaling, it also goes back to the conversations that the enterprises are having around scaling, also what the investment community calls scaling. And often it's more of the same, where it could be deepening relationships or deepening your service abilities and that conversation is also something that needs to take place. The investment community also needs to understand that it's not just, ok, another 100,000 homes have two lights, but it could also be that 50,000 homes have moved from two lights and a mobile phone to these three other services… [2]

Despite the existence of alternatives, least-cost optimization is the organizing principle behind the approach described below. These assumptions are important to keep in mind in order to understand the context for this research and its potential applications.

3.2.1 A RECORD OF WORK IN THE FIELD

The field research for this thesis was conducted with a team of researchers from the Massachusetts Institute of Technology (MIT) and the Instítuto de Investigación Technológica-Universidad de

Pontificia Comillas (IIT-Comillas)[6] over nearly two years, including four trips to India. These field trips included at least 35 conversations with stakeholders at all levels, from high-level central government officials to low-income, rural villagers living on an island in the Ganges River, as well as extensive data gathering. The Tata Trusts generously funded all four trips through the MIT's Tata Center for Technology and Design. This section will contain a brief summary and description of the key takeaways from each trip in order to provide a record of the inspiration for the method proposed in this thesis.

JULY/AUGUST 2013 [7] [8]

Initially, the stated goal of the research project that informs this thesis was to identify the size and nature of the market for microgrids in India. On this first trip to India, about one month prior to the official kick-off of the project, the goal was to figure out ways to further study this market and determine opportunities to improve the existing means by which unelectrified people in India were currently being supplied. At this point, we had a nascent idea about the opportunity to use geographic information systems (GIS) to conduct a market analysis or planning exercise and wanted to gauge stakeholder reactions to this idea. We also intended to make early contacts with stakeholders that would help us better understand the broader context of rural electrification in India.

Over the course of two weeks, we had many meetings in New Delhi with national-level government officials at the National Planning Commission, Ministry of New and Renewable Energy, and Ministry of Rural Development, as well as meetings in Patna and Bangalore with smaller scale entrepreneurs like SELCO, a Karnataka-based company that predominantly sells solar home systems. Even though rural electrification was a major national priority in India and several ministries are charged with addressing the issue through policy, officials told us that there is little communication between ministries, though there are some attempts to coordinate programs to minimize duplication of effort [12]. We also learned that the effects of this disorganization trickled down to impact entrepreneurs attempting to more efficiently identify communities that might be potential customers. For example, SELCO

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[6] As is the nature of academic research, the team varied in size and attendance on each trip, due to changes in the research focus of some students and faculty. Over the course of two years, I traveled and conducted conversations with stakeholders in collaboration with the following individuals: Professor Ignacio Pérez-Arriaga, Dr. Robert Stoner, Professor Rajeev Ram, Dr. Reja Amatya, Dr. Claudio Vergara, Douglas Ellman, Andres Gonzalez-Garcia, Kevin Simon, Daniel Strawser, Brian Spatocco, Wardah Inam, Vivek Sakhrani, Patricia Levi, and Vivian Li. Formally, the individuals working on the Reference Electrification Model include Professor Ignacio Pérez-Arriaga, Dr. Robert Stoner, Dr. Reja Amatya, Douglas Ellman, Dr. Claudio Vergara, Andres Gonzalez-Garcia, Patricia Levi, Vivian Li, and Lily Mwalenga.

[7] Stakeholders engaged: National Planning Commission, Ministry of New and Renewable Energy, Ministry of Rural Development, Husk Power, SELCO, Akanksha Chaurey (ITPS Energy), the World Bank, The Energy and Resources Institute (TERI).

[8] Sites visited: Husk Power microgrid site in Korbaddha Pataili Village, Samastipur, Bihar (escorted by local JPAL representative); Urban slum outside Bangalore (escorted by SELCO); Village in rural Karnataka (escorted by SELCO)

described the process of finding villages as extremely time consuming because they either relied on personal connections to direct them to new customers or had to send staff members around on motorbikes to scope out opportunities to expand their market [16, 17, 18]. The key insight was that electrification planning in India, at multiple levels, was frequently uncoordinated and serious uncertainties about who needed to be served where arose from the inaccessibility of shared, high-quality data.

JANUARY 2014[9] [10]

The second research trip took place after about six months of investigation into the possibility of using GIS to facilitate early-stage electrification planning. At the time, the plan was to identify locations that were particularly suitable for microgrids or solar home systems based on both technoeconomic criteria, such as distance from the existing grid, as well as socioeconomic, environmental, and political criteria, (e.g., level of income, etc.). On this trip our goal was to vet this early concept with some of the contacts from our previous trip, as well as several entrepreneurs based in New Delhi, Jaipur, and Bangalore and to ask for feedback on the prospective utility of such a tool.

The key takeaway from this trip was that stakeholders we spoke with were generally interested in using a GIS tool like the one we proposed. They offered several ideas for features they would like to use, particularly focused on tools that could help estimate and plan for costs of doing projects in particular places. In addition, we gained more insight into the challenges that confront entrepreneurs in the microgrid and solar home system markets in India and the types of business models being tried by these companies.

JULY 2014[11] [12]

After the January trip, our team began to focus on the actual development of the model, which is called the Reference Electrification Model (REM). By July we had a functioning prototype and an example of the results we had previously promised. Our goal for the July trip was to find partners in the energy ministry of one or two states that would be willing to engage with us by sharing large

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[9] Stakeholders engaged: Gram Power, Barefoot College, Akanksha Chaurey (ITPS Energy), OMC Power, Tata Power Delhi Distribution Limited, SELCO, Tata Power Solar, IBM India

[10] Site visit: Villages in rural Jaipur, Rajasthan (escorted by Barefoot College); Villages near Indore, Madhya Pradesh (escorted by Tata Trust)

[11] Stakeholders engaged: SELCO, Census of India, Central Electricity Regulatory Commission, New Ventures India, World Resources Institute, Mera Gao via MORSEL, Karnataka Energy Department, Bihar Energy Department and Bihar State Power Holding Company Ltd, Husk Power, Boond Energy, Tata Power Delhi Distribution Limited, Akanksha Chaurey (ITPS Energy), Tata Power Solar, IDinsight

[12] Site visit: Barabanki, Uttar Pradesh (escorted by MORSEL)

amounts of detailed data about their electricity network in exchange for the opportunity to have us tune our model to the types of planning questions they might want to answer. Through the Tata Trusts we connected with Tata Power Delhi Distribution Limited, a private utility serving northern Delhi, which was very interested in helping us gather data and develop partnerships in order to further develop our model. They arranged a meeting for us with the Chairman of the Bihar Energy Department/Managing Director of the Bihar State Power Holding Company (CMD) Pratayaya Amrit, who had recently taken office in Bihar after Prime Minister Narendra Modi took office. After presenting our prototype to the CMD, he said he was interested in supporting us to do a pilot study of a district in Bihar. We ultimately selected Vaishali District because data about the existing electric grid (11 kV lines) were available and ready to be shared. We took this data with the agreement that we should show a first draft of an electrification plan for Vaishali district on our next trip in January 2015.

Our other goal for this trip was to enhance our understanding of consumer attitudes towards rural electrification solutions as well as daily electricity demand for rural people who had recently gained access to electricity. We traveled to Barabanki District, in Uttar Pradesh, to visit several villages where Mera Gao, a microgrid vendor, had installed small microgrids that powered about two lights and a mobile phone charger in each home. In these villages, we heard that these small-scale electricity solutions enabled easier access to mobile phone charging and some evening lighting, but the level of electricity provided was not meeting all of the potential demand for electricity. Villagers also helped us develop a better sense of their electricity demand and shared their aspirations about what types of appliances they might be interested in using if they had disposable income.

We also learned that while many of the government officials and entrepreneurs we met with were very interested in the idea of our model, they were not as interested in being partners in the process of vetting the model, perhaps because data sharing required a significant time commitment.

JANUARY 2015[13] [14]

Our primary goal for our fourth research trip was to present a first draft of an electrification plan for Vaishali District to the CMD of the Bihar Energy Department and Bihar State Power Holding Company Ltd. in the hopes of gaining additional support to gather more detailed and more accurate data. For

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[13] Stakeholders Engaged: Akanksha Chaurey (ITPS Energy), World Bank India Energy Group, Ministry of New and Renewable Energy, Mrinmoy Chattaraj (Independent Consultant), Central Electricity Regulatory Commission, Ministry of Power/Rural Electrification Corporation, Bihar Energy Department and Bihar State Power Holding Company Ltd., Bihar Electricity Regulatory Commission, Bihar Department of Agriculture, Vaishali District Magistrate, Khonargat Power Substation (PSS), IDinsight, Forum of Regulators

[14] Site visit: Raghopur, Vaishali, Bihar (escorted by Vaishali District Magistrate's staff)

example, we wanted to review the map we had been given in the summer with the utility's engineers in order to confirm the locations of the 11 kV lines, the locations of the distribution transformers, and the locations of substations so that we could digitize the hand-drawn map to the best of our abilities. We also wanted to know more about their approach to grid planning, the present performance of the grid, and their expectations for the future. We spent one week in Patna (the capital of Bihar) in order to increase our chances of having time to gather this data and we were successful in many ways.

After a preliminary meeting with the Managing Director (MD) of the North Bihar Power Distribution Company Ltd. (NBPDCL), many staff members were empowered to share data (in both hard and soft copy) with us. Though many were skeptical of our proposal that solar-powered microgrids might be viable in Vaishali District and useful to the utility, the staff was very helpful. We traveled to the capital of Vaishali District, a city called Hajipur, to meet with the NBPDCL's Executive Engineer for the district. He shared a lot of data about the reliability of the network, maintenance practices, and hourly electricity demand from a variety of distribution feeders. During our meeting with the CMD we successfully secured his continued support for the project and our data needs, though he echoed his subordinate's concerns about the idea of using solar on a large scale in Vaishali. He believed that most people might be opposed to solar because they perceive it to be less desirable than electricity from the grid.

On this trip we also attended one of the regular meetings (the 45th) of the Forum of Regulators, which includes CERC and representatives at the highest level from all the SERCs. There we presented our approach to planning and explained how the model could be used to evaluate technology options under the different off-grid regulatory schemes that CERC and the Forum itself had proposed, in the hopes of inspiring the SERCs to adopt off-grid regulation in their states.

Overall, we got a better sense of some of the potential political ramifications of our model. Almost everyone we interacted with at the Bihar Energy Department, the Bihar State Power Holding Company Ltd., and the North Bihar Power Distribution Company Ltd. was insistent that the preliminary results of our model were interesting, but that off-grid electrification was mostly unnecessary in Vaishali, except in one very specialized area, because the grid would be extended to nearly all villages within the next two years. These reactions, coupled with the claims that solar-powered systems may be undesirable in the district, are claims that we could not ground truth since Bihar has a track record of poor electricity access and we did not interview rural consumers about their attitudes towards solar. That said, there are undoubtedly elements of truth in these statements, but there could also be a strong motivation for these officials to insist that grid extensions will happen quickly because they have promised this to constituents [5]. Such comments are at least indicative of a notable degree of skepticism towards off-grid electrification.

3.2.2 DEVELOPING AN OFF-GRID ELECTRIFICATION DECISION TOOL: A PROCESS DESCRIPTION

The conception of what a rural electrification planning “tool” should be has evolved drastically since the project began. What has remained constant, though, is a tension between the aspiration to automate electrification planning to more rapidly address the scale of the problem and the necessity of addressing the detailed spatial dynamics that make automation challenging. A core assumption of this work, validated by multiple meetings with stakeholders (described above), is that the socioeconomic, political, regulatory, and other local variables are critical to any electrification plan that might one day be implemented. We have held this assumption paramount despite the fact that these variables are difficult to model in the technoeconomic optimization model we ultimately developed.

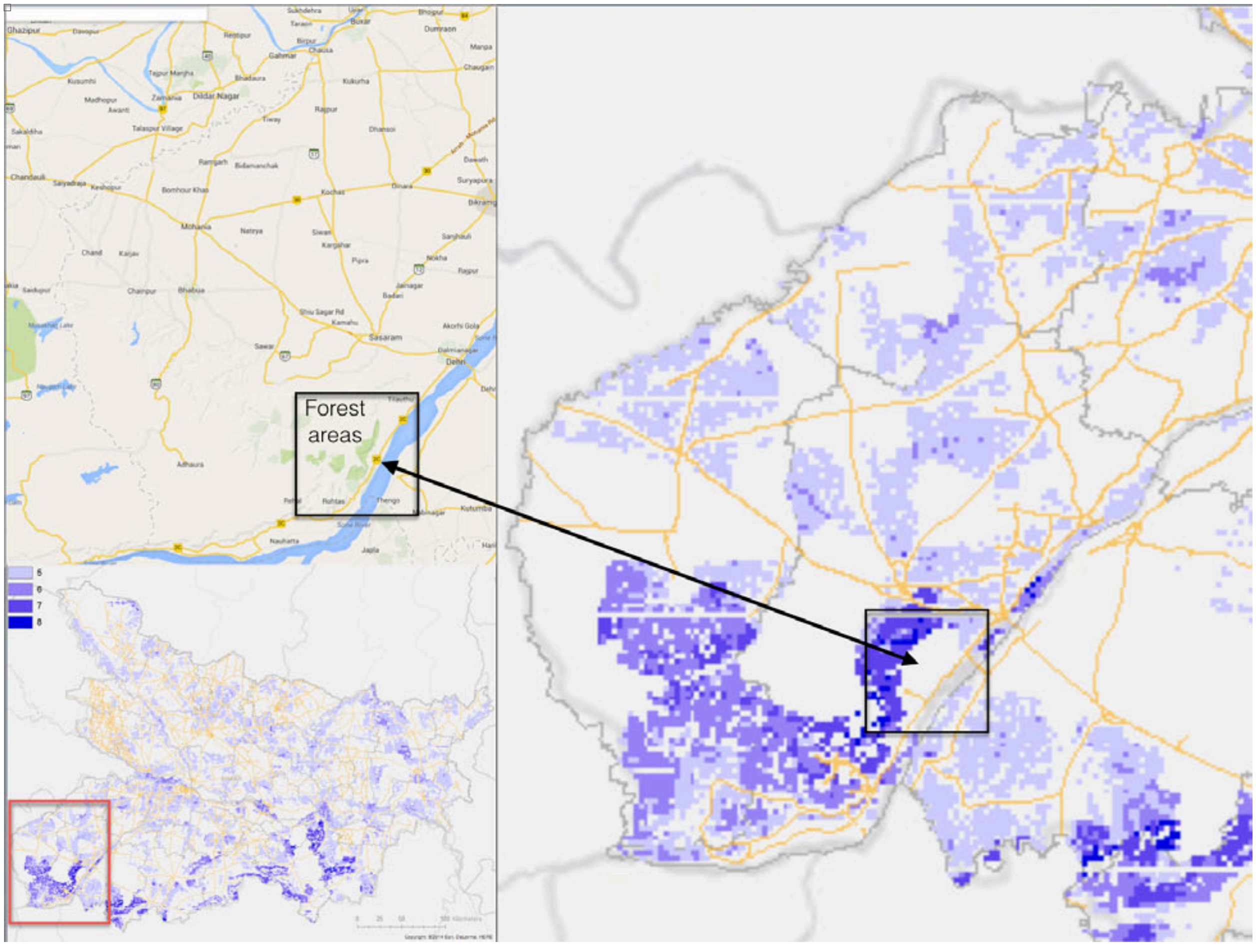
Still, as a team, we have acknowledged to ourselves from the outset that factors that cannot be easily quantified represent the biggest obstacle to developing an approach to rural electrification planning on a large scale. Thus, the proposed software tool is just one part of the ultimate “tool” or planning methodology discussed in this thesis, which also describes a means for integrating computer-aided planning with other means of understanding electrification technology decisions in order to create recommendations that are far more tuned to the context in which they may be implemented.

The next section will explain in greater detail the evolution of our approach to the technoeconomic and qualitative components of this planning methodology, in order to illuminate the logic that has developed in the process.

3.2.2.A EVOLUTION OF THE LOGIC FOR A RURAL ELECTRIFICATION PLANNING TOOL: THE LIMITS OF A GIS-BASED APPROACH

The initial goal for this thesis was to figure out where, in space, the people who lack access to electricity are and what their electricity needs might be. Given that these questions have spatial dimensions, the first approach was to develop a geographic information systems (GIS)-based tool to illuminate a process by which we might answer these questions. The logic was to bring together multiple layers of large scale datasets about India, like the Census of India, the National Sample Survey, solar irradiation in India, etc., to develop a complex suitability analysis that could help make technology decisions by highlighting locations that are suitable to a particular electrification mode. These decisions would hinge on the presence of favorable environmental, infrastructural, and social conditions, such as distance from the grid, access to social and financial services, slope of the terrain, and availability of energy resources. I created a version of this model for a class project in Spring 2014. An example of the results can be seen in Figure 3.2, in which the dark purple areas are most suitable for microgrids.

FIGURE 3.2 Example of microgrid site identification with suitability analysis (analysis by author)



The concept of a GIS-based electrification planning tool is not novel. As described in Chapter 2, several spatial modeling tools have been designed for application in developing countries. These models generally attempt to assess least-cost technology options with highly aggregated data about where people are (population density), their ability to pay (poverty indices), and the price of fuels like diesel and kerosene along with any information about the existing grid in order to estimate the costs in context of different technology decisions. In general, though, lack of available, geocoded data means the accuracy of the cost estimate is extremely hard to determine since cost drivers can be hidden in the details of a particular location. As a result, cost comparisons are typically based on the difference in LCOE instead of the differences in overall cost of two different types of electrification plans for a given area.

In reviewing the existing planning tools, not only was it unclear how to propose something drastically more useful with a fundamentally similar approach, but also other weaknesses of attempting to develop a high-level tool emerged. For example, how reliable is a cost estimate if there is no way to model the amount of equipment required for different technology decisions in a given region? Or, for factors that cannot easily be reduced to a single cost number, how is it possible to weight such factors in a way that is not arbitrary? Ultimately, it became difficult to imagine a situation in which the level of detail was not a barrier to making effective cost comparisons as well as to accounting for qualitative factors, like socio-economic and political dynamics.

3.2.2.B FINDING THE MISSING LINK: HOUSEHOLD IDENTIFICATION FROM SATELLITE IMAGERY

With the benefit of financial support from the Tata Trusts, we focused on developing a tool that could overcome two limitations: a) the level of detail at which it is possible to make cost comparisons between technology decisions for individual households and b) the ability to account for non-technoeconomic factors. On the first limitation, we had an important breakthrough that marked the complete shift away from using GIS and purely spatial methods to model electrification decisions: we discovered that we could determine the locations of buildings in India.

At first blush, particularly to those used to working in the developed world, this may not seem like such an important discovery. But to those focused on planning in developing world contexts where many have no formal address or Google Street View has not ventured, it can be extremely challenging to know precisely where the people are who most need service. In locations where governments do not collect or make available the building locations, tax assessor records, or other types of documents that contain the spatial locations of buildings, the best way to see where buildings are is to look at satellite imagery. On a small scale, it is relatively easy to georeference a satellite image of a small area and manually identify all the houses, but on a larger scale, this would require automation to be feasible.

A PhD student and fellow in the Tata Center for Technology and Design was part of a group of students who began developing a very early stage algorithm that could detect buildings in satellite imagery and extract the shape and coordinates of the buildings. This research opened up the possibility of collecting large amounts of data on individual household locations and modeling electrification decisions at the household level, instead of at higher levels of settlement aggregation (e.g., hamlet, village, etc.). This capability represented the opportunity to propose a novel (as far as we knew at the time), automated approach to large-scale electrification planning in developing countries, since the existing regional planning tools were generally designed to make decisions without this information or the benefit of automation.

With the knowledge that object extraction from satellite imagery was possible and since our colleague had other goals for his work, my research team decided it was important to develop our own version of an object extraction algorithm. Dr. Claudio Vergara, a post-doctoral associate on our team, and two other researchers from IIT-Comillas and Universidad Politécnica de Madrid have partnered to work on this algorithm for our group. Although the development of this building extraction algorithm has proceeded rapidly, there are important limitations. First, there is an important trade off between accuracy and cost. An algorithm could use many different methods in order to discern an object in an image from its surroundings, but the accuracy of any approach is at least partially related to the resolution of the image being analyzed. Low-resolution imagery is freely available through Google Earth, however, even to the naked eye it can be extremely difficult to differentiate buildings from their surroundings, especially thatched huts and other structures common in rural India. On the other hand, high resolution could enable a higher degree of accuracy, but it can be extremely, if not prohibitively expensive. Currently, the cost of high quality satellite imagery is probably one of the most important barriers to the widespread diffusion of this type of technique in planning, though costs may drop in the future.

The power of this type of approach is also limited by the ability to train an algorithm to detect variations in construction materials. At a basic level, the algorithm uses color differentiation to detect differences in the image that might indicate a house as opposed to, say, a field. In a region where all buildings are constructed somewhat uniformly from similar materials, the problem is simpler, but in areas where buildings may take various forms and the materials can vary substantially, it is much more difficult to train the algorithm to identify buildings accurately. In some situations, it is possible that the algorithm will misidentify something as a building that is actually a field or a latrine (false positive) or that it will not identify a building where one actually exists (false negative).

Both of these limitations present significant obstacles to accuracy. Since the output of the algorithm will be used as input to another model, these limitations have important implications for the manner in which the resulting dataset of identified buildings is used.

RURAL ELECTRIFICATION MODEL (REM)

The possibility of obtaining the locations of rural buildings inspired a second transformational idea that finalized the decision to abandon a GIS-only approach to modeling: we could use and modify an existing electrification planning tool initially designed to plan distribution networks and remunerate Spanish distribution companies (and later used in numerous studies in several countries) for a developing country context. The previously existing model, developed by researchers at IIT-Comillas in Spain, is called the Reference Network Model (RNM). RNM takes in a utility's data about the location of all buildings in a region and their demand profiles, then designs the minimum-cost network or extension to the existing network that also meets given quality-of-service specifications, and uses a user-provided catalog of equipment to build the network. RNM gives the cost of the required reinforcements and the total network cost and estimated performance indices. Since RNM was designed for the developed world, though, it does not have the capability of modeling electrification technologies other than the centralized distribution grid. The idea was to keep the network design component of the original model, but add the capability of electrifying buildings via either microgrids or isolated systems in order to compare the costs of those technology systems. By combining the building-extraction algorithm with a modified version of RNM that could both design expansions to the distribution grid, as well as microgrid systems, we realized we could produce automated and detailed technoeconomic rural electrification plans with more sophisticated cost estimates.

The decision to adopt this approach represented an important shift in the team's conception of a planning tool. The proposed adaptation and extension of RNM has allowed for the development of a far more complex model of the technoeconomic aspects of choosing an optimal electrification mode, however that complexity has come with a trade off. It became necessary to only model variables that described the technical systems or that could be analyzed in terms of financial cost, while all other variables (socioeconomic, political, regulatory, and other relevant factors) either need to be taken into account *a priori* (i.e., influence the scenario being modeled or the technoeconomic variables included) or *ex post* (i.e., influence the interpretation of the results of REM and affect the ultimate recommendations).

This shift illuminated the importance of a much more comprehensive methodology in which a technoeconomic model that can estimate the costs associated with a set of electrification decisions is a component in a broader analysis.

3.3 REFERENCE ELECTRIFICATION MODEL (REM): A TECHNOECONOMIC MODELING SOFTWARE FOR RURAL ELECTRIFICATION PLANNING

3.3.1 HOUSEHOLD IDENTIFICATION

The building identification algorithm is still a work in progress. Currently, it operates on free RGB satellite images from Google Earth and uses color differentials to distinguish buildings from the landscape. Work on the algorithm is focused on improving its accuracy relative to human ability to identify buildings in satellite imagery.

3.3.2 REM

The Reference Electrification Model (REM) is a software tool intended to determine the optimal least technical cost electrification solutions to expand access to electricity in a region. For example, a planner could want to know where, in a district, it is cheapest to use solar-powered microgrids to distribute electricity to large clusters of people. REM could then be used to determine where there are settlements in areas with good solar resources and a large number of people who could more cheaply get electricity from a microgrid than from the centralized grid or individual solar home systems. Another planner or entrepreneur could be just as curious about finding areas where it is cheapest to extend the centralized grid or areas where there are isolated homes that might be ideal individual home system customers.

REM's primary objective function is to choose the minimum technical cost method of providing electricity to every unelectrified household in the study area. Aside from the straightforward costs of equipment, the primary determinant of the cost of each system is distance: distance between buildings or distance from existing grid infrastructure. Before explaining REM's decision making process in more detail, it is critical to note that this objective function assumes that the objective of a planner or entrepreneur is a least technical cost plan. This is an important assumption, since it does not ensure that every household is connected to an electricity source that is able to supply a prescribed level of consumption with some specified reliability level (i.e., quality of service), without specifying constraints on reliability or assessing a cost penalty for energy not served.[15] This objective function may be more applicable to some users than others. For example, a government planner may want to maximize the number of people connected to the grid. Under this scenario, cost may very well be a constraint, but it would not be the primary objective. An entrepreneur might also not want to minimize cost if he or she thinks that cost is not the primary driver behind consumer preferences. In other words, the underlying logic of REM must be taken into consideration in different contexts and its results must be interpreted based on the priorities of the planner using the tool.

This section will describe the input data required for REM to make electrification decisions, the process by which it determines the optimal electrification mode, and the manner in which results are output.

3.3.2.A INPUT DATA

Inputs to REM can be organized into two categories: regional inputs and individual inputs. Regional inputs are data about the region that apply to all or large clusters of buildings or demand points (e.g., houses, schools, etc.) in the region. Individual inputs are data that are specific to each building or demand point.

3.3.2.A.I REGIONAL INPUTS

LOCATION OF BUILDINGS

In order to develop a detailed system design, it is necessary to know the latitude and longitude of all buildings in the study area. This is the most basic input to the model and this level of specificity is critical for the realistic calculation of technical feasibility, as well as for cost estimation.

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[15] The present version of REM uses the cost of non-served energy as an additional planning cost, instead of reliability targets.

EXISTING ELECTRICITY DISTRIBUTION GRID

The location of the existing distribution feeders and transformers must be obtained for the study area. In the absence of this data, which can be challenging to obtain, it is possible to run the model assuming that no existing distribution grid exists (greenfield mode) or to use GIS to create a proxy distribution system that may approximate what actually exists. Another limitation of modeling the existing grid is that, in general, it changes frequently. A utility may have plans to expand the system or parts of the infrastructure may be destroyed by natural disasters, so it can be difficult to ensure that existing grid data is up to date (unless the distribution utility keeps a complete GIS record of its facilities, which is not the case in the areas of interest for this thesis).

ADMINISTRATIVE OR OTHER CONTEXT-RELEVANT BOUNDARIES

Buildings should be grouped by the most relevant administrative or context-relevant boundary available. This information can be important both for processing a large dataset by analyzing it in smaller chunks and/or for ensuring that the results are produced subject to administrative or other organizing constraints. For example, breaking the analysis of a district into its sub-districts can ensure that a single system does not cross over jurisdictional boundaries where political interests, rules, and requirements, as well as citizen preferences may differ.

UNELECTRIFIED HOUSEHOLDS

Amongst all the buildings in a region, it is necessary to determine which buildings are currently connected to the existing grid or are electrified already by other means, and which buildings require electrification. The model does not make determinations about whether existing grid infrastructure is cost effective. Buildings that are classified as electrified may not be considered in the model, which will be the case for the example described in this thesis. Grid extension may require joint consideration of upstream network reinforcements (outside of REM) that are needed for the existing electrified and newly electrified customers.

ENERGY RESOURCES

The availability of different energy resources (e.g., solar irradiation, diesel availability, biomass resources, potential sites for mini-hydro plants) in a given area is necessary in order to determine the suitability of different types of generation. This data must be aggregated at the relevant unit of analysis, whether that is a value for each building, a value for a given area within the study region, or a single value for the entire study region.

COST OF NON-SERVED ENERGY (CNSE)

To compare costs between a grid extension and an off-grid system it is necessary to know the cost, to consumers, of energy that is not served in order to account for the reliability of each system (or unreliability, as the case may be). This concept is actually quite subjective, but is intended to represent the cost (i.e., the loss of utility) incurred by consumers when there is no electricity at a time when they were planning to use it. REM requires two values for CNSE, one for essential load and another for nonessential load. The CNSE value for essential load should be higher than the CNSE value for nonessential load in order to represent the greater cost (equivalently, loss of utility) to the consumer for not meeting the most valuable demand. CNSE is also needed to size the generation source in a microgrid so that a theoretically optimal trade-off is reached between cost of supply and quality of service. There could be multiple ways of arriving at a value for CNSE, but one way of calculating CNSE value is to determine the cost of an alternative energy solution (e.g., kerosene) that might be used when electricity is not available and adopt that value as a proxy, possibly adjusted by some arbitrary factor to account for the inconvenience of procuring the alternative energy source or to account for the type of demand not served (i.e., essential or non-essential).

GENERATION EQUIPMENT CATALOG

A catalog of generating equipment to be considered, its specifications, and the cost of each piece of equipment is necessary in order to create a detailed system design and effectively compare costs between different systems and designs. Generation equipment includes components like solar panels, batteries, diesel generators, inverters, and other power electronics. Although it is probably impossible to collect an exhaustive list of all possible generation components in use throughout a region (e.g., there could be several models of solar PV panels), that is not a problem as long as there is a representative specification for each type of equipment that should be considered.[16]

NETWORK TECHNICAL REQUIREMENTS AND EQUIPMENT CATALOG

This data set includes typical load voltage, generator voltage, network lifetime, reliability targets, and cost of network losses experienced in the region being studied or used in the Reference Network Model catalog. The catalog also contains equipment specifications, such as the technical parameters, costs, and failure rates of conductors, transformers, and substations.[17]

RELIABILITY OF THE EXISTING GRID

In order to provide a more informed comparison between grid extension and off-grid systems it is necessary to know the reliability of the supply of electricity from the existing grid (i.e., the number of hours per year the grid is expected to be supplying electricity and when). This value can be expressed as one overall percentage or broken up into a percentage for off-peak reliability and peak reliability in order to reflect, for instance, the fact that in rural India outages are more likely to occur during peak demand hours. Reliability is also important to the concept of CNSE.

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[16] REM can be used to design optimally just one microgrid for a specific village, for instance. In that case the level of accuracy in the catalog of equipment has to reflect a satisfactory level of reality.

[17] For more information see Ellman, Douglas. 2015. "The Reference Electrification Model: a Computer Model for Planning Rural Electricity Access." Master's Thesis, MIT.

PRICE OF DIESEL

It is common throughout India to use diesel generator sets as a primary or supplementary source of electricity. Some microgrids also use a mix of solar and diesel generation in order to meet demand in areas where solar irradiation is more volatile. For this reason, it is necessary to model the price of diesel for generation. Estimating the cost of diesel is not so simple, since the official cost per liter does not take into account several associated costs, such as the cost of transporting the diesel to a rural marketplace, the cost of traveling to purchase diesel, as well as the cost of storing and protecting such a desirable product.

DISCOUNT RATE

A discount rate is necessary to determine the net present value of a given project to the owner of the assets (e.g., the project developer). Depending on the planner running the model, the discount rate could be adjusted to reflect the assessed risk of power projects in a region, estimated time needed to recover the up-front investment, and several other factors.

3.3.2.A.II INDIVIDUAL INPUTS

CLASSIFICATION OF BUILDINGS

If data are available, buildings can be categorized by customer type (e.g., house, school, hospital, etc.), but this is not strictly necessary for the model to produce preliminary results. The added specification of customer types makes it possible to specify different electricity demand profiles, since households typically have different electricity demand profiles than public buildings, for example.

CHARACTERIZATION OF DEMAND

Following the classification of buildings, the demand for each building needs to be characterized. To design electrification solutions for unelectrified buildings it is necessary to estimate how much electricity each building might consume if it had access to electricity. Since the model will try to meet specified demand at the lowest technoeconomic cost, more detail about demand at each individual load point is likely to have an influence on the results. Characterizing demand requires data about either a) the hourly demand profile of similar buildings in a similar context (which includes affordability, geographical proximity, type of economic activity, type of house, etc.) that do have access to electricity, b) constructing an hourly demand profile from a reasonable inference about what types of appliances the occupants of the building might use and how often, or c) setting a demand target. For the second method, characterizing demand may also require weather data and the timing of sunrise and sunset in the region in order to construct a more representative hourly demand profile. Once the demand profile is constructed, it must be classified into one of two tiers: 1) essential load (e.g., lighting) or 2) nonessential load (e.g., television).

3.3.2.B DATA PROCESSING AND COST COMPARISON

REM requires several steps of data analysis in order to produce least-cost electrification decisions and cost estimates. The steps can be organized into the following categories: determination of the analysis region, pre-clustering steps, clustering steps, and design and comparison of options. This section will briefly explain those steps and mention other issues that could be addressed by the model, but that are not implemented yet.[18]

DETERMINATION OF ANALYSIS REGIONS

The first step involves organizing the units of analysis. Depending on the size of the region to be studied, it may be necessary to enhance computational efficiency by breaking the buildings in the study area into smaller groups or "analysis regions," which can be processed more quickly. These analysis regions may be informed by administrative boundaries, if relevant, or by some other means that fits the goal of the analysis.

PLANNING TIME HORIZON

REM is a static model, so it only plans for a specified time horizon and produces results that will meet demand in the final year of that time range. It cannot produce results showing changes over time. Therefore, a planning time horizon needs to be specified, along with a demand growth rate and population growth rate.

PRE-CLUSTERING STEPS

The next step is to build a look-up table of possible microgrid generation designs. This process saves computing time when running the model. First, it is necessary to simulate the generation design ahead of time for a number of microgrids of different sizes (size is specified by the number of customers served) covering a range of expected situations, so that rough cost comparisons can be done prior to the network design step. Demand profiles for a given day for various microgrid sizes are simulated, then, for a sample of potential microgrid sizes, the cost of generation for different generators (e.g., solar panel, diesel generator, etc.) is determined. This value in each simulation is calculated and saved.

CLUSTERING

Next, the buildings within each analysis region must be organized into clusters of buildings that are likely to be supplied by the same electrification mode. This step is done using the MST optimization method, which connects all points in a dataset and clips any branches that do not meet a certain criterion. In this case, the criterion is based on a cost estimate that is a function of the length of the

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[18] This section is based on the master's research of Douglas Ellman, another member of the team. For a more detailed explanation of REM's process and how the process was developed please see Ellman, Douglas. (2015). "The Reference Electrification Model: a Computer Model for Planning Rural Electricity Access." Master's Thesis, MIT.

branch and the potential demand of the building points. Each building in an analysis region is connected to another by a branch and those branches are sorted from short to long. Moving sequentially through the list of branches, the model will estimate the cost of keeping the two buildings connected and the cost of separating the points using the pre-solved generation costs and the network power flow. This first half of the clustering steps organizes the buildings into connected clusters and isolated buildings not connected by any branches.

In the next half of the clustering process, clusters of connected buildings are then evaluated in order to see if it is cheaper to connect the cluster to the centralized grid or to treat it as a microgrid. It is important to note that these cost comparisons are not based on detailed system designs, but based on heuristics determined in the pre-clustering phase and power flow modeling. Thus, the cost estimates are essentially educated best guesses that will be refined at a later step in the process.

DESIGN AND COMPARISON OF OPTIONS

1. Grid extension

   For this step, it is important to specify whether the model should run in greenfield (no existing grid) or brownfield (existing grid) mode. Here we shall assume that the existing grid is known (i.e., has been input) to the model. In brownfield mode, the model locates the nearest 11 kV distribution transformer and estimates the cost of connection to that point. Then based on the reliability of the network and CNSE, it determines the percentage of time that electricity is not supplied and imposes a cost penalty. The model then compares the cost of this connection to the least-cost off-grid system design for the cluster. The cheapest option is selected for the cluster. If the least-cost option is grid connection, that cluster is removed from consideration in the next comparison. If the least-cost option is a microgrid then the cluster is included in the comparison between microgrids and isolated home systems.

2. Microgrid

   For the remaining clusters (i.e., those not connected to the grid), the network design capability enabled by RNM is used to design a microgrid network. Generation is selected by interpolating the pre-solved generation design and cost estimate for the more detailed network. The cost is compared to the cost of electrifying all buildings in the cluster using an isolated home system. If a microgrid is the cheapest option for a cluster then that decision is finalized. If a cluster can be electrified more cheaply using isolated systems, then the buildings in that cluster are considered in the next step.

3. Isolated home system

   Buildings considered in this step are evaluated based on the cost of electrification via an isolated home system or the cost (based on CNSE) of not electrifying the building at all. If an isolated home system is the final decision, the model determines the least-cost source of energy generation, which is based on a cost comparison between the pre-solved costs of generation determined in the pre-clustering step.

3.3.2.C REM OUTPUT AND INTERPRETING THE RESULTS

At the conclusion of the processing steps described above, REM will output results visible in two formats. First, it will output information about each cluster or isolated building, including the type of system assigned to it, the estimated cost of the system, and the type of generation. Second, it will output files that can be visualized using GIS software so that a full map of the study area can be evaluated (see Chapter 4).

DESCRIPTION OF A “BASELINE” SCENARIO

In order to run REM, it is necessary to organize the inputs mentioned above (and additional inputs, as the case may be) to specify a “Baseline.” Here, the term “Baseline” will denote the reference case in a given REM analysis. In most situations, the Baseline will be the most accurate representation of current reality in a given study area. This allows for sensitivity and/or scenario analyses that can illuminate how different assumptions or priorities impact REM’s electrification decisions.

INTERPRETING REM RESULTS

Interpreting the results of REM requires three considerations: 1) contextual variables that were not included as inputs to the model (e.g., relevant, non-administrative boundaries), 2) limitations to the data used as inputs to the model, since they may not accurately represent reality (e.g., assumptions about demand profiles in the absence of information about how much electricity an unelectrified household would consume if it had electricity), and 3) consideration of future changes in the study area (e.g., grid extensions and upgrades, migration, demand growth, etc.), since REM can currently only model static circumstances.

In order to address the latter two considerations, it is necessary to conduct sensitivity analyses for a given study area. The first consideration is a much larger limitation and will be addressed in the next section of the methodology.

SENSITIVITY/SCENARIO ANALYSIS

REM allows a planner to ask a wide range of planning questions and study the various possible outcomes. Sensitivity analyses can be used to see how sensitive REM recommendations are to small or large changes in assumptions. By adjusting input values or constructing test scenarios for REM it is possible to compare different planning priorities or simulate the results for certain expectations about the future. As will be discussed in more detail in the next section, there are variables considered in the model that are similarly influenced by socioeconomic, political, or regulatory factors for which sensitivity and/or scenario analyses might render useful insight.

3.4 IDENTIFYING SOCIOECONOMIC, POLITICAL, AND REGULATORY FACTORS IN THE PLANNING PROCESS

As mentioned earlier, in many conversations with stakeholders, we heard a common refrain: electrification is not a technical problem, it's a human problem [12, 14] and that "non-technical details often make the difference." [46] This component of the planning methodology directly addresses that claim by seeking to understand how issues that arise between stakeholders in this space influence electrification projects.

Table 3.1 represents an extensive, but not exhaustive, list of factors that influence off-grid electrification and that has been derived from personal conversations with stakeholders (see Appendix A for the list of stakeholders), literature review (Prayas 2012, Holland et al 2001, Kumar et al 2009), and my team's observations from visiting villages connected to off-grid systems during trips to India (see section 3.2). It is important to point out that while I initially categorized factors under four headings, these groupings are not as clear cut in reality and several factors may be reasonably placed in several categories.

TABLE 3.1 Identified factors that influence electrification planning in India

	Factor	Description	REM-compatible
Technoeconomic	Scalability	Ability to achieve economies of scale in the operation of generation and transmission assets, maintenance, and revenue collection would improve the likelihood that solution can serve many people.	Yes
	Grid compatibility	A microgrid designed to connect with the centralized grid minimizes risk for off-grid investors because grid extension to the site would not render the asset a sunk investment.	Yes
	Distance to the nearest distribution transformer	Distance between a load point and a distribution transformer, which steps down or steps up voltage, requires longer, more expensive wire to connect the building and mitigate losses.	Yes
	Customizeability of the off-grid system design	Ability to modify components of an off-grid system to better suit the needs of the end user.	Yes
	Presence of an anchor load	For microgrids, proximity of commercial, industrial, or public institution that has relatively constant demand helps flatten out load in a community and enables the design of a larger system.	Yes
	Reliability of the grid	The number of hours per day/month/year that the centralized grid is able to provide consumers with electricity	Yes
	Distance between households	The space between households helps determine and design a networked system like a grid extension or microgrid.	Yes
	Energy resources available	The availability of solar irradiation, diesel fuel, hydrological sources, biomass stock, etc.	Yes
	Load profile	The consumption pattern of electricity consumers (e.g., residential, commercial, agricultural, etc.).	Yes*
Socioeconomic	Business model	The adaptability of the business model to the needs or abilities of the consumer base.	No
	Ability to pay for electricity	The amount of available daily/weekly/monthly income individuals have to spend on electricity services.	No
	Ability/willingness to pay for more electricity in the future	An individual's capability or aspiration to use more electricity and/or purchase more electricity-consuming appliances.	No
	Electricity theft	The unpaid use of electricity either by tampering with a system, hooking a wire onto an existing distribution line, etc.	No
	Livelihood uses	Agricultural machinery, light manufacturing, etc. that requires electricity and helps the user generate more income.	No
	Access to financing/financial institutions	Proximity of a bank and/or ability to receive a line of credit from the bank in order to finance a purchase	No
	Cost of non-served energy	An abstract value that represents how much "cost" an electricity consumer bears when there is a power outage.	Yes
	Educational attainment	Level of education attained by an individual	No
	Literacy	Ability to read written language.	No
	Presence of informal market for kerosene and diesel	Kerosene is rationed and subsidized for many consumers. Informal market have emerged, built on kerosene theft from the Public Distribution System and resale.	Yes
	Convenience of procuring and storing kerosene or diesel fuel	Amount of time and/or money required of an individual to obtain kerosene from both the formal or informal market.	No
Sociotechnical	Expectation that grid connection is imminent	The individual/community perception that the grid will soon be extended to the village can influence receptivity to off-grid electrification systems.	No
	Perception that grid is unreliable	The individual/community perception that the grid does not provide reliable electricity service can influence receptivity to off-grid solutions.	No
	Perception of solar-powered electricity as second-rate	The perception that solar-powered electrification systems do not provide the same quality of electricity as the centralized grid or other electrification system can influence the receptivity of customers to many off-grid systems.	No
	Perception that electric light is superior to light from kerosene	Consumer preference for electric lighting over the light produced from kerosene can facilitate better business prospects for off-grid entrepreneurs.	No
	Expected demand growth	Expectations about amount and rate of electricity demand growth after first connection influences the size and design of an off-grid system.	Yes**
Social	Caste differences	Caste differences between groups of individual living in proximity can create conflicts when implementing off-grid projects	No
	Religious differences	Religious differences between groups of individual living in proximity can create conflicts when implementing off-grid projects.	No
	Engagement with a community development institution	An engaged community development institution can make it easier to implement off-grid electrification solutions because the institution can facilitate interactions between customers and an outside project developer.	No
	Gender of decision-making adult	Gender of the decision-making adult may influence how a household approaches the decision to purchase off-grid electricity.	No
Political	Political promises of free electricity	Politicians who promise citizens free electricity during political campaigns set the unrealistic expectation that electricity is free.	No
	Policial influence over grid extension plans	The ability of some politicians to dictate where utilities extend the grid based on personal or political objectives.	No
	Election cycle	The speed at which politicians turn over due to short election cycles can result in rapidly shifting attitudes towards electrification efforts	No
	Administrative boundaries	Different administrative regions can have different laws or policies that affect the implementation of policy or off-grid businesses.	Yes
	Agenda for elected officials	The current political agenda affects dictates whether effort is focused on electrification programs or funding universal access.	No
Regulatory	Off-grid system standards	Technical standards for the manufacture and performance of off-grid systems can influence the quality and longevity of the off-grid system.	Yes
	Existence of off-grid regulation	The existence or absence of off-grid electrification regulation can affect how the market for off-grid electrification systems operates.	Yes
	Standards for grid compatibility (grid code)	Technical standards that allow a microgrid and the centralized grid to interoperate can reduce the risk of grid extension to off-grid investments, but increase the the specificity of technical standards governing off-grid systems.	Yes
	Subsidies for off-grid electrification	Government subsidies for off-grid electrification can facilitate cost-recovery for off-grid businesses or create challenges if subsidies are difficult for individuals or businesses to access due to administrative delays.	No
	Local tariff assessed to rural customers	The tariff that individuals pay for electricity from the grid or an off-grid system can influence tariff expectations of unelectrified individuals.	No

* With the current version of REM, we only model an estimated load profile for residential buildings.

** Expected demand growth can be modeled using REM, but only via estimation or prediction since REM is a static model.

3.4.1 ELICITING THE PLANNERS' PERSPECTIVE

Through numerous conversations with the stakeholders we met in India (see Appendix A) who work on rural electrification, it has become clear that planners, such as state and local government officials, electric utility employees, and private project developers, face substantial obstacles in the development of off-grid electrification plans that are financially sustainable and meet the needs of rural people. These obstacles arise due to incomplete data, regional, cultural, demographic, and socioeconomic differences, highly politicized ideas about electricity, and many other root problems. In some cases, factors arise out of a confluence of issues that are found in one specific area. Since off-grid electrification projects are hyper-local, they are particularly sensitive to these complex spatial variations, making it difficult to design solutions that are scalable.

Prior to determining which factors to focus on and how to better categorize those factors, it was first necessary to answer a broader question: "Which non-technical issues typically influence successful rural electrification and under what circumstances?" With this question in mind, we first determined that it was important to remove all technoeconomic factors that were easily accounted for using REM (see Table 3.1). In reviewing the remaining factors we amassed, I became curious about which non-technical factors planners really thought were most important to achieving positive outcomes when planning off-grid projects and why. It seemed reasonable to expect that any given planner trying to implement the approach to planning described in this thesis might have a slightly different set of priorities than the next, but given that so much attention is focused on technoeconomic factors it seemed worth narrowing down the list to provide additional insight on what a select group of planners might agree are critical non-technical factors.

The next section describes the process of gathering more experiential insight on the nature of those non-technical factors and the approach to further narrowing the list of factors in Table 3.1 based on planners' input.

3.4.1.A SEMI-STRUCTURED INTERVIEW

Semi-structured interviews with stakeholders (see Appendix A) were used to develop deeper understanding of a shorter list of issues that impact rural electrification because they are a useful means of soliciting varying perspectives from stakeholders on a specific set of factors (Singleton, Jr. and Straits 2010). These interviews were not intended to be comparative or explanatory in a statistical sense, but instead to enable a more robust qualitative description that includes a variety of individual insights.

Interviewee selection was driven by the goal of capturing the viewpoints of a wide range of players representative of the various stakeholder groups engaged in Indian rural electrification that we interacted with on our trips in country. These stakeholder groups include government officials at the national, state, and district level, NGOs, consultants, utilities, and off-grid electrification entrepreneurs. The broad list of stakeholders we engaged (see Appendix A) were identified through professional connections, institutional contacts facilitated by MIT's Tata Center for Technology and Design, and by recommendations from other stakeholders. Initial outreach was predominantly executed through email communication, though in a few cases contact was initiated by a phone call made on the team's behalf. Meetings took place in India at a location chosen by the candidate and were informal. Telephone or video calls were arranged when co-location was impossible.

Semi-structured interviews were then conducted with seven candidates based on my assessment of their roles in the electrification ecosystem. Only six interviews are used in the analysis because one respondent needed to stop the interview short in order to make it to another obligation and further attempts to continue the interview were inconvenient for the interviewee. Though the interviews were informal in the sense that the conversation did not follow a prescribed order, these interviews were structured in the sense that they all focused on the same set of factors and were intended to elicit individual insights. Participants in this second round of interviews were contacted by email and presented with a formal description of this thesis research project and the interview protocol. Participants had the option of anonymity should their opinions be presented in this document. Interviews were recorded and transcribed, then coded according to the smaller list of factors used in the pilot survey described below). Participants were also offered the opportunity to review the document or the specific section where their words were mentioned and some modifications were upon their request. A sample questionnaire is included in Appendix B.

These interviews are not intended to inform experimental analysis, but instead, to offer a glimpse of the range of perspectives on rural electrification that exist in India. That said, with only six respondents, the perspective and ideas shared in the interview and presented here should be interpreted as the experiences of individuals who work in this field, not as a generalization. Despite the small sample size, these views are described here in order to expand knowledge about the obstacles to rural electrification that have and may continue to plague India's national goal of achieving universal access to electricity.

3.4.1.B PILOT SURVEY

As discussed earlier in this thesis, the list of factors that impact the feasibility and efficacy of rural electrification projects is long and complex. Determining which factors are most important or influential is inherently complex, which makes it difficult to narrow the list down to a size that can be meaningfully discussed in the context of a thesis. These considerations include point of view (i.e., some factors will seem more important to planners than customers and vice versa), location of the project, and goal of the project. The semi-structured interview process focused on the planners' perspective, but the list of factors included in that process was still quite long and it did not ask participants to consider the importance of factors in a structured hierarchical manner. This was an intentional decision. Semi-structured interviews were conducted before dissemination of the survey since some participants were involved in both. The goal was to have the more expansive information gained through the interview process inform the survey results, without interviewees feeling as though their survey responses should influence their comments in the interview.

In order to get a sense of the relative importance of different factors to the electrification planning process, survey participants were asked to complete a survey (distributed via Survey Monkey, an online survey design platform) intended to elicit their personal priorities when implementing or studying an electrification plan. Respondents (n = 10) were asked a series of 25 questions organized into three broad categories, "Technology," "Socioeconomic," and "Regulatory." For each question, they were asked to recall previous professional experience creating or implementing an electrification plan and then rank the importance of each of the listed factors on a modified Likert scale ranging from "Irrelevant - 0" to "Critically important – 3."

Survey respondents had the option of indicating their name and affiliation, however for the purposes of the analysis no names or specific affiliation (only general industry membership) is revealed.

To analyze the results, it was necessary to determine a ranking mechanism. This mechanism will be described in more detail in Chapter 4, however it is relevant to note here that the qualitative values on the Likert scale were assigned numerical values to facilitate analysis. In order to avoid awarding points to factors deemed "Irrelevant," that level was assigned a value of "0." The survey instrument is included in Appendix C.

Once the most important factors are identified, those factors are considered for further analysis, which includes the information gathered through the semi-structured interviews as well as the informal conversations documented during each trip to India. The analysis (Chapter 4) of the survey results and interviews is guided by Barney Glaser and Anselm Strauss's grounded theory approach, which "advocates loosely structured research designs that allow theoretical ideas to 'emerge from the field in the course of the study (Miles and Huberman 1994 in Singleton, Jr. and Straits 2010).

3.4.1.C LIMITATIONS OF THE RESEARCH DESIGN

The most important limitation of this component of the methodology is its vulnerability to selection bias. In both the interview component, as well as the pilot survey component, the goal was to engage some of the many stakeholders we had already met in India who represented different types of planners (government officials, NGOs, entrepreneur, etc.) engaged in rural electrification. Though there are few interviewees and survey respondents they do represent several types of planners (see Table 4.2 in the next section). That said, out of the world of stakeholders we could have met with in Vaishali or Bihar, not to mention throughout India, I have not been comprehensive in sample selection.

Still, the presence of selection bias is not necessarily just in the small number of participants, but also in the group of stakeholders I targeted. The Tata Trusts, our funders, and MIT, our home institution, are well-known names worldwide. Since we largely were able to make connections with individuals and companies through the professional contacts of someone from either Tata or MIT, there is unavoidable bias towards a particular type of stakeholder that is connected to this network. There is no way of knowing how planners engaged in rural electrification in India that we did not meet differ or are similar to the stakeholder population we engaged.

These types of bias have consequences for the data produced by this study as well as the generalizability of the results. The analysis in Chapter 4 draws from planners who work throughout India, but are not representative of all planners in India, and as such, should be read as descriptive of the many socioeconomic, sociotechnical, social, cultural, and other factors that impact rural electrification, not explanatory. This research sheds light on the complexity (to co-opt a well-worn pun), but it does not explain it.

3.4.2 UNDERSTANDING CONSUMER DEMAND

The amount of electricity a household will want to use and the time at which they will want to use it is a critical input to REM because it is an important factor to consider when designing generation and storage. But electricity demand is not just a technoeconomic factor, it is also a socioeconomic one. The quantity of electricity a household can consume is determined by the planner or operator of the supply technology, along with the household’s ability to afford the available electricity service and electric appliances. Determining the potential demand of unelectrified households, therefore, is quite challenging for a variety of reasons. For one, individuals may not be able to accurately imagine their electricity needs or their ability to afford electricity services before they have electricity. Or, a planner may decide to serve a pre-set level of demand according to certain budget (or other) constraints regardless of the consumer’s aspirations or needs. Since REM requires that every load point have a demand profile and since we hypothesize that assumptions about that demand profile will have an important influence on the ultimate results of the model, a key component of this methodology is developing an estimated demand profile for all buildings in the study area. That demand profile is based on the best available knowledge about how recently electrified rural villagers in India use electricity, assuming no restrictions on the electricity service available to them (i.e., reflective of electricity consumer aspirations or needs after first gaining electricity access). I will refer to this demand characterization as the “natural demand” profile in order to enable comparison to other types of demand profiles. Other means of representing demand other than the “natural demand” will be discussed in Chapter 4.

3.4.2.A SELECTING A STUDY REGION

Electricity demand varies by location, depending on weather patterns, occupational needs, sleep habits, cooking techniques, and other social factors. As a result, in order to demonstrate this method it was necessary to select a study region for which a demand profile could be reasonably estimated. Through a collaboration with the Bihar Energy Department and State Power Holding Company, we selected Vaishali District in the state of Bihar as the study region. This case study will be described in further detail in Chapter 4, however, it is necessary to know that the following process for determining a "natural demand" for residential buildings was executed with Vaishali in mind, though a similar process could be implemented for another region, as well. It is important to note that REM does not have to be run with this demand. As I suggested in the previous section, demand could also be specified according to a planner's electrification or business objectives.

3.4.2.B GATHERING DEMAND DATA

To develop the "natural demand" profile (i.e., the latent demand we can expect unelectrified households to have once they have electricity), we use a combination of data sources about appliance ownership and electricity consumption to overcome our limited ability to gather data specific to residents of Vaishali district. One source of data was a collaboration with political scientist and Columbia University Associate Professor Johannes Urpelainen (who has been central to this aspect of the research). In addition to sharing the raw data from India's 66th National Sample Survey on monthly consumer expenditure, which also includes data about appliance ownership and electricity consumption for over 100,000 people throughout India, Professor Urpelainen has given us the opportunity to collaborate with him in conducting a randomized control trial to study the economic and social impact of Mera Gao Power microgrid systems on the lives of rural villagers in Barabanki District, Uttar Pradesh. The households allocated to the experimental group were approached by Mera Gao, a microgrid startup company, and offered the opportunity to join with their hamlet in purchasing electricity via a microgrid. In the course of the nearly two-year study, which is ongoing, Professor Urpelainen will conduct four surveys, a baseline survey, summer survey, midline survey, and endline survey to determine the impact of electrification via the microgrid on the experimental communities as compared to the control communities. Our team contributed several questions about appliance ownership and demand use patterns to the midline survey (Appendix D), which was conducted in October 2014. There were 1,578 respondents to the midline survey, from households located in various hamlets throughout the district of Barabanki. The results of the midline survey are important for determining the natural demand, described in the next section, despite the fact that it is based on a study of villagers in a different state.

3.4.2.C DETERMINING THE *NATURAL DEMAND* PROFILE FOR RESIDENTIAL BUILDINGS

1. DETERMINE A BASIC APPLIANCE SET

In order to specify a basic set of appliances that might be used by unelectrified households in Vaishali, we first used data from the National Sample Survey (66th). After selecting only the households surveyed from Bihar, we looked at the appliance ownership patterns of households who used electricity as a primary source of light and were classified as rural. We further focused on households in the lowest 50 percent for monthly consumer expenditure since we assume that the poorest electrified households would be most similar to rural, unelectrified households. We then reviewed the combinations of appliances owned by these people — which include lights, a mobile phone, fan, and television set — and assumed that this set of appliances would be most similar to the set of appliances desired (within reasonable expectations) by currently unelectrified rural households in Bihar.

We vetted these assumptions during the January 2015 trip to Bihar and confirmed that low-income rural villagers in Vaishali tend to prioritize this basic set of appliances [45]. Importantly, we assume this set of appliances in estimating our natural demand profile even though many unelectrified households may not necessarily be able to afford them. This set of appliances also corresponded to the range of appliances owned by villagers surveyed in Barabanki, though not every villager with electricity owned all of these appliances. This decision represents a value judgment that it is better to plan for a level of electricity consumption that we deduce rural people may want once they have electricity rather than to plan for what they can currently afford.

2. DETERMINING THE CONSUMPTION PATTERN

Once the appliance set is specified, it is necessary to estimate the general pattern of usage for each appliance (time of day and time of year, where applicable) as well as the overall electricity demand annually. We use data gathered from the questions our team contributed to the Barabanki midline survey in order to produce these demand profiles as well as hourly demand data from a rural distribution feeder collected at the Khonargat Power Sub-Station in Hajipur, Vaishali. It is important to acknowledge again that the Barabanki data are used, despite the fact that Barabanki District is in a different state than Vaishali District. The difference in context is justified given that Bihar and Uttar Pradesh have two of the worst electrification rates in India (16.4% and 36.8% respectively, as of 2011) and that the villagers participating in Barabanki study are extremely low-income, rural farmers or day laborers, most of whom have received electricity for the first time. Hence, they share key characteristics with rural villagers in Vaishali district (Census of India 2011).

In the Barabanki midline survey we asked participants several questions about what types of appliances they own and what times of day they use those appliances in three seasons: winter, spring, and the rainy (monsoon) season. Using the average pattern of usage for each appliance in the set specified above, in combination with weather data and the time of sunrise and sunset, we construct a residential demand profile that represents those patterns for every hour of the year.

In order to take into account the natural variability in demand within and across households, we use this natural demand profile as a template. Before REM is run for Vaishali, we develop a customized demand profile for each building in the dataset by assigning a probability that any individual household has a given appliance turned on during the time specified in the natural demand profile. We then simulate a year of electricity consumption for each household by randomly assigning hours of consumption to each appliance, conditioned by data about the time of sunrise and sunset and hourly temperature. In other words, we assume some lights can be on between 5 pm and 7 am and assign a probability that a given household has the lights on at any hour in that interval. Lighting demand is randomly assigned based on that probability as well as the timing of sunrise and sunset (as measured by solar irradiance). That general process is used for each appliance in the set for every unelectrified residential building considered in the study. The resulting profiles can also be used to calculate annual consumption.

The importance of demand to electrification planning and the challenges related to demand estimation are discussed in more detail in Chapter 4.

4. ANALYSIS

4.1 ANALYSIS OF THE CRITICAL SOCIOECONOMIC, REGULATORY, AND POLITICAL FACTORS

The analysis explained in this chapter constitutes a demonstration of the rural electrification planning methodology described in the previous chapter. The analysis is presented in two parts: the qualitative analysis of the critical factors that influence the viability of off-grid electrification projects and the interpretation of the quantitative results of planning scenarios run using REM. The qualitative analysis is intended to reveal some of the key factors considered important to rural electrification, the qualitative relationships between those factors, and the insights derived from different assessments of their importance. The quantitative analysis will demonstrate how scenario analysis can be used to account for non-technoeconomic variables either before running REM (*a priori*) or while interpreting REM results (*ex post*) for Vaishali District in the state of Bihar.

While the scenario analysis is focused on Vaishali district, the qualitative analysis is the result of fieldwork, meetings, and interviews with stakeholders who operate throughout India. If a planner or entrepreneur were to implement this method in reality, it would generally make more sense to determine the key factors by speaking with people working in the specific study region.

First, an analysis of the factors derived from the field notes and interviews is presented (see a complete record of interviews, personal communications, and notes from the field in Appendix A). Second, an analysis of the planning priorities survey and the key factors selected is presented along with insights about how to consider such factors in the planning process. Next, contextual information about Vaishali district and the way in which the electrification situation is modeled in REM will be described. Fourth, the three different residential electricity demand scenarios will be analyzed and the implications of using the results as part of a planning exercise will be discussed.

4.1.1 DISTILLING THE FACTORS: EXPLORING KEY FACTORS THROUGH QUALITATIVE METHODS

The method used here to conduct the qualitative analysis is an iterative one that combines data from both fieldwork and semi-structured interviews as well as survey results to determine what sorts of non-technical factors planners believe are linked with more successful, effective off-grid projects that achieve either private or public sector goals. The final result is a more focused explication of seven factors that influence off-grid electrification planning, which are difficult or impossible to account for using REM. The results highlight the importance of eliciting consumer input and determining consumer needs throughout the planning and implementation process.

A CATALOGUE OF FACTORS

Determining and categorizing the range of factors that emerged over the course of two years of fieldwork was an iterative process of gathering insight about a factor and repeatedly vetting the existence of that factor with other stakeholders. Through this process a list of 39 factors organized into six categories — technoeconomic, political, regulatory, social, socioeconomic, and sociotechnical — emerged. Some of the factors span more than one category and some have different implications depending on whether the issues were described by someone on the supply side, like a planner or project developer, versus someone on the demand side, i.e., an electricity consumer. Table 3.1 (Chapter 3) contains a description of each category and factor.

From this list, the next iteration was to determine which factors could be accounted for quantitatively or spatially within REM (even if it has not yet been implemented in the model) and which factors could not. The intention was to vet the latter set of factors in the field on the team's fourth trip to India in order to determine a set of factors to explore further through semi-structured interviews and the planning priorities survey instrument.

After the fourth trip to India, I narrowed the list down to 25 factors (Table 4.1) that, according to my assessment at the time, could not obviously be modeled by REM, but that stakeholders had confirmed were critical to positive off-grid electrification projects. With this list of factors in mind, a semi-structured interview instrument (Appendix B) and a survey instrument (Appendix C) were developed to gather more focused insights on these factors. The six semi-structured interviews and the pilot survey were intended to complement each other, with the first providing deep insight and context and the latter providing a mechanism for ranking or weighting the factors relative to each other to get a sense of planners' perceptions of the problem.

TABLE 4.1 Shorter list of factors vetted with stakeholders by the author and teammates in January 2015

	Factor	REM-compatible
Socioeconomic	Business model	No
	Ability to pay for electricity	No
	Ability/willingness to pay for increased electricity demand in the future	No
	Electricity theft	No
	Livelihood uses	No
	Access to financing/financial institutions	No
	Educational attainment	No
	Literacy	No
	Convenience of procuring and storing kerosene or diesel fuel	No
Sociotechnical	Expectation that grid connection is imminent	No
	Perception that grid is unreliable	No
	Perception of solar-powered electricity as second-rate	No
	Perception that electric light is superior to light from kerosene	No
	Expected demand growth	Yes*
Social	Caste differences	No
	Religious differences	No
	Engagement with a community development institution	No
	Gender of decision-making adult	No
Political	Campaigns that promise free electricity	No
	Policial influence over grid extension plans	No
	Election cycle	No
	Administrative boundaries	Yes**
	Agenda for elected officials	No
Regulatory	Existence and availability of government subsidies for off-grid electrification	No
	Local tariff assessed to rural customers	No

* Expected demand growth can be modeled using REM, but only via estimation or prediction.
** Administrative boundaries are an input to REM and used to cluster buildings, however data about difference in governance structure etc. are take into account

The semi-structured interviews touch on five categories of factors outlined in Table 4.1 (above): political, sociotechnical, socioeconomic, regulatory, and social. Each one- to two-hour long interview focused more on some topics than others, depending on the interests and expertise of the interviewee. The interviews were not intended to elicit background information about rural electrification planning since that information had previously been discussed during interactions in the field. The interviews covered the same range of factors as the survey, though not every interviewee ultimately commented on every factor. A list of sample interview questions is included in Appendix B.

The survey instrument asked respondents to review each of 25 factors and decide how important each factor is to achieving positive outcomes for off-grid projects. What follows is a more detailed description of the survey, an analysis of the survey results, and a deeper discussion of the implications of those results in the context of insight from the semi-structured interviews and field notes.

4.1.1.A PILOT SURVEY: PRIORITIES FOR RURAL ELECTRIFICATION PLANNING

The survey asked respondents to review 25 factors that a broad range of stakeholders believed to be influential in the rural electrification planning process and to determine how important each factor was to the achievement of positive outcomes for an off-grid electrification project. They were asked, explicitly, to reflect on their own personal experiences. The intention was to have each respondent recall lessons learned and assess the importance of each individual factor based on that memory. The survey instrument is included in Appendix C. Ultimately, out of 15 planners and entrepreneurs, 10 individuals responded to the survey participation request. While this is a relatively small number of respondents, Table 4.2 shows that the participants represent multiple types of stakeholders in the field of rural electrification and represent the range of individuals engaged in this research effort over the last two years.

TABLE 4.2 Summary of survey participants by industry affiliation

Industry	Number of Respondents
Government	1
Think Tank	2
Non-governmental organization (NGO)	1
Off-Grid System Vendor*	1
Utility	0
Consulting	4
Academic	1

* One participant works for an organization that is both an NGO and an off-grid system vendor

Importantly, three participants did not respond to every factor. For each factor, there was never more than one respondent who opted to skip the factor. Non-responses may be attributable to lack of experience with a given factor combined with lack of certainty that the factor was irrelevant. This interpretation is based on previous conversations with some of the respondents, since five out of ten respondents also participated in the semi-structured interviews. It is also plausible that a respondent experienced confusion about a prompt or accidentally skipped an element, as are several other explanations. I did not follow up with respondents about non-response out of respect for what may have been a personal decision, as well as respect for their time. I mention these possible explanations largely as reasoning for my analytical decisions. Since the goal was to compare the relative importance of the factors (as assessed by the respondents) it was necessary to adjust for the fact that some factors had ten responses, while others had nine.

Under these circumstances I want to reiterate the limitations posed by the small number of responses before moving on. As anyone with even a tiny amount of exposure to statistics will recognize, the small number of responses to a survey that could have feasibly addressed a population of what must be hundreds of stakeholders engaged in rural electrification is problematic for making any sort of statistical inference. As discussed in Chapter 3, neither correlational nor causal inferences were expected to result from the use of this survey instrument. Instead, this survey captures a snapshot of perceptions from a somewhat diverse group of planners, both in terms of industry affiliation and location within India.

The respondents currently work or have worked on off-grid electrification projects in many places throughout India, including the states of Bihar, Karnataka, Orissa (Odisha), and likely several others. Their perceptions are intended to provide some insight into how planners think about the importance of non-technical factors and narrow the range of factors discussed in detail in this thesis.

To analyze the results from the survey it was necessary, first, to convert the qualitative measures of importance (irrelevant, not important, important, critically important) to numbers (0, 1, 2, 3, respectively). While the quantitative difference between "irrelevant" and "not important" is not actually one unit, representing these value judgments quantitatively made it easier to compare the relative importance of each factor. To do this, I calculate three measures: the percentage of respondents who rate a factor "important" or "critically important," the percentage of respondents who rated a factor "critically important," and the standard deviation among the responses to each factor. Standard deviation is used as a means of measuring the degree of consensus on the assessment of the factor. In other words, it answers the question: how much did the respondents agree on the factor's importance?

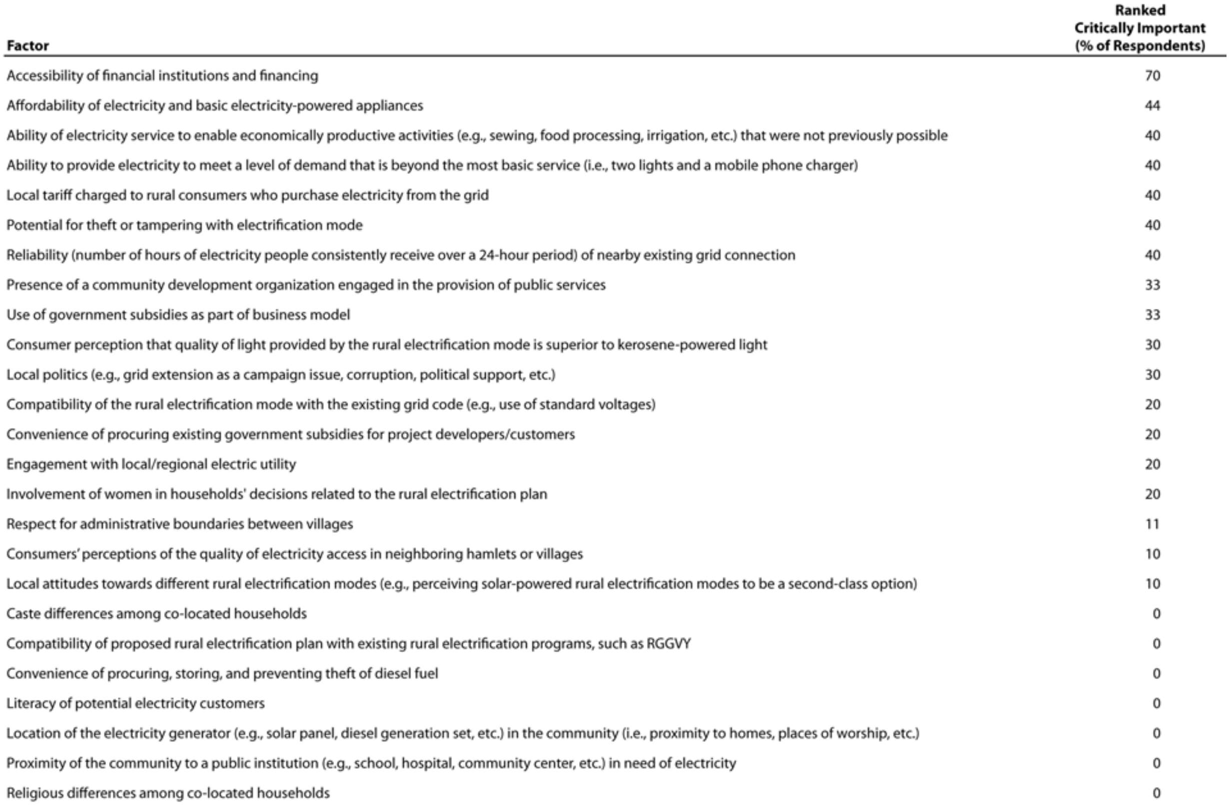
Table 4.3 shows the ranking of the 25 factors according to the percentage of responses in which the rating was "important" or "critically important." Four factors received a score of 1.0, which indicates that all respondents rated the factor as either "important" or "critically important." In these four cases, the difference in standard deviation reflects the fact that they did not all receive the same number of "important" and "critically important" ratings. These four are ordered in Table 4.3 according to the number of times the factor was rated "critically important."

TABLE 4.3 Ranking of factors rated “critically important” or “important”

Factor	Ranked Important or Critically Important (% of Respondents)
Affordability of electricity and basic electricity-powered appliances	100
Presence of a community development organization engaged in the provision of public services	100
Consumers’ perceptions of the quality of electricity access in neighboring hamlets or villages	100
Local attitudes towards different rural electrification modes (e.g., perceiving solar-powered rural electrification modes to be a second-class option)	100
Local tariff charged to rural consumers who purchase electricity from the grid	90
Reliability (number of hours of electricity people consistently receive over a 24-hour period) of nearby existing grid connection	90
Consumer perception that quality of light provided by the rural electrification mode is superior to kerosene-powered light	90
Accessibility of financial institutions and financing	80
Ability of electricity service to enable economically productive activities (e.g., sewing, food processing, irrigation, etc.) that were not previously possible	80
Ability to provide electricity to meet a level of demand that is beyond the most basic service (i.e., two lights and a mobile phone charger)	80
Potential for theft or tampering with electrification mode	80
Local politics (e.g., grid extension as a campaign issue, corruption, political support, etc.)	80
Convenience of procuring existing government subsidies for project developers/customers	80
Involvement of women in households' decisions related to the rural electrification plan	70
Use of government subsidies as part of business model	67
Compatibility of the rural electrification mode with the existing grid code (e.g., use of standard voltages)	60
Engagement with local/regional electric utility	60
Caste differences among co-located households	56
Compatibility of proposed rural electrification plan with existing rural electrification programs, such as RGGVY	56
Proximity of the community to a public institution (e.g., school, hospital, community center, etc.) in need of electricity	56
Literacy of potential electricity customers	50
Religious differences among co-located households	44
Convenience of procuring, storing, and preventing theft of diesel fuel	40
Location of the electricity generator (e.g., solar panel, diesel generation set, etc.) in the community (i.e., proximity to homes, places of worship, etc.)	33
Respect for administrative boundaries between villages	22

I also analyzed how the ranking might differ if it were based only on the percent of responses rates “critically important” without concern for the remaining responses.

TABLE 4.4 Ranking of factors rated “critically important”



Factor	Ranked Critically Important (% of Respondents)
Accessibility of financial institutions and financing	70
Affordability of electricity and basic electricity-powered appliances	44
Ability of electricity service to enable economically productive activities (e.g., sewing, food processing, irrigation, etc.) that were not previously possible	40
Ability to provide electricity to meet a level of demand that is beyond the most basic service (i.e., two lights and a mobile phone charger)	40
Local tariff charged to rural consumers who purchase electricity from the grid	40
Potential for theft or tampering with electrification mode	40
Reliability (number of hours of electricity people consistently receive over a 24-hour period) of nearby existing grid connection	40
Presence of a community development organization engaged in the provision of public services	33
Use of government subsidies as part of business model	33
Consumer perception that quality of light provided by the rural electrification mode is superior to kerosene-powered light	30
Local politics (e.g., grid extension as a campaign issue, corruption, political support, etc.)	30
Compatibility of the rural electrification mode with the existing grid code (e.g., use of standard voltages)	20
Convenience of procuring existing government subsidies for project developers/customers	20
Engagement with local/regional electric utility	20
Involvement of women in households' decisions related to the rural electrification plan	20
Respect for administrative boundaries between villages	11
Consumers’ perceptions of the quality of electricity access in neighboring hamlets or villages	10
Local attitudes towards different rural electrification modes (e.g., perceiving solar-powered rural electrification modes to be a second-class option)	10
Caste differences among co-located households	0
Compatibility of proposed rural electrification plan with existing rural electrification programs, such as RGGVY	0
Convenience of procuring, storing, and preventing theft of diesel fuel	0
Literacy of potential electricity customers	0
Location of the electricity generator (e.g., solar panel, diesel generation set, etc.) in the community (i.e., proximity to homes, places of worship, etc.)	0
Proximity of the community to a public institution (e.g., school, hospital, community center, etc.) in need of electricity	0
Religious differences among co-located households	0

This criterion produces a somewhat different ranking of factors, with the two rankings sharing three factors in common:

1. Affordability of electricity and basic electricity-powered appliances;
2. Local tariff charged to rural consumers who purchase electricity from the grid;
3. Reliability of nearby existing grid connection (number of hours of electricity people consistently receive over a 24-hour period).

The standard deviation amongst the highest scoring factors under this ranking scheme is much higher than in the first ranking scheme, suggesting a higher degree of disagreement amongst the respondents.

Ultimately, I used the factor ranking based on the percent of “important” and “critically important” responses to prioritize factors for this thesis for two reasons. First, the standard deviation of responses or the level of agreement on the importance of each factor was higher under this scheme. Second, and related to the first, since it is difficult to determine what leads someone to differentiate between “important” and “critically important,” but both responses are distinctly positively important relative to the other two possible responses ("not important" and "irrelevant") it made sense to ensure that these factors were considered. In other words, the scale was effectively binary. Under the scheme that only ranked factors based on the percentage of "critically important" responses, several factors that ranked highly in the first scheme fell far in the ranking simply because they had more "important" scores than "critically important" scores, despite the fact that, in general, there was more consistency in the scoring.

Hence, the focus factors were narrowed to those factors in which 90% or more of the ratings were "important" or "critically important."

These factors include:

1. Affordability of electricity and basic electricity-powered appliances
2. Presence of a community development organization engaged in the provision of public services
3. Consumers' perceptions of the quality of electricity access in neighboring hamlets or villages
4. Local attitudes towards different rural electrification modes (e.g., perceiving solar-powered rural electrification modes to be a second-class option)
5. Local tariff charged to rural consumers who purchase electricity from the grid
6. Reliability (number of hours of electricity people consistently receive over a 24-hour period) of nearby existing grid connection
7. Consumer perception that quality of light provided by the rural electrification mode is superior to kerosene-powered light

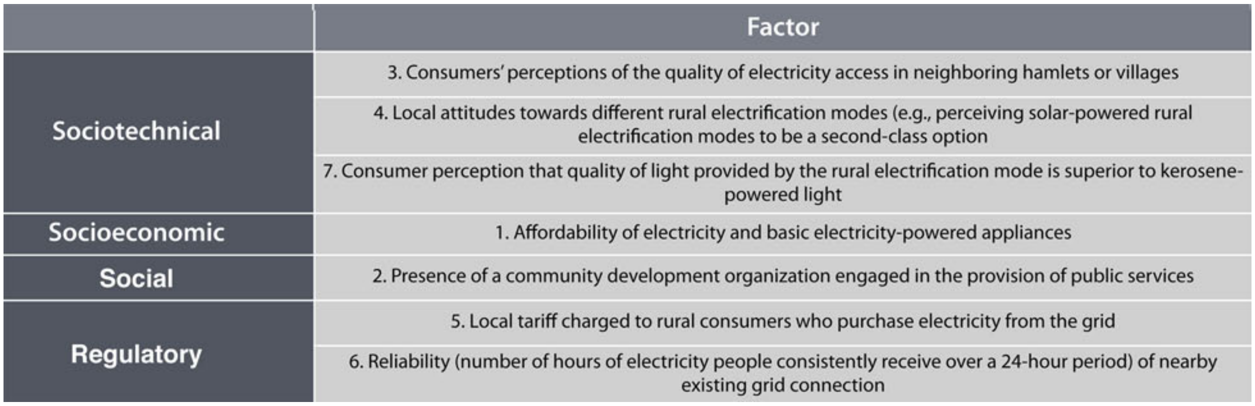
It is important to note another limitation here: in some sense the distinction between the so-called seventh factor and the eighth factor in the ranking is nearly arbitrary and potentially problematic. One could reasonably argue that the top 15 factors should all be considered. In this analysis, the arbitrary nature of the cut-off is particularly distinct since the eighth factor — "accessibility of financial institutions and financing" — received a rating of "critically important" seven times — more than any other factor. Despite this, it apparently dropped in the ranking since only one of the other three respondents rated the factor "important" and two rated it "not important," limiting the overall percentage of responses that were either "important" or "critically important." It follows then that the standard deviation of the responses for this factor was also higher, approximately twenty percentage points, than the standard deviation for the top seven factors identified above.

In the next section, I will discuss my interpretation of why the survey respondents might have inadvertently reached a degree of consensus on the importance of the seven factors listed above. Then, I will explain how those factors have influenced the outcomes of off-grid projects by presenting insight gathered from the semi-structured interviews and field notes.

4.1.2 DISCUSSION

To begin this discussion, it might help to review the selected factors another time, but this time they are organized by category.

TABLE 4.5 Top seven factors ranked “important” or “critically important” organized by factor category



	Factor
Sociotechnical	3. Consumers’ perceptions of the quality of electricity access in neighboring hamlets or villages
	4. Local attitudes towards different rural electrification modes (e.g., perceiving solar-powered rural electrification modes to be a second-class option
	7. Consumer perception that quality of light provided by the rural electrification mode is superior to kerosene-powered light
Socioeconomic	1. Affordability of electricity and basic electricity-powered appliances
Social	2. Presence of a community development organization engaged in the provision of public services
Regulatory	5. Local tariff charged to rural consumers who purchase electricity from the grid
	6. Reliability (number of hours of electricity people consistently receive over a 24-hour period) of nearby existing grid connection

It is possible to observe outright that three of the seven factors (those under the heading “Sociotechnical”) are clearly focused on consumer perceptions or attitudes. Five out of seven factors (under the heading “Sociotechnical,” “Socioeconomic,” and “Social”) are related to how a planner might interact with off-grid customers and understand their needs and preferences. The two factors — the local grid tariff (factor 5) and reliability (factor 6), for short — have applications to regulation, hence the category, but they could also be construed as socioeconomic and sociotechnical factors, respectively. They both are linked to consumer perception of the value of electricity, though reliability (factor 6) could also be treated as a technoeconomic factor that can and is modeled in REM. Still, these observations suggest that one major piece of the planning process that is missing from REM is data about consumer needs and preferences with respect to a given technology.

To better understand this assertion, I will discuss how these seven factors fit into a social acceptance of technology framework, using insight from interviews and informal conversations as examples of how real planners contend with these factors. In the process of exploring how these factors influence off-grid projects, I mention several other factors included in the survey that did not make the top seven, highlighting the complex dynamics planners must consider.

4.1.2.A CONSUMER PERCEPTIONS AND NEEDS

I want to underscore the importance of a discussion about consumer perception in the context of a thesis that describes a technoeconomic planning model by sharing part of a comment from Bharath Jairaj whose work at WRI is focused on strengthening ties between stakeholders to promote rural electrification:

> You know sometimes we forget this is eventually about the consumers and we shouldn't make this a utility versus minigrid kind of conversation. There is the consumer who is the key stakeholder in this whole space, but often has virtually no voice in the conversation [2].

To understand why, broadly, consumer perceptions, needs, and preferences about electricity services and energy technology could be considered so important to planners, it is useful to draw parallels with experiences planning and implementing renewable energy projects in the developed world. In many locations, renewable energy projects that appeared rational to policymakers from a technoeconomic perspective have failed or been seriously delayed by challenges at the local level because of a lack of "social acceptance" of the project or of the new, unfamiliar technology. These challenges motivated researchers in the 1980s and 1990s to study how non-technical factors influence the outcomes of renewable energy projects in countries like Germany, France, and Finland (Wüstenhagen et al 2007). Interestingly, many similar challenges arise for planners and entrepreneurs working on rural electrification in India, yet these lessons have either not been learned or have not been easy to translate to a new context.

FIGURE 4.1 Wüstenhagen et al’s (2007) Social Acceptance Framework

Fig. 1. The triangle of social acceptance of renewable energy innovation.

Wüstenhagen et al (2007) offer a useful definition of social acceptance of energy technologies and that definition aligns well with my use of the phrase “consumer perceptions and needs.” Their definition breaks social acceptance into three types, which can be interdependent: socio-political acceptance, community acceptance, and market acceptance.

They define socio-political acceptance as broad, policy-level acceptance of certain technologies, community acceptance as the acceptance of how siting decisions and projects are implemented, and market acceptance as the adoption of the technology by consumers through their interaction with market actors (e.g., investors) or early adopters. Figure 4.1 shows how Wüstenhagen et al (2007) break down social acceptance into the three constituent parts I summarized and list some of the elements associated with each part. I will discuss the top seven factors identified above first through the lens of these social acceptance categories, I will then discuss possibilities for combining insights about consumer perception with technoeconomic planning.

SOCIO-POLITICAL ACCEPTANCE OF OFF-GRID RURAL ELECTRIFICATION

Socio-political acceptance, according to Wüstenhagen et al (2007), exists on a spectrum from global to local, but at least in India, acceptance at any point on the spectrum seems to influence acceptance at the other points. In other words, politicians may broadly accept national renewable energy and rural electrification policy, but will still campaign on promises of free grid electricity creating confusion for those at other points on the spectrum. Likewise, rural villages may support politicians who ultimately accept off-grid electrification as one way of extending electricity access, but when those villages are faced with a project in their own village they may feel as though the political process has denied them a grid connection.

This socio-political confusion seems to suffuse consumer attitudes towards solar-based off-grid systems in particular, and off-grid electrification projects, in general. Planners and officials at nearly every level told us, broadly, that people prefer a grid connection to a solar panel [4, 13, 42], yet there are politicians in power who have created and supported programs like the Jawaharlal Nehru National Solar Mission to expand solar capacity on and off the grid (MNRE).

An official from one utility told us that people believe solar is an inferior form of electricity and when distributed generation projects are attempted citizens instead persistently demand a grid connection. He offered one example in which he visited an area electrified with a microgrid by an NGO, but said the people complained that it was “fake power.” When the grid was eventually extended to that community, he claimed that the NGO’s investment “went down the drain.” He added that solar-powered solutions might work in the most remote regions, but in more populated areas close to major cities unelectrified people will not pay for solar because (subsidized) grid electricity is cheaper. He emphasized the importance of securing local acceptance for solar-powered off-grid solutions because otherwise people will not pay for service [42].

Despite solar’s mixed reputation, there is no denying that if you drive through many parts of rural India you will see people using solar panels on their homes, on public buildings, to power street lamps, etc. Villagers we spoke to in several states offered more nuanced opinions about solar. For example, one villager in Uttar Pradesh, who could not afford to join in the purchase of microgrid electricity with his neighbors, said he was thinking about purchasing a solar-powered lantern because he had recently heard it was more cost efficient than a battery-powered flashlight. It was true, at least anecdotally, that not everyone we met felt strongly positive about solar. Another man in the same village was currently purchasing electricity from a microgrid, but said the quality of light was low and that it was not bright enough to cook by at night. Of course, given the poor reliability of the centralized grid, not everyone felt strongly positive about grid electricity either [52].

The official’s role in the process of electrification in his state is worth coming back to for a moment. He is involved in the leadership of a utility whose job is to extend and maintain the operation of a grid that is known for poor coverage and performance. Our team spoke to others at the utility and many derided solar-powered systems as being too small or too undesirable. Meanwhile, more people in this state don't have electricity than many other states in India. Oddly, the official told us, he had recently installed a solar panel on the utility and energy department's headquarters to be a role model for solar acceptance.

I would argue that at the local level the perception that solar is inferior is as much fueled by the economics, i.e., the discrepancy in the cost to consumers between off-grid electricity and subsidized grid electricity, as it is by the politics and political messaging surrounding electricity access throughout India. While none of the factors strictly labeled as "political" in Table 4.5 (above) ranked in the top seven, the perception that solar and other forms of off-grid electricity are second class or inferior is probably an outgrowth of national and state-level political campaign promises of free or very cheap grid electricity. That message trickles down through the state energy departments, utilities, and on to the consumers creating confusion about which policies are really in their best interests.

This political messaging is likely exacerbated when politicians, seemingly intentionally, extend the grid to locations that have previously been electrified by microgrids or another off-grid system. For example, a somewhat highly publicized project to electrify a village in Bihar spearheaded by Greenpeace International was subverted when, just a few weeks after the 100 kW microgrid they built started operating, a politician came to the village and announced he would bring them a grid connection (Bloomberg 2014, Daily Mail 2014). Today, the villagers in Dharnai now receive electricity from the grid as well as from the microgrid, according to Mrinmoy Chattaraj, who previously worked with Greenpeace on the project:

> That's the kind of comparison they have started doing at that point of time I remember, between the true electricity, purest electricity, rather, and the duplicate, not the genuine electricity, which was the microgrid… I think the people were much more mentally programmed to see that any form of electricity should be free. It's a mental block I would say. It will get over. It will take certain time. And the politicians have done more damage to the people by actually giving false promises and assurance and building such kind of institutional mentality I would say. It's damaging, really it's damaging for such kind of projects [3].

Ironically, Chattaraj reports that the villagers in Dharnai rely more on the microgrid electricity than they do on the grid electricity, which he says is typically available about 15 hours per day with varying quality.

The Dharnai microgrid is a prime example, but other interviewees mentioned similar, though less dramatic challenges overcoming politically-driven skepticism of solar and off-grid systems. For example, SELCO Associate Director Ananth Aravamudan explained the dynamics his company typically encounters when trying to sell solar home systems in Karnataka:

> I mean we have heard of villages backing out because some politician... told them if you put solar in your village then its likely you will be deprioritized on grid expansion roadmap…People feel they are spoiling their chances of getting grid into their village because government will see they have light already and say let me take the grid the other way. I think it's mostly myth, but perception makes up various things [1].

One Bihar-based analyst working for an NGO that conducts impact evaluation on behalf of policy-makers explained the political influence on consumer perception this way:

> I know people are using solar and I feel like that's a solution that people are using because they don't have grid electricity and so therefore they are interested. But it would be a really tricky sell if people think they are just getting shorted… It's one of those things where it's clear that the grid is not going to come to so many people for so long and therefore it probably would be optimal to have this sort of solution but they [politicians] are not going to renege on what they promised. Even though realistically, they are not going to be able to fulfill their promise for a long time it would look bad politically if people thought they just decided not to do it [grid extension] at all [5].

Sushanta Chatterjee, Joint Chief of Regulatory Affairs with India's Central Electricity Regulatory Commission and one of the leaders behind several proposals for more structured microgrid regulation, said that the policymakers in India were aware of the general resistance to solar due to high cost, despite its potential benefits. He said that political messaging would not be a problem if policies and regulation can address concerns over the reliability and cost of solar and other off-grid systems since then the economics would work in the favor of those technologies, instead of the centralized grid [4].

MARKET ACCEPTANCE OF OFF-GRID RURAL ELECTRIFICATION

Political messaging, alone, is not to blame, though. Market acceptance or adoption of new technology requires a communication process between consumers and vendors (Wüstenhagen et al 2007), but few widespread enablers of that communication exist. As discussed in Chapter 1, India's limited regulation of the off-grid sector means that few standards constrain off-grid vendors. Thus, the quality of off-grid systems (e.g., solar panels and other equipment) is difficult to control. Chattaraj, who worked on the Greenpeace microgrid, pointed out that in his experience, "prejudices" against microgrids arose when villagers had or witnessed a bad experience with a shoddy solar home system or other solar lighting technology. He said:

> Most of the time they are low quality, low standard home lighting systems ha[ve] made solar on bad name in those parts…From villagers' point of view, it's like the grid, which they have seen growing up, that's the source of electricity [3].

He also explained that this expectation about the grid, combined with previous encounters with low-quality solar home systems, made it challenging to engender acceptance that off-grid systems can be a quality source of electricity among villagers. "People have seen the systems failing in past so they really need to understand how this impact can happen," Chattaraj said [3].

Like the challenges surrounding the perception of solar power and the quality of off-grid systems, another challenge to market acceptance is the continued dependence on familiar alternatives, like kerosene. Electricity can be a substitute for kerosene-fueled lighting (the price of kerosene is often used to estimate willingness to pay for electricity), but it is not a perfect substitute. About 74 million households with no access to electricity use kerosene for lighting, but even people who do have electricity use kerosene as back up during power outages (Rao 2012). This issue is closely related to another factor ranked in the top seven by respondents—experience with the reliability of electricity from the nearby grid — since people who are used to kerosene-fueled light may need to adjust to electric lighting and may still purchase kerosene to supplement their grid connection or off-grid electricity (Kobayakawa & Kandpal 2014). They may continue to use kerosene as a back up source of fuel for lighting to anticipate unreliable service. Kobayakawa and Kandpal (2014) estimated that villagers connected to a 120 Wp solar-powered microgrid in West Bengal continued to spend an average of 30 INR ($0.47) per month on about 2 liters of kerosene to fuel lamps early in the morning when electricity from the microgrid was not available and to supplement their electric lighting. This practice reduces the economic benefits of electricity and could affect the acceptance of off-grid systems in the market.

A former intern for Simpa Networks, a solar home system company based in Uttar Pradesh, said that villagers wanted electricity for things kerosene could not do, such as to power televisions, fans, etc. They expressed less interest in having electricity to replace kerosene as a source of light [19].

One villager we met in Barabanki, Uttar Pradesh was the head of a household with a grid connection, but his family still purchased about five liters of kerosene per month to provide light during electricity outages. Three of the five liters were unsubsidized and procured on the black market. That same family also owned a solar light that his children use to study at night [52].

His neighbor reported that subsidized kerosene was 17 rupees per liter (other villagers nearby said the rate was 18 rupees/liter, or nearly $0.30), while the rate for black market kerosene was between 50-55 rupees per liter ($0.79-$0.87). This second villager had both a grid connection and a connection to a microgrid. He said he was no longer purchasing kerosene, though he still used a halogen gas lamp.

A representative of OMC Power, a microgrid company based in Gurgaon, Haryana (near New Delhi), also reported that it was challenging for them to convince families to stop using kerosene, even though families found it expensive [25].

It may not seem problematic that people with nominal access to electricity still choose to purchase kerosene to supplement their electricity service, but from the perspective of both microgrid entrepreneurs and planners it is. Grid connection for rural consumers is often extremely unreliable, but off-grid systems, though generally more reliable, typically are not sized to provide more than six to eight hours of service per day or less. Consumers who want more reliability or availability are essentially hedging against the risk of not having energy services, like lighting, when they need it by buying kerosene.

Entrepreneurs are concerned that sustained use of kerosene even after a household has received access to an off-grid system minimizes the added value of the microgrid or individual home system. Companies typically market off-grid systems by pointing out that a family will save money by purchasing electricity for light instead of kerosene, but this argument assumes the two are perfect substitutes. If households are buying both then they are probably not realizing as much economic benefit from electricity, meaning those households have less disposable income to purchase more electricity-consuming appliances or simply consume more watts-hours per day. This unexpected trend could create problems for an entrepreneur's business model, especially if they initially assumed customers would reinvest kerosene savings into the services or system upgrades that the company provides. The continued purchase of kerosene is a clear market signal that consumers are still uncertain about the reliability of the off-grid technology they are using.

This failure of market acceptance raises concerns about socio-political acceptance as well. Planners in the public sector are more likely concerned that the lack of market acceptance strains policy objectives i.e., the continued need to fund substantial kerosene subsidies through the Public Distribution System (PDS). In India, kerosene is only legally sold through the PDS, so for Indian public officials that are otherwise primarily focused, by mandate, on grid extension, the advantage of privately sold off-grid systems is a decrease in dependence on kerosene subsidy, which costs India $4-6 billion dollars annually (Rao 2012). Rao (2012) found that kerosene subsidies, which are tightly rationed, are regressive and bring fewer financial benefits to rural households (as compared to urban ones), largely because household rations are benchmarked to cooking needs, not lighting.

Furthermore, in reaction to the kerosene subsidy program, kerosene mafias have emerged that sell kerosene informally to villagers, like those discussed above. This sort of black market activity fuels illegal behavior, such as kerosene theft, and creates vested interests in maintaining the illegal kerosene business. If these vested interests have political sway or informal control of the kerosene (or diesel) market, people may perceive the threat of retribution from local mafia leaders as a strong incentive to continue purchasing kerosene regardless of their satisfaction with an off-grid system or they may refrain from purchasing an off-grid system at all. In either case, the informal market for kerosene is counterproductive to both on and off-grid electrification efforts (Rao 2012, [4]).

Market acceptance is also linked to perceptions about quality. For example, another villager in Barabanki said that prior to being connected to a microgrid he purchased two liters of kerosene per month, but no longer needed kerosene since he began purchasing electricity from a microgrid. This villager was connected to the same type of system as some of the villagers mentioned earlier, though with one crucial difference: he was given four lights as compared to the standard two light package because he had allowed the microgrid company to install the solar panel on his roof [52]. Although this particular villager had accepted the new technology, this example raises an important question worth considering in future research: what level of electricity service is necessary to make kerosene and electricity perfectly substitutable when it comes to lighting? Or, more broadly, what level of service facilitates market acceptance?

The local tariff levied from grid electricity consumers is also an important mediator of market acceptance. As mentioned in the discussion of the relationship between the grid tariff and socio-political acceptance, the tariff for grid electricity is highly politicized, but it also sets public expectations for the price of electricity. These expectations of free or nearly free electricity create challenges for private actors in the space who cannot sell electricity at these rates. As one commissioner of the now defunct National Planning Commission told our team in 2013, microgrids will not work until the gap between the grid tariff and microgrid (or off-grid) tariff is addressed [44]. Large-scale utilities can operate with below-cost tariffs because they are kept afloat by the government, but private businesses cannot afford to compete, even with some government subsidy, which is not always dependable. Yet, as long as consumers believe that they are over-paying for electricity because they see others paying less for the grid, challenges with market acceptance will persist.

Importantly, off-grid companies are finding ways to deal with this dilemma in an effort to promote acceptance. A representative from the Minda Group's off-grid group NextGenTech said it was easier to deploy technologies in villages where people already knew through observation or first-hand experience that grid electricity is unreliable and appreciated the value of electricity and electric lighting [24].

SELCO also succeeds in making sales to customers with unreliable grid electricity — as of 2013, roughly 50 percent of their customers had a grid connection, but it was highly unreliable [16].

Based on Greenpeace's experience, though, it seems that for villagers to accept that a microgrid was a reliable source of electricity required proof. Chattaraj said that, ironically, now that the villagers experience the unreliable grid connection "they rely more on the microgrid electricity." In addition, the business model for the microgrid included a three-tiered cross-subsidizing tariff system in which agricultural and commercial users cross-subsidize residential consumers. This method of overcoming the gap between the grid tariff and the cost of service for an off-grid system was also recommended to us by an official at the Ministry of New and Renewable Energy as a good strategy for off-grid entrepreneurs [39].

SELCO told us that, at least in the informal economy, social dynamics are what push people to pay or not — automation works better in the formal economy [16]. This is an important point to remember when considering REM's role in electrification planning. It also raises a question about the interplay between access and perceptions of quality that is difficult to understand. From the perspective of a researcher or planner with relatively reliable electricity, the value of having electricity is clear and supersedes many concerns about where that electricity comes from. But from the perspective of a villager who does not have electricity considering whether to pay for a service that politicians have repeatedly said will be free, observation of others may not be sufficient information for him or her to develop a sense of how much they value electricity and what characteristics about the service they value more than others. Perhaps, the assumption that a person or village that does not have electricity will care little about the type of system that provides it is born of a mindset that is relatively accustomed to 24/7 supply availability and used to paying (to varying degrees) for that service. In other words, most people born into an environment with access to full electricity may not need to be shown, explicitly, the value of that service because, for them, it is hard to imagine a life without it. Thus, they may have few questions about how electricity arrives at their outlet as long as it does. But for those used to living without electricity, it is difficult to make judgments about quality and value in the presence of so many options (grid, microgrid, home system) with different degrees of reliability and in the absence of a lifetime of proof that electricity is useful and that the mechanism of delivery is not nearly as important as the reliability of that mechanism.

A consultant who has been working in the field for several years, succinctly illustrated the breakdown in understanding between those seeking to provide electricity and those who need electricity, but are skeptical about off-grid systems, "BPL people don't just need light and mobile – they need value from light and mobile." [46]

While off-grid entrepreneurs have adjusted their business models to foster greater market acceptance, India's Central Electricity Regulatory Commission (CERC) also believes it has a role to play in facilitating the commercial viability of microgrids and ensuring the best outcomes for consumers [34]. In 2011, CERC proposed model microgrid regulation that would ensure a regulated tariff for electricity from microgrids and create a franchisee relationship between off-grid entrepreneurs and local utilities. The regulation would also put in place equipment standards that would serve as a quality control mechanism to help consumers make easier decisions about whether or not to purchase electricity from an off-grid system (ABPS Infra 2012).

The consultant, who is skeptical that independent project developers will ever be able to effectively compete with utilities since few if any are commercially viable, supports the regulation because it uses existing institutions to try out a new business model [46]. Whether or not she is right remains to be seen, however, if a version of the model regulation passes then market acceptance could prove less of a challenge for private actors in the rural electrification market.

COMMUNITY ACCEPTANCE OF OFF-GRID RURAL ELECTRIFICATION

Community acceptance of renewable energy generation projects in the developed world may revolve more around siting decisions and so-called NIMBYism (the Not-In-My-Backyard attitude), however in the context of rural electrification community acceptance seems to revolve more around value creation, capacity-building, and behavioral change, particularly with regard to consumption and payment. Indicators of community acceptance might include growing demand, timely payment, and the absence of theft or system tampering.

For many new rural customers that purchase an off-grid electricity service, it is the first time they have ever had electricity at home. Oftentimes, they must develop new daily habits in order to best utilize the service, particularly if the system only allows users to consume electricity at certain hours or for a certain number of hours. As one representative from SELCO told us, the company often has "to do the work of creating demand." [16] Interestingly, we were told that when people understand the value of electricity they care a lot about how their service compares to their neighbor's. More recently, in describing SELCO's expanding efforts to develop solar-powered products, like sewing machines and solar water pumps, to expand access to income generating activities, Ananth Aravamudan said SELCO often has to help consumers find ways to access new markets in order to maximize the benefits of the solar-powered product [1].

The companies we talked to also seem to foster community acceptance through payment collection practices. Gram Power hires local entrepreneurs to be responsible for sales, maintenance, and payment collection. They told us that these entrepreneurs are typically village opinion leaders that other members of the community "will vouch for." [22] Kuvam told us they do not target individual homes when signing on new customers, but has them self-organize into groups to sign up for the service [23].

SELCO engages with communities in various ways to secure the level of community acceptance that ensures payment. For one, they work with local financial institutions to develop financial products that allow consumers to make payments in ways that are aligned with their income stream. For example, in rural areas many people do not earn enough steady income to save so it is easier for them to make small daily payments than to make a large payment at once. SELCO also tries to use social pressure to encourage payment. Usually that social pressure comes from connection to a local bank or from a community leader [16]. The utility official we spoke with also emphasized the importance of securing local acceptance of the off-grid project in order to ensure payment and maintenance [42].

As part of the effort to facilitate payment, companies also need to build community acceptance to discourage theft, which can subvert business outcomes as well as community acceptance by degrading the quality of light consumers experience. For example, at one hamlet we visited in Barabanki, Uttar Pradesh the villagers had recently been connected to a Mera Gao microgrid, a company that sells small systems in the region, however, within about two months of using the service many of the villagers were unhappy with the system because the light was too dim. One villager told us he had gone three or four days with no electricity and when it was on the quality was bad. He told us he knew that someone was illegally connecting to the wires and that some villagers were illegally using an extra bulb. He thought these transgressions were the source of the problem because whenever the Mera Gao maintenance person came to check on the system during the day (when no electricity was available) nothing appeared to be wrong. The villager told us that he wanted to disconnect from the service because he was so unsatisfied [52]. This situation is exactly what both off-grid entrepreneurs and planners fear since this villager may now be skeptical of off-grid electricity for a long time to come.

While theft can be managed or monitored through hardware, such as smart meters, load limiters, or equipment that runs on non-standard voltages [1, 10, 22, 23, 32], these pieces of equipment can sometimes be expensive or imperfect so companies attempt to prevent theft through community engagement and social pressure.

For the implementation of the Dharnai microgrid in Bihar, Chattaraj commented numerous times that building trust with the community was a prime focus of the overall project to ensure the microgrid could operate effectively. He said they achieved trust through several mechanisms, but most notably by helping to create capacity within the village to maintain a democratically-elected village electricity committee that included representation from each caste, gender, and any other social grouping. Chattaraj said Greenpeace also wanted to build a sense of ownership within the village, so the body functions as a mechanism for villagers to work together to diffuse disputes, ensure payment, and manage the threat of theft and tampering.

> Now this was the central body that was driving all the initiatives in terms of capacity building, they were driving in terms of handholding with these people. They were also the collecting agents; they were also the implementers. They were a part of the project from day one to right now [3].

Chattaraj emphasized that Greenpeace invested so much time in this effort because they never intended to stay in Dharnai to operate the microgrid. They hired a third party operator to help manage on-the-ground operations, but ultimately they wanted the community to own and perpetuate this project. Part of their goal was to prove that building community acceptance in this way could prove to investors that rural electrification projects were sustainable. Of course, the arrival and acceptance of the centralized grid changed some plans for the microgrid. He says the focus now is to find a way to integrate the microgrid with the existing grid [3].

SELCO [1] and Gram Power [22] also look for this sort of village unity when assessing villages for microgrids, in particular, since a majority of households in a village must agree to use and pay for the same system.

Caste and religious differences can sometimes create challenges to community acceptance when the residents of a village cannot get past their differences. For example, Ananth Aravamudan (SELCO) said it can be very difficult to serve villages where two castes co-exist:

> Well we have actually walked out of a few villages because of this problem. When we see that there is no unity and people are not able come to us with one voice, and they say this group wants separate system and this group a separate system, we just walk out [1].

According to Wüstenhagen (2007), community acceptance has a time dimension. In other words, overall the stakeholders described processes of overcoming price expectations, usage and payment habits, and capacity building to manage inter-community differences that required giving rural customers time to adjust to the new electricity system.

4.1.2.B INCORPORATING CONSUMER PERCEPTION INTO TECHNOECONOMIC PLANNING

What is most striking from this review of how consumer perceptions affect the planning process, especially for off-grid entrepreneurs, is the presence of the end user in each factor and the amount of effort required to understand and incorporate consumer perspectives into the planning process. Accounting for such variety and variability and the dynamics at the heart of technology attitudes seems impossible in an automated least-cost technoeconomic planning assessment. Mallett (2007) describes three models of technology adoption and cooperation that may usefully illuminate why a focus on end-users and a focus on large-scale technoeconomic planning may seem incompatible. The first model involves one major actor pushing new technology out to the public, the second model involves public-private partnership or public-private-academic partnership to champion for adoption of a technology, and the third model focuses on the engagement between end users and stakeholders in making technology decisions. The factors that the pilot survey revealed to be important to respondents could be addressed through the third model, while a technoeconomic planning tool, like REM, fits better within the framework of the second model. Mallett (2007) points out, though, that the second and third model could be complementary. That potential is what the methodology described in this thesis is intended to realize.

For example, there may be a couple of ways more awareness of and engagement with consumer perceptions as a critical factor in off-grid projects could alter how a planner might use a tool like REM to facilitate planning. For one, encountering consumer perception in the planning process carries a transaction cost. As all of the off-grid companies mentioned above report, addressing consumer perceptions about technology happens at multiple stages in the process of building a single project and takes a substantial amount of time. That time could be considered in terms of project costs (labor, materials) and potentially estimated in ways that lead to more detailed, if imperfect cost assessments.

Another way to consider consumer perceptions is to evaluate the results of REM in the context of information about the political climate, the reputation of the microgrid or solar-home system vendors operating in the region, and insight from NGOs or other organizations working to bring services to rural villages — in addition to data about the extent and reliability of the existing grid (which is modeled) — to develop an early-stage indication of where to expect acceptance and opposition. A meta-study of past projects that looks at the relationships between several contextual variables and acceptance of off-grid projects might enable such an idea.

It is possible to imagine a future in which perceptions about solar and the quality of electricity from different systems do not vary so widely in India. In that future, regulation would probably play an important role. Mandated and enforced quality standards for off-grid systems will help communicate to customers the necessary information they need to assess what sort of quality and reliability of electricity to expect when they sign up for a particular kind of service. In this future scenario, consumer perception will always vary and more likely as not, people's opinions will be influenced by their neighbors, but the overall level of trust that any given system will meet expectations of value and quality would be much higher, making project outcomes more predictable for planners and business less risky for entrepreneurs.

4.2 SCENARIO ANALYSIS: THE CASE OF DEMAND IN VAISHALI DISTRICT, BIHAR

4.2.1 VAISHALI

4.2.1.A BASIC INFORMATION

FIGURE 4.2 Official map of Vaishali District, Bihar (UNICEF 2011 from Vaishali District Website)

Vaishali District is in the northern Indian state of Bihar that is just across the Ganges River from Patna, Bihar's capital city (for a map of Bihar in the context of India and a map of Vaishali in the context of Bihar see Appendix E). The district is home to about 3.5 million people as of 2011 (Vaishali District website). Population density is approximately 1,700 people per square kilometer, with just under 94% of the population living in rural areas (Vaishali District website). A map of the district produced by UNICEF in 2011 shows that there are 18 sub-districts, or blocks, however these administrative boundaries changed between the census conducted in 2001 and the one conducted in 2011. Population has grown nearly 29% during this time period, as well (Census of India 2011). The primary language in Vaishali is Hindi, though the most commonly spoken dialect is "Bajjika" (DPMCC 2010). The district headquarters of Vaishali District is Hajipur.

4.2.1.B ELECTRIFICATION IN BIHAR

Vaishali District has a household electrification rate of 11.1%, worse than the Bihar state electrification rate (Census of India 2011). The state's recent political history has much to do with the underdevelopment of many public services, including electricity. From 1990 to 2005, Lalu Prasad Yadav and his wife, Rabri Devi — members of the Janata Dal party — were sequentially chief ministers of Bihar. Their tenure is associated with a dismantling of the state that is still blamed for Bihar's extensive poverty, despite the fact that Yadav seemingly espoused a positive agenda focused on lower caste empowerment (Witsoe 2011). According to Witsoe (2011), Yadav did not see the state as an "agency of development," but rather a "tool of political struggle" against a powerful elite class. In practice, that meant he purposefully understaffed state agencies (he fired upper caste workers, but could not find qualified lower caste workers to replace them) and intentionally neglected to spend money from the national government on public projects, such as roads and electricity (Mathew & Moore 2011). Yadav was known for his corrupt practices (not that previous politicians weren't). Yet, according to Witsoe (2011), this corruption was not problematic for his supporters because they felt a kinship with a government that was corrupt in favor of their caste (versus corrupt in favor of the elite castes) even if that government failed to deliver services. In this vacuum of public service delivery and rule of law, informal networks and mafias took shape to replace the typical functions of the state (Mathew & Moore 2011).

This brief recent history is important context in order to understand a little bit about why electrification in Bihar lags far behind many other states. When we traveled elsewhere in India, most people were shocked to hear that we had plans to travel to or had recently been in Bihar, describing the state as backward and dangerous. When we discussed electrification in Bihar with one representative from a utility in another state (he was born in Bihar), he described the electricity situation as particularly bleak, saying he thought it would be two centuries before everyone in the state was grid connected.

In Bihar today — ten years since Yadav's reign — attitudes about the state are dramatically more positive, or, at least that is true of the people we encountered in Patna and Hajipur, Vaishali. An associate for IDinsight, a development consulting organization that works with policymakers to help them make evidence-based decisions, said both the previous and the current Chairman and Managing Director (CMD) of the Bihar Energy Department/State Power Holding Company Ltd were well-liked and worked hard to prioritize development of the electricity sector [5]. Mathew and Moore (2011) write that today the state is experiencing what some have called a "governance miracle" initiated by Nitish Kumar who took office in 2010, though the state still faces many entrenched social and political challenges in order to truly make progress.

Our case study in Vaishali is, in some ways, connected to this political renewal. When we visited the Bihar Energy Department and State Power Holding Co. Ltd. In July 2014, the CMD had only been in his position a few weeks. His appointment came shortly after the national election of Narendra Modi and the resignation of Bihar Chief Minister Nitish Kumar (he was replaced by Jitan Ram Manjhi). The Lead Associate for IDinsight, who was part of the evaluation cell within the energy company, later told me that we had arrived in the midst of a "massive shuffle." The old CMD, she said, was explicitly focused on improving revenue collection, but at the time, the new CMD was explicitly focused on rural electrification, which was timely, given our research. She said both the current CMD and his predecessor embodied reasons to be more optimistic about electrification in Bihar than the people we had spoken to elsewhere were. Both the previous and the current CMD were very focused on improving many failures of the system, but the nature of the political cycle and the rapid turnover of leadership in government agencies, like the energy department, has been a major obstacle to sustained electrification progress. [5]

When we met with the CMD in July, we presented a planning approach that was predominantly focused on REM and he asked us to complete a study as quickly as possible. Although he originally recommended a different district in Bihar, we ended up agreeing to study Vaishali because it was one of the few districts for which there was a map (hand-drawn, not digitized) of the medium voltage (11 kV) distribution network. Initially, this was the only official data the CMD's staff shared about Vaishali, which we assumed was an implicit message indicating that we should prove we would actually follow through if we wanted access to more data.

Upon further study (and confirmed during our January 2015 trip), we realized Vaishali is both a good and a bad place to run an initial study using REM. On the good side, the electrification rate in the district was very low, only 11.1% of households use electricity as a primary source of light, and the district is almost entirely (93.4%) rural (Census of India 2011, Vaishali Official website).

The disadvantage, according to the individuals we spoke to at the Bihar Energy Department, the State Power Holding Company Ltd., and the North Bihar Power Distribution Co. Ltd. is that Vaishali's electric grid is relatively well developed compared to other districts farther from Patna and the district is extremely dense. Most people, the CMD told us, will expect a grid connection (regardless of the recommendations produced by REM) and will not want to pay a higher price for off-grid solar-powered solutions [42]. When we spoke with the NBPDCL's Executive Engineer in Vaishali he laughed at the prospect of microgrids in the district, saying that off-grid systems were not a cost-effective solution for most places in Vaishali because people expected 24/7 service.[19] He told us that with the help of funding from the national government (through the RGGVY program) every village in Vaishali would have a grid connection within two years. He, and those at the Bihar Energy Department, separately, recommended that we focus on Raghopur, a sub-district in Vaishali, located in the Ganges River in between Vaishali mainland and Patna — the only place that might not be grid connected soon due to seasonal flooding.

It is impossible to know whether every village will be grid connected in the next two years and, even if that does come to pass, to know whether complete village electrification would ensure that every household in every village would have electricity access (see India's definition of electrification mentioned in Chapter 1). As the IDinsight associate pointed out, grid connectivity is a recurring political promise and yet electricity access is rare, however, she said the current CMD is prioritizing rural electrification [5]. The methodology described in this thesis can still be useful to the CMD and his staff in providing cost estimates of different mixes of technology solutions and suggesting policy recommendations. The IDinsight associate emphasized that the use of a planning approach like ours is contingent on making near-term recommendations. She said there is a real focus on what can be done "now" because bureaucrats, like the CMD, do not know with certainty if they will still be in office in the next six months [5]. With this context in mind and limited time to do on-the-ground fieldwork in Vaishali, we produced a study of the district. To introduce that study, I will first describe how we characterized electricity demand in Vaishali in the context of a broader discussion about the importance of demand as a factor in rural electrification.

4.2.2 DEMAND

4.2.2.A UNDERSTANDING AND CHARACTERIZING ELECTRICITY DEMAND IN ELECTRIFICATION PLANNING

Electricity demand represents one of the most complicated factors to consider when it comes to rural electrification. In developed countries, where most houses are metered, determining the load profile of a house, or several houses in a region, is relatively straightforward. Historical data is used to predict

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[19] It is important to note that hourly demand data collected from the substation where the executive engineer works confirms that the customers do not get 24/7 service from the grid either, due to load shedding and maintenance issues.

future demand and these estimates are sufficient for large-scale, centralized grid planning. In the rural parts of developing countries like India, most buildings that are connected to the grid do not have meters and there is even less information available to predict what the unelectrified households might consume once they have electricity access.

This uncertainty about electricity demand and how it changes over the time is at the heart of the rural electrification challenge, but not every stakeholder attempts to understand it the same way. From the perspective of a utility or an off-grid vendor, determining current demand and estimating future demand is a major preoccupation of their technoeconomic planning process because data about individual household demand as well as coincident demand (peak demand) are critical to decisions about whether it makes economic sense to extend the grid, what size off-grid system to build (e.g., generation and storage), and how much service to provide while still covering costs (Kobayakawa & Kandpal 2013). These estimates are particularly important to off-grid project developers because it is difficult to cheaply modify most off-grid systems to serve more load if the demand estimate is wildly off. Regulators, policymakers, and national or state-level planners are concerned with determining specific demand thresholds associated with welfare or economic development outcomes and designing policies and programs to meet that demand. From this viewpoint, the focus is less about an accurate representation of current demand than about supplying sufficient electricity to enable welfare maximizing and economically productive demand. In other words, these planners worry about enabling as much demand as possible, typically subject to a budget constraint, particularly since there is no agreed upon minimum level of electricity necessary to meet basic needs (Khandker et al 2012, World Bank 2013).

For consumers, electricity demand is a function of electricity availability, the affordability of electricity service and electricity-consuming appliances, household needs, habits, and aspirations, as well as local context. As off-grid electrification efforts have become more well known there has been a growing effort to understand electricity demand from the consumer perspective in order to inform power system planning and social policy. For example, in a study of a village with a solar-powered microgrid in West Bengal, Kobayakawa and Kandpal (2014) discovered not all households chose to be connected to microgrid. They studied this phenomenon and found that households that opted to connect to the system when it was commissioned were more likely to have school-age children and more likely to have relatively high, stable income. They also found that connected households were more likely to have land and livestock, suggesting that income or wealth is linked to electricity demand. My team's collaboration on the randomized control trial in Barabanki, which will be discussed in more detail in Chapter 4, is another example of such a study. In addition, a group at the University of California – Berkeley is currently conducting an ongoing study of demand in partnership with Gram Power, a microgrid vendor based in Jaipur, Rajasthan [22].

All of these studies, and others, are focused on understanding consumers, but they are motivated by the planner's problem.[20] How much electricity should we serve to low-income people who have never had electricity before? How much might electricity demand grow once people have a connection to an electrification system? Or, how much electricity access is necessary to spur development and mitigate poverty?

There is relatively little research on the causal relationship between electricity connection and demand growth — what Sovacool (2011) refers to as the climb up the "energy services ladder" — as well as the relationship between electricity demand and development. These gaps in the literature are largely due to the previously limited emphasis on behavioral, social, political, and other determinants of poor, rural consumers' electricity consumption (Sovacool 2014). Similarly, little is known about the aspirations of unelectrified rural people and how those aspirations — in terms of how electricity can improve their lives — change over time.

One determinant of electricity demand that is heavily emphasized is affordability: consumers' ability to pay for electricity services. Affordability was also ranked as one of the most important rural electrification planning factors in the survey discussed in the previous section (4.1), so its relationship to electricity demand bears discussion here. One reason affordability is so important is that it is often used as a proxy for electricity demand by off-grid electrification planners in India (Khandker et al 2012). Off-grid entrepreneurs typically develop consumer archetypes that are defined by a level of affordability and a pre-defined level of service, such as what I will call the "minimum basic service level," which includes two lights and a mobile phone charger available for four to six hours per day and typically costs the consumer between 100 – 200 INR ($1.50-$3.00) per month [6, 20, 22, 47, 32]. When it comes to residential electrification, some off-grid power providers allow for more than one consumer archetype [20, 22], but many, like Mera Gao Power, do not. For example, the only way consumers connected to a microgrid that provides this minimum basic service can increase their demand is to push for a larger system or purchase an additional off-grid system (like a diesel generator or solar home system). Neither option is always possible or affordable. Sanjoy Sanyal, a consultant at New Ventures India, says most of the entrepreneurs he works with who offer this basic level of service do so because it allows them to run their operations most efficiently. Those companies that provide more service, he said, are motivated by the ideology of providing power for productive uses "and prompted more than a little bit by the type of funding they got." [6]

This practice of determining and managing demand based on affordability makes sense from a business perspective, as Sanyal suggests, however there is little evidence this particularly popular

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[20] Research motivated by the consumers' problem would be far more focused on what consumers want to achieve and working with rural, unelectrified communities to determine whether and what types of electricity services can meet those needs.

consumer archetype leads to the development outcomes — the "ideology" Sanyal mentioned — that some planners and project developers aim to achieve. In cases where consumer demand growth is less constrained, demand appears to grow, though not in a generalizable way (Kobayakawa and Kandpal 2014, 4, 39).

The complex nature of electricity demand, both its determinants and how it influences electrification planning, makes it an interesting factor to study using REM because demand can be modeled as a technoeconomic factor, but its unpredictability makes it a socioeconomic and sociotechnical factor, as well. In the following sections, I will discuss the method we used to develop demand profiles for unelectrified households in Vaishali District, discuss how socioeconomic factors that influence demand could be accounted for by comparing demand scenarios to see how they impact the results produced by REM, and analyze two different demand growth scenarios in Vaishali District.

4.2.2.B CHARACTERIZING ELECTRICITY DEMAND FOR VAISHALI[21]

As a result of limited time to gather information about electricity demand information for rural households in Vaishali District, I use data gathered from a variety of sources to develop a best guess at what demand might be for unelectrified Vaishali households that gained access to electricity for the first time. In other words, represent the "consumer perspective" on demand. Three primary pieces of information are needed to construct the "natural demand" for the Baseline scenario: appliances owned, time of use, and whether or not the demand is critical (high CNSE) or non-critical (low CNSE). These three components are conditioned by data about daily temperature, sunrise/sunset, and other seasonal information, which makes it possible to simulate an hourly demand profile for the Baseline that approximately represents what a low-income, rural electricity consumer might use on a daily basis in the course of one year while accounting for some degree of day-to-day variability.

I will then compare that Baseline scenario to two modified demand scenarios intended to represent the policymakers' or planners' demand priorities: a) one in which each building's demand is expected to double over the course of five years and b) one in which I assume the number of buildings in Vaishali increases, as a proxy for population growth. These higher-level demand scenarios are designed to demonstrate questions about demand that planners or entrepreneurs might want to study using REM when planning electrification for rural consumers.

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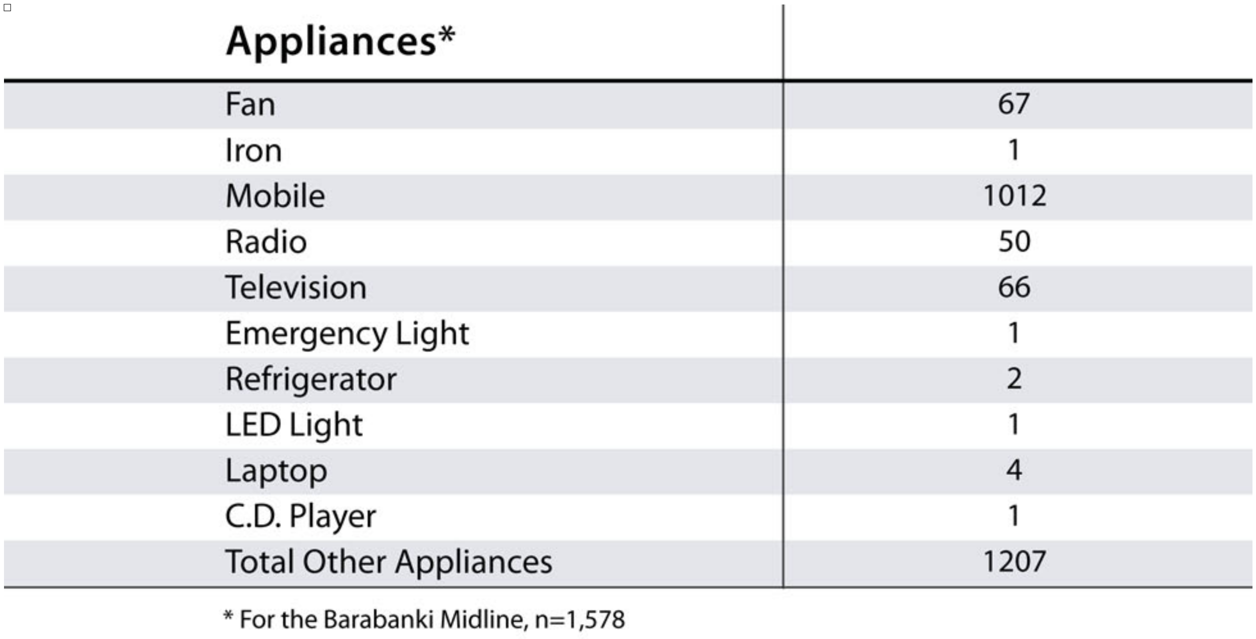
[21] The analysis that follows was done in collaboration with Douglas Ellman, TPP '15, with input from other members of the research team. The break down of responsibilities is as follows: demand characterization logic (both), scenario specification (author), data processing (both), script development and model runs (Ellman), production of raw results (Ellman), processing of raw results and mapping (author), discussion of results (author).

APPLIANCES

To determine a possible demand profile we first determined a plausible appliance set that low-income, recently electrified consumers might own. Using data gathered from the questions we contributed to the Barabanki midline survey (see Appendix D), we deduced that the recently electrified consumers could reasonably be expected to own about four lights, a fan, a television, a radio, and a mobile phone (which they would need to charge) based on reported appliance ownership by respondents in the survey (the full list of questions MIT contributed to the Barabanki midline survey is included in Appendix D).

TABLE 4.6 Summary of Barabanki appliance ownership



Appliances*	
Fan	67
Iron	1
Mobile	1012
Radio	50
Television	66
Emergency Light	1
Refrigerator	2
LED Light	1
Laptop	4
C.D. Player	1
Total Other Appliances	1207

* For the Barabanki Midline, n=1,578

This list of appliances was vetted with the NBPDCL Executive Engineer of Vaishali [45]. We determined the power rating for each appliance from a review conducted by Prayas Energy Group of the typical specifications of appliances used throughout India (Prayas 2013). It is important to note that when we actually modeled demand, we did not include radios or mobile phone chargers because the power consumption of each appliance contributed very little to the overall demand and omitting them made computing faster.

To account for the likelihood that not every household would own one of every appliance, we needed to determine an ownership probability for each appliance. The National Sample Survey 2009-2010 (66th round) of Consumer Expenditure is a survey of 100,855 households throughout India that documents monthly expenditure on a variety of goods as well as appliance ownership. Focusing specifically on households in Bihar that were classified as rural and as electrified (n = 797), we determined an appliance ownership probability based on the fraction of rural households that reported owning each appliance (see Table 4.7).

TIME OF USE

Once a set of appliances is determined it is necessary to estimate when households are most likely to use those appliances in terms of time of day and/or time of year. For example, households are generally unlikely to use a fan very often during the winter months, but are likely to have it on frequently during the warmer months. Again, using data gathered from the Barabanki midline survey based on questions we asked respondents about the time of day and year they use appliances, we estimate usage intervals for the lights, fan, and television based on the Barabanki survey respondents' reported usage times (see Figures 4.3-4.5).

FIGURE 4.3 Times of the day and year that Barabanki residents use lights

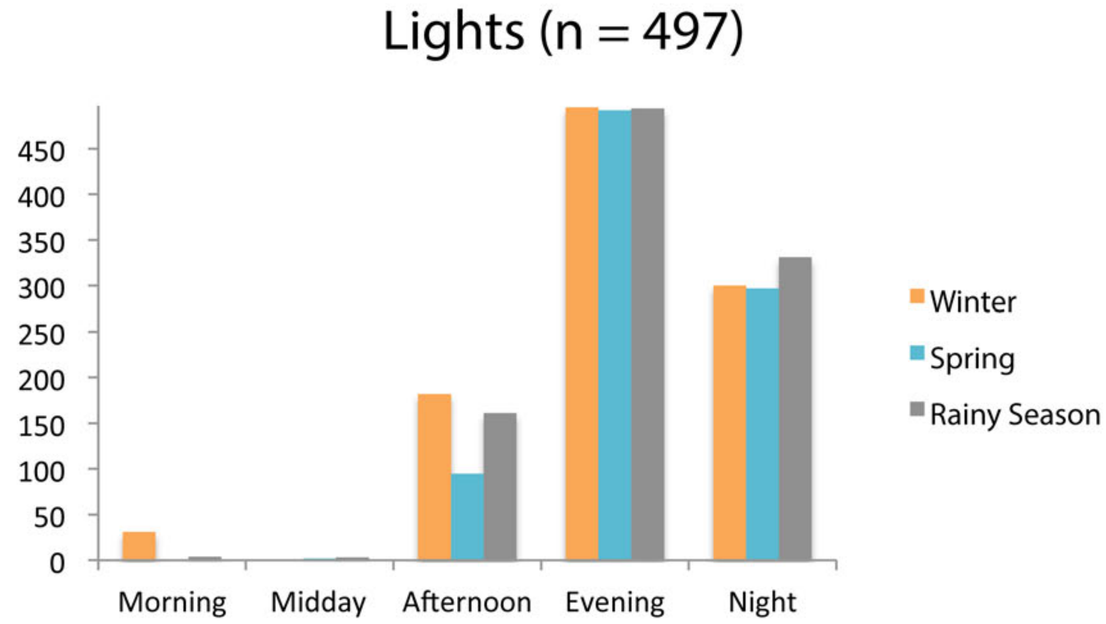


FIGURE 4.4 Times of the day and year that Barabanki residents use a fan

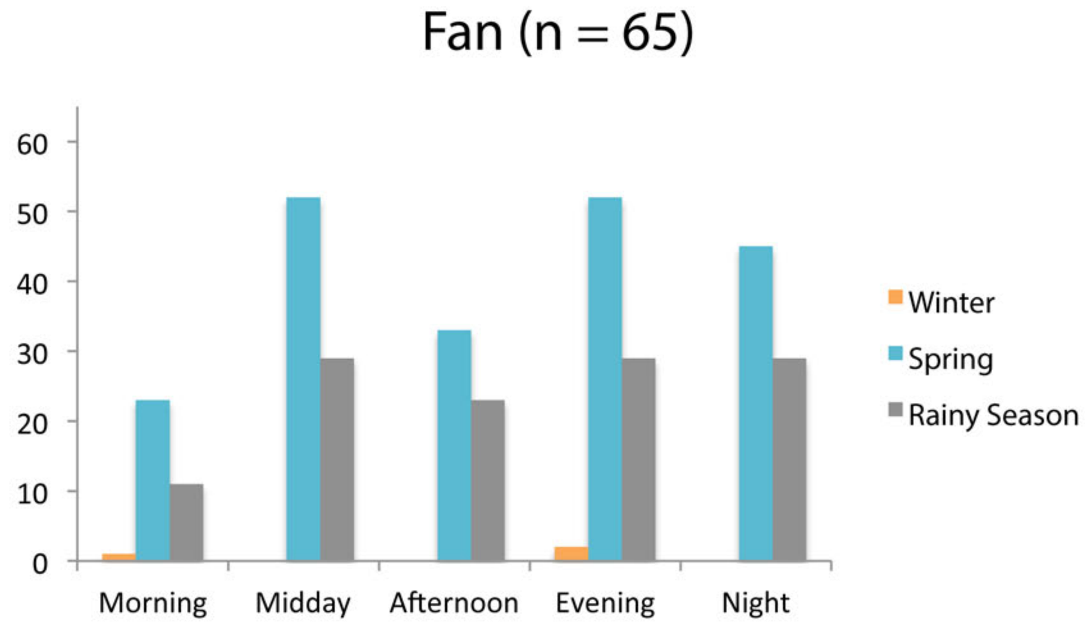
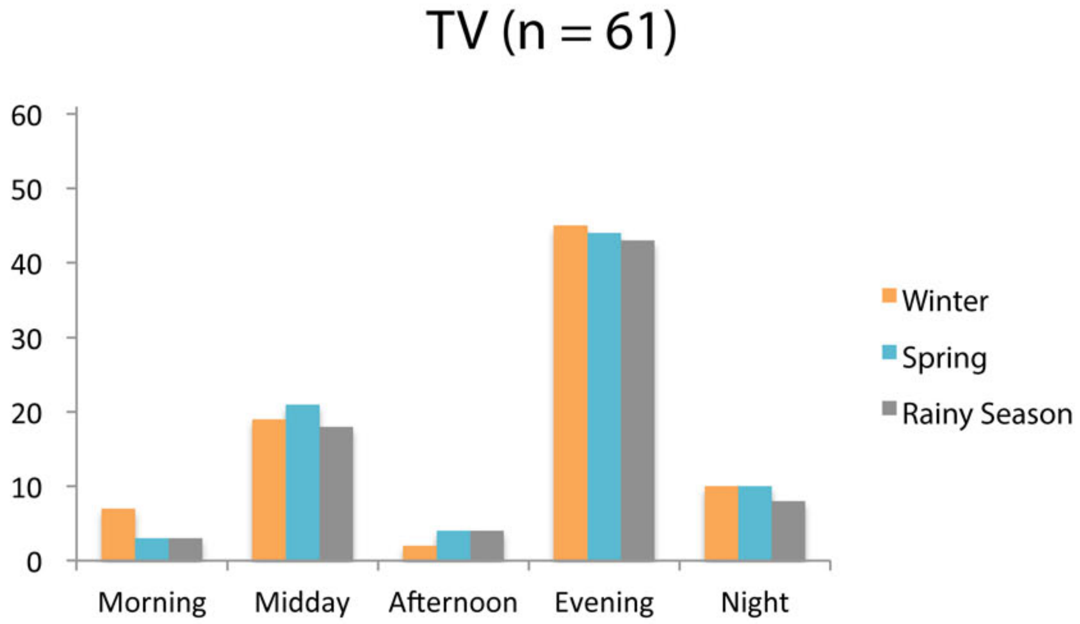


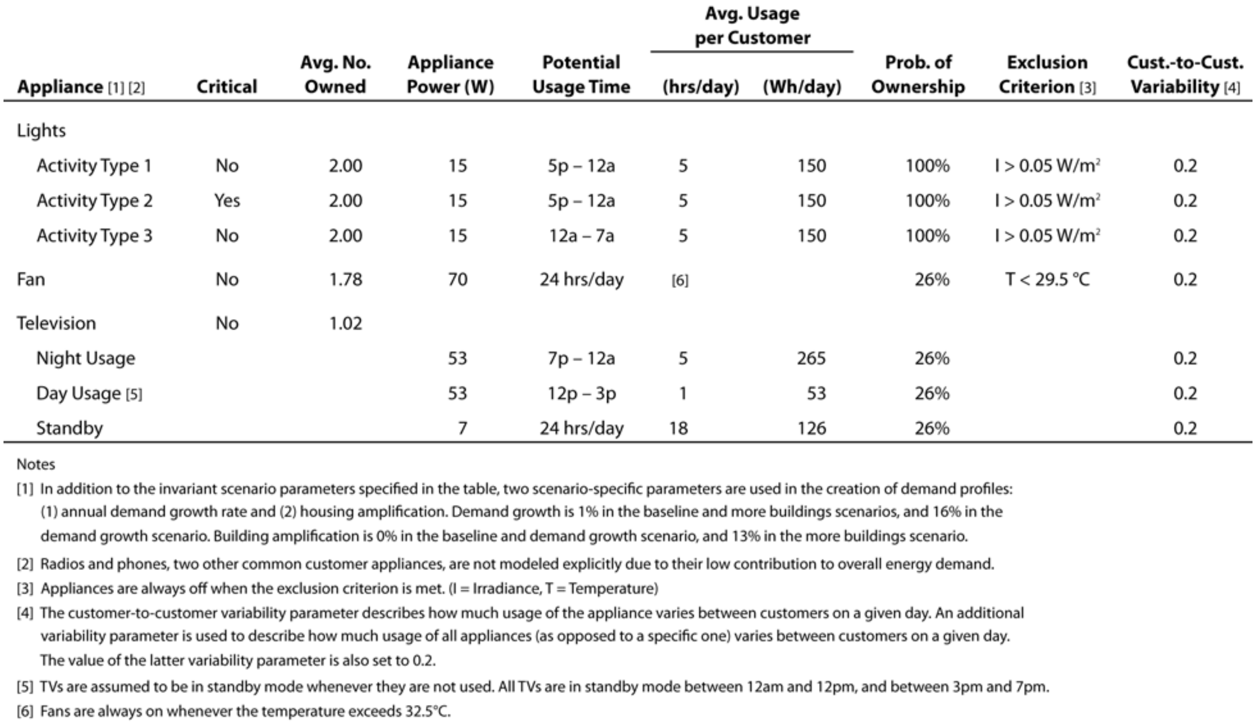
FIGURE 4.5 Times of the day and year that Barabanki residents use a TV



Since we simulate every hour of a year in order to create a demand profile, we also represent hourly weather as well as solar irradiance (watts per meter squared) data from the National Renewable Energy Laboratory's PVWatts Calculator India, an online resource that uses a typical year's weather day to calculate solar potential. We use this information in order to constrain the intervals of time available to use each appliance. For example, fans can only be used in intervals when temperature is greater than 32.5° Celsius.

To account for variability in whether a household actually uses an appliance during the interval specified and to account for the possibility of day-to-day variability we assign a probability value to each type of variability (0.2 and 0.2, respectively). Combining all of these elements together, we come up with the set of demand specifications in Table 4.7 to inform the simulation of the "natural demand" for Vaishali. It is helpful to note that each appliance is modeled as an "activity" for which the distinguishing information is the amount of energy the activity can consume, not the particular appliance type. In other words, "Lights – Activity Type 1" refers to non-critical load that consumes up to 150 watt-hours over the potential time interval in which that activity can occur, it does not refer to any particular type of lights.

TABLE 4.7 Specifications used to model the "Natural Demand" in the Baseline scenario



					Avg. Usage per Customer				
Appliance [1] [2]	**Critical**	**Avg. No. Owned**	**Appliance Power (W)**	**Potential Usage Time**	**(hrs/day)**	**(Wh/day)**	**Prob. of Ownership**	**Exclusion Criterion** [3]	**Cust.-to-Cust. Variability** [4]
Lights									
Activity Type 1	No	2.00	15	5p – 12a	5	150	100%	$I > 0.05$ W/m^2	0.2
Activity Type 2	Yes	2.00	15	5p – 12a	5	150	100%	$I > 0.05$ W/m^2	0.2
Activity Type 3	No	2.00	15	12a – 7a	5	150	100%	$I > 0.05$ W/m^2	0.2
Fan	No	1.78	70	24 hrs/day	[6]		26%	$T < 29.5$ °C	0.2
Television	No	1.02							
Night Usage			53	7p – 12a	5	265	26%		0.2
Day Usage [5]			53	12p – 3p	1	53	26%		0.2
Standby			7	24 hrs/day	18	126	26%		0.2

Notes

[1] In addition to the invariant scenario parameters specified in the table, two scenario-specific parameters are used in the creation of demand profiles: (1) annual demand growth rate and (2) housing amplification. Demand growth is 1% in the baseline and more buildings scenarios, and 16% in the demand growth scenario. Building amplification is 0% in the baseline and demand growth scenario, and 13% in the more buildings scenario.

[2] Radios and phones, two other common customer appliances, are not modeled explicitly due to their low contribution to overall energy demand.

[3] Appliances are always off when the exclusion criterion is met. (I = Irradiance, T = Temperature)

[4] The customer-to-customer variability parameter describes how much usage of the appliance varies between customers on a given day. An additional variability parameter is used to describe how much usage of all appliances (as opposed to a specific one) varies between customers on a given day. The value of the latter variability parameter is also set to 0.2.

[5] TVs are assumed to be in standby mode whenever they are not used. All TVs are in standby mode between 12am and 12pm, and between 3pm and 7pm.

[6] Fans are always on whenever the temperature exceeds 32.5°C.

4.2.3 SCENARIOS

For each scenario, we make the following key assumptions:[22]

CUSTOMER LOCATIONS

Customer locations are first determined using an algorithm that extracts building locations from satellite data. Since the algorithm is still under development, the extracted set of buildings contains far fewer buildings than would be expected based on Vaishali's total population. To account for this, we randomly generate additional buildings, proportional to the density of the extracted set of buildings outputting a final set of buildings for each scenario that more closely reflects the population in the district.[23]

ELECTRIFIED CUSTOMERS

We assume some percentage of all buildings in the data set are already electrified and thus do not need to be considered by REM. We uses data about the number of electrified customers obtained from the NBPDCL in Bihar to determine the number of electrified buildings, then used buffers around the existing grid lines to assign the appropriate number of buildings closest to existing grid lines to be electrified. We removed these buildings from the initial set of buildings data before running REM. Figure 4.6 depicts an image of Vaishali with electrified buildings removed around the existing grid lines (pink) and unelectrified buildings (gray).

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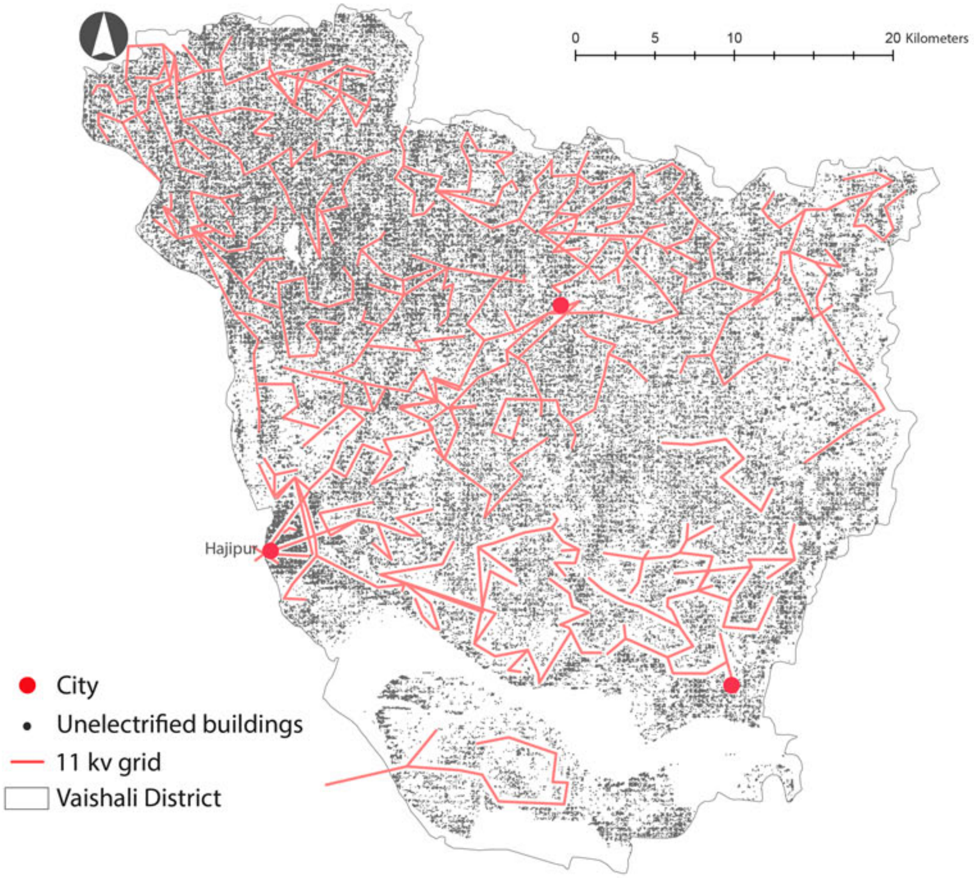
[22] This is an incomplete list of assumptions because many are not strictly relevant to the discussion here. For a more detailed and complete list of assumptions please see Doug Ellman's master's thesis (Ellman 2015).

[23] The full buildings (extracted buildings plus randomly generated buildings) data set is the same for both the Baseline and the Demand Growth scenarios. The full buildings data set for the More Buildings scenario uses a different set of randomly generated buildings, thus most buildings do not match across all three data set hampering the ability to make certain comparisons between all of the scenarios.

FIGURE 4.6 Map of buildings in Vaishali assumed to be unelectrified and the existing 11 kV grid



CUSTOMER ARCHETYPE

We assume all buildings represent the unelectrified residence of one household and that all households have approximately the same demand profile.

DESIGN LIFETIME

REM will design for a five-year project lifetime. The results reflect the optimal technology decision to meet demand in the fifth year.

DISCOUNT RATE

We assume a discount rate of 10%, based on a developing world renewable energy investment scenario developed by Shrimali et al (2014).

COST OF NON-SERVED ENERGY (CNSE)

We assume two values for CNSE, one for critical load ($2.00) and one for non-critical load ($1.50).

What follows is a description of the Baseline scenario and two alternative demand scenarios: the Demand Growth scenario and the More Buildings scenario.

4.2.3.A BASELINE

The Baseline scenario is intended to represent the best estimate of the current state of the electric grid in Vaishali. In the Baseline scenario, all buildings are assumed to have the “natural demand” profile. In this scenario, we assume that electricity demand for each household grows at 1% per year. The specifications for the Baseline scenario are included in Table 4.8.

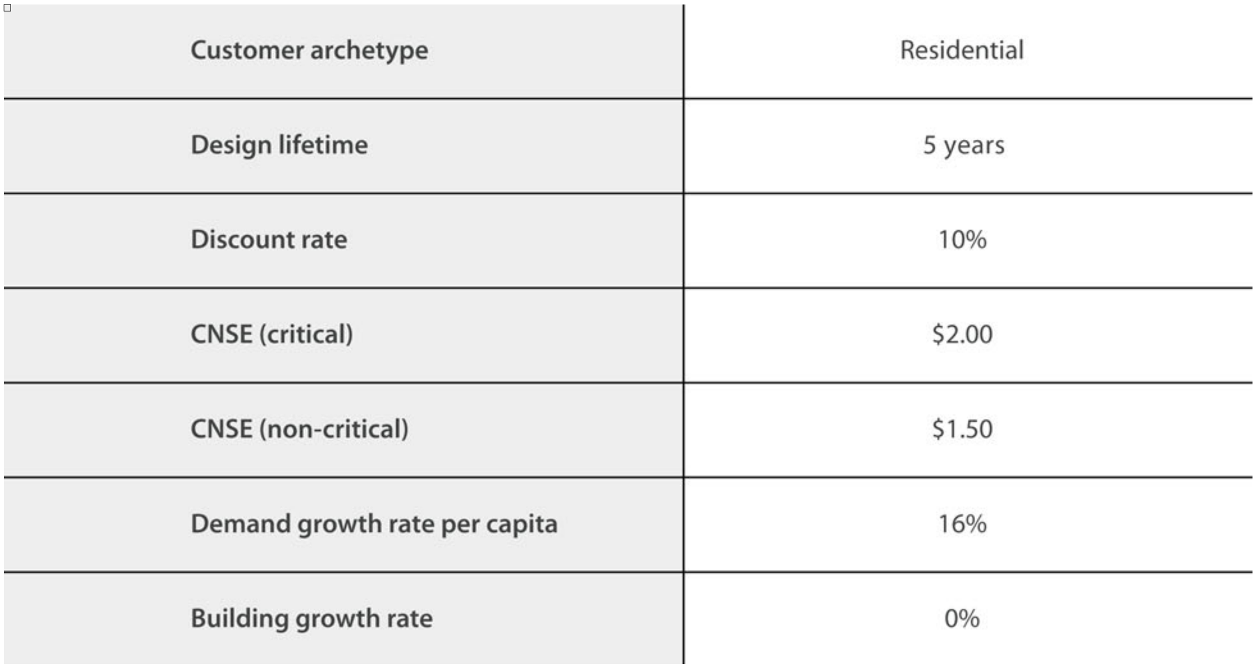
TABLE 4.8 Specifications and assumptions in the Baseline scenario

Customer archetype	Residential
Design lifetime	5 years
Discount rate	10%
CNSE (critical)	$2.00
CNSE (non-critical)	$1.50
Demand growth rate per capita	1%
Building growth rate	0%

4.2.3.B DEMAND GROWTH

The Demand Growth scenario is intended to represent the technoeconomic electrification solutions for Vaishali assuming that the same set of electrified buildings in the Baseline scenario increase electricity consumption more rapidly than assumed in the Baseline. In this scenario, we assume that electricity demand for each household grows at 16% per year or, in other words, demand nearly doubles over the five-year period. The specifications for the Demand Growth scenario are included in Table 4.9.

TABLE 4.9 Specifications and assumptions in the Demand Growth scenario



Customer archetype	Residential
Design lifetime	5 years
Discount rate	10%
CNSE (critical)	$2.00
CNSE (non-critical)	$1.50
Demand growth rate per capita	16%
Building growth rate	0%

4.2.3.C MORE BUILDINGS

The More Buildings scenario is intended to represent the technoeconomic electrification solutions for Vaishali assuming there are many more buildings to electrify than in the Baseline or Demand Growth scenarios. This scenario is designed to demonstrate how solutions might be different if population in Vaishali were to increase. In this scenario, we randomly generate and site 13% more buildings over five years proportional to where other buildings are currently densely pack or dispersed. This process is intended to serve as a very rough proxy for population growth. Between the 2001 and 2011 census, population in Vaishali grew nearly 29%. We selected the growth rate for this scenario based on the assumption that Vaishali's population would grow by nearly 29% in the next ten years, as well. Given that actually simulating population growth would require not only modeling more buildings, but more demand for some buildings, as well as more attention to where additional buildings are located relative to migration patterns in the district, there are serious limitations to the utility of this scenario. Despite these limitations, the exercise is a useful first step at understanding the impact of many more buildings on the results and is designed primarily for demonstration purposes. Finally, in this scenario we assume that electricity demand for each household grows at 1% per year. The specifications for the More Buildings scenario are included in Table 4.10.

TABLE 4.10 Specifications and assumptions in the More Buildings scenario

Customer Archetype	Residential
Design Lifetime	5 years
Discount rate	10%
CNSE (critical)	$2.00
CNSE (non-critical)	$1.50
Demand growth rate per capita	1%
Building growth rate	13%

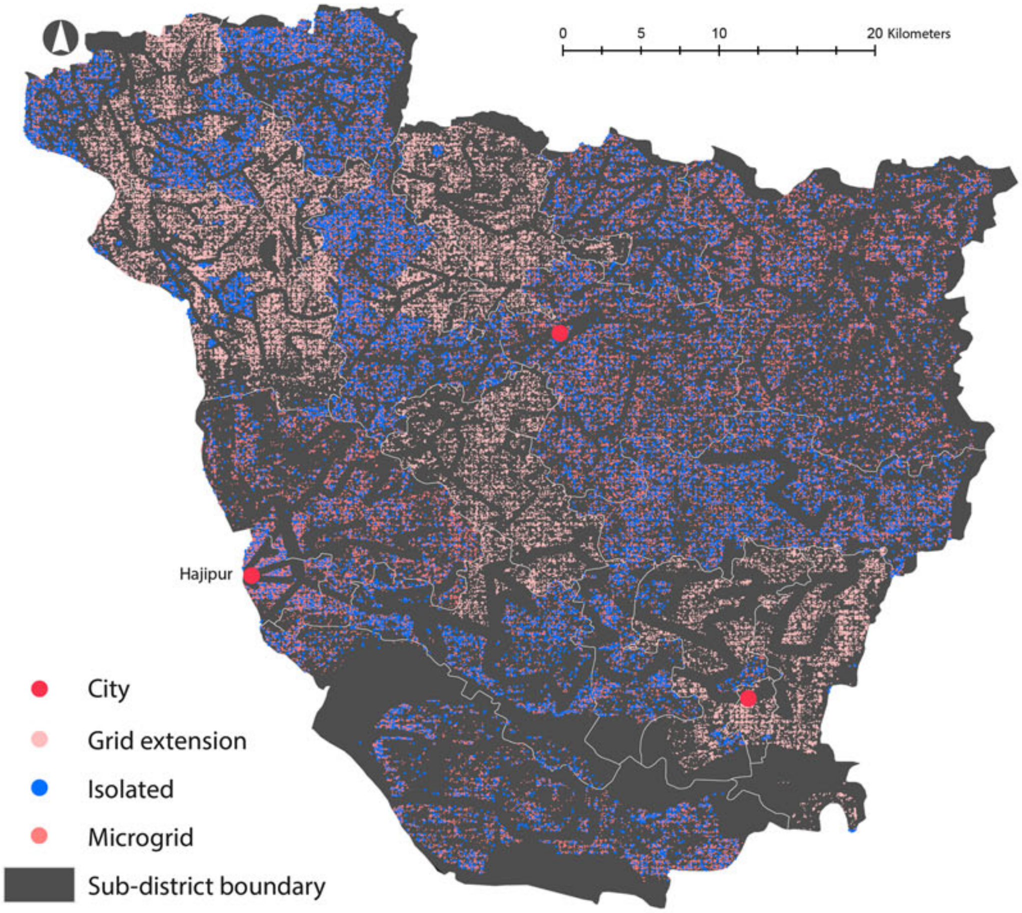
4.2.4 ANALYSIS

The results of each scenario, are presented as maps in Figures 4.7, 4.9, 4.11. Before discussing each scenario, a few notes on how to read the maps. The distinct lines on the map represent the areas around grid lines where we assumed, given the absence of data, that buildings were already electrified (see Figure 4.6). The grid lines are not presented on the map to limit distractions, given the large number of buildings analyzed. A map of Vaishali containing the grid lines is included in Figure 4.6.

4.2.4.A BASELINE

A total of 499,992 unelectrified buildings were considered in the Baseline scenario. The largest percentage of buildings, 58%, were assigned to microgrids, while 35% were assigned to grid extension and the remaining 7% were not assigned to any system (i.e., left unelectrified). To compare costs of different technology solutions and determine the least-cost technology option, the annual financial cost of the system and the annual cost of non-served energy (CNSE) were summed. Some buildings were left unelectrified because the annual financial cost of an individual home system plus CNSE was more expensive than building nothing at all (and incurring the cost of never serving energy).

FIGURE 4.7 of Baseline results by customer



The average annual financial cost of grid connection per building was $44.61 (st. dev = $6.63) while the average cost per kWh of demand served was $0.42 (st. dev = $0.06). On average, the grid served about 40% of demand (st. dev = 0.04%) and the average annual CNSE per building was $130.02 (st. dev = $0.50).

Microgrids ranged in sized, with 16 customers connected to a single system, on average (st. dev = 23). The average financial annual cost of a microgrid connection per building was $87.55 (st. dev = $30.26) and the average cost per kWh of demand served was $0.73 (st. dev = $0.10). Meanwhile, the microgrids served about 48% of demand (st. dev = 24%), on average, and the average annual CNSE per building was $101.28 (st. dev = $54.28).

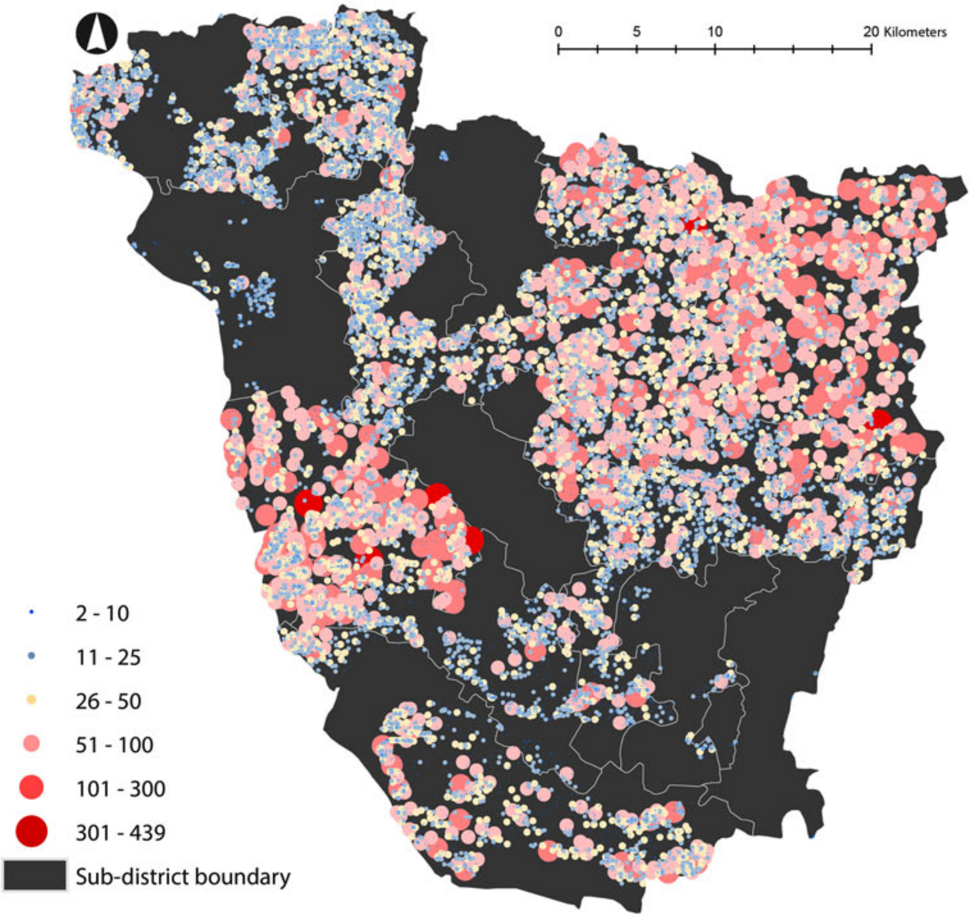
Upon quick inspection, grid connection appears cheaper, in general, however CNSE plays an important role in the cost comparison. The large group of microgrids around Hajipur, the capital city of Vaishali, provides a good example of how CNSE impacts cost comparison between technologies.

The conventional wisdom is that grid extension is the cheapest option in urban and peri-urban areas because buildings are close to each other, making it easier to achieve economies of scale. In this scenario, though, the reliability of the grid near Hajipur is worse, on average, than the reliability of microgrids and the average annual CNSE per grid-connected building is higher. Since the grid is unreliable and the cost of CNSE is high, grid extension becomes more expensive than a microgrid for these buildings, despite population density and the proximity to grid infrastructure.

Microgrid size (in terms of number of people connected to the system) is also relevant to this example. Figure 4.8 shows the distribution of microgrids of different sizes throughout Vaishali (a breakdown of this map by microgrid size is provided in Appendix F).

For a summary table of results aggregated by customer from all three scenarios see Table 4.13

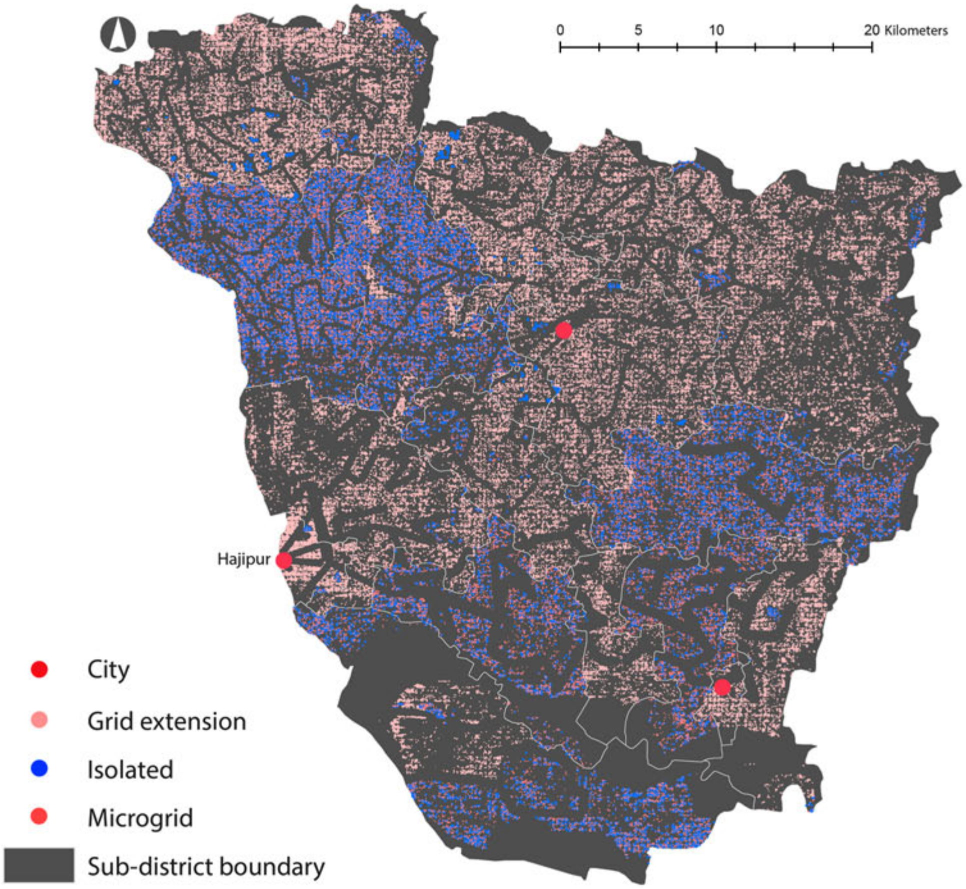
FIGURE 4.8 Microgrid locations by number of people connected to each system in the Baseline scenario



4.2.4.B DEMAND GROWTH SCENARIO

A total of 499,992 buildings were considered in the Demand Growth scenario. The largest percentage of buildings, 60%, were assigned to grid extension, while 36% were assigned to microgrids. The remaining 4% were either left unelectrified or assigned to a solar home system. This is the only one of the three scenarios in which any buildings were assigned to an individual home system (6% of total isolated buildings).

FIGURE 4.9 Demand Growth scenario results by customer



The average annual financial cost of grid connection per building was $72.62 (st. dev = $16.03) while the average cost per kWh of demand served was $0.40 (st. dev = $0.09). On average, the grid served about 40% of demand (st. dev = 0.04%) and the average annual CNSE per building was $227.27 (st. dev = $1.11).

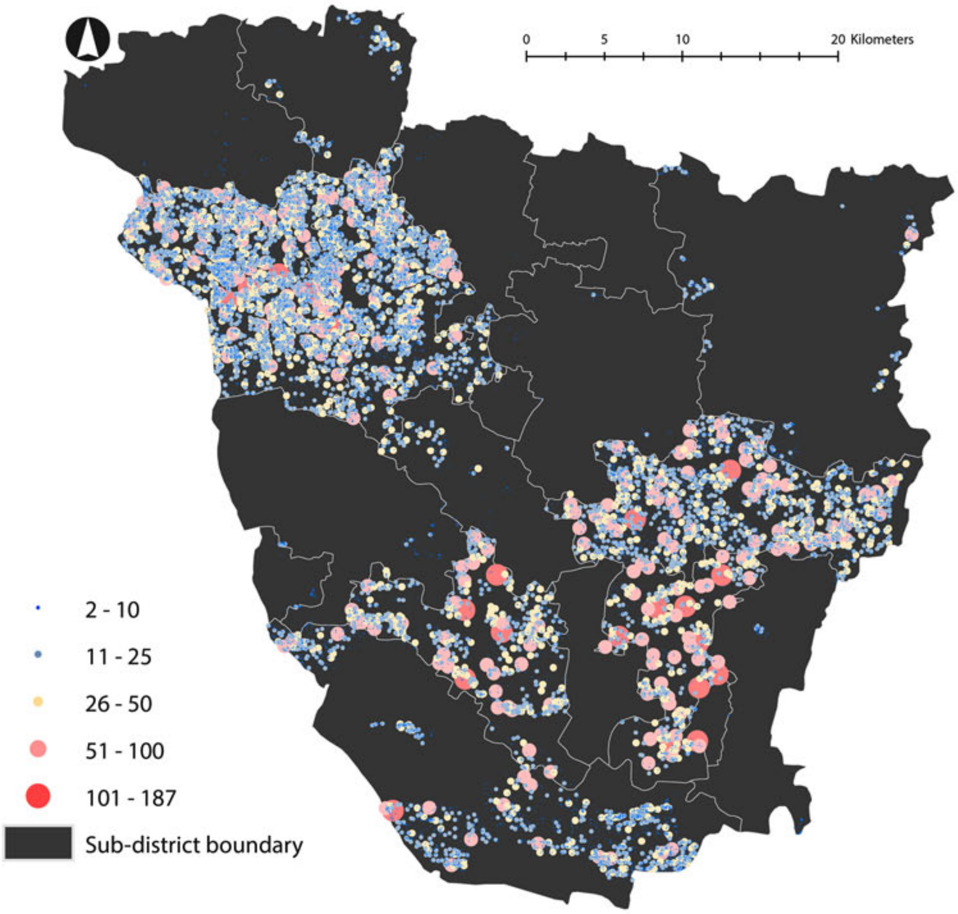
Microgrids were smaller on average than in the Baseline, with eight customers connected to a single system, on average (st. dev = 11). The average financial annual cost of a microgrid connection per building was $172.56 (st. dev = $57.02) and the average cost per kWh of demand served was $0.72 (st. dev = $0.11). Meanwhile, microgrids served about 55% of demand (st. dev = 25%), on average, and average annual CNSE per building was $151.66 (st. dev = $92.84).

In this scenario, the majority of buildings surrounding Vaishali's three urban areas are connected to the grid, likely because it becomes more economical to serve a larger demand.

It is also worth noting that the cost per kWh of energy from an individual home system in this scenario is $1.08, more than double the cost per kWh of grid extension and $0.30 more than the cost per kWh of energy from a microgrid.

Figure 4.10 shows the distribution of microgrids of different sizes throughout Vaishali in this scenario (a breakdown of this map by microgrid size is provided in Appendix G).

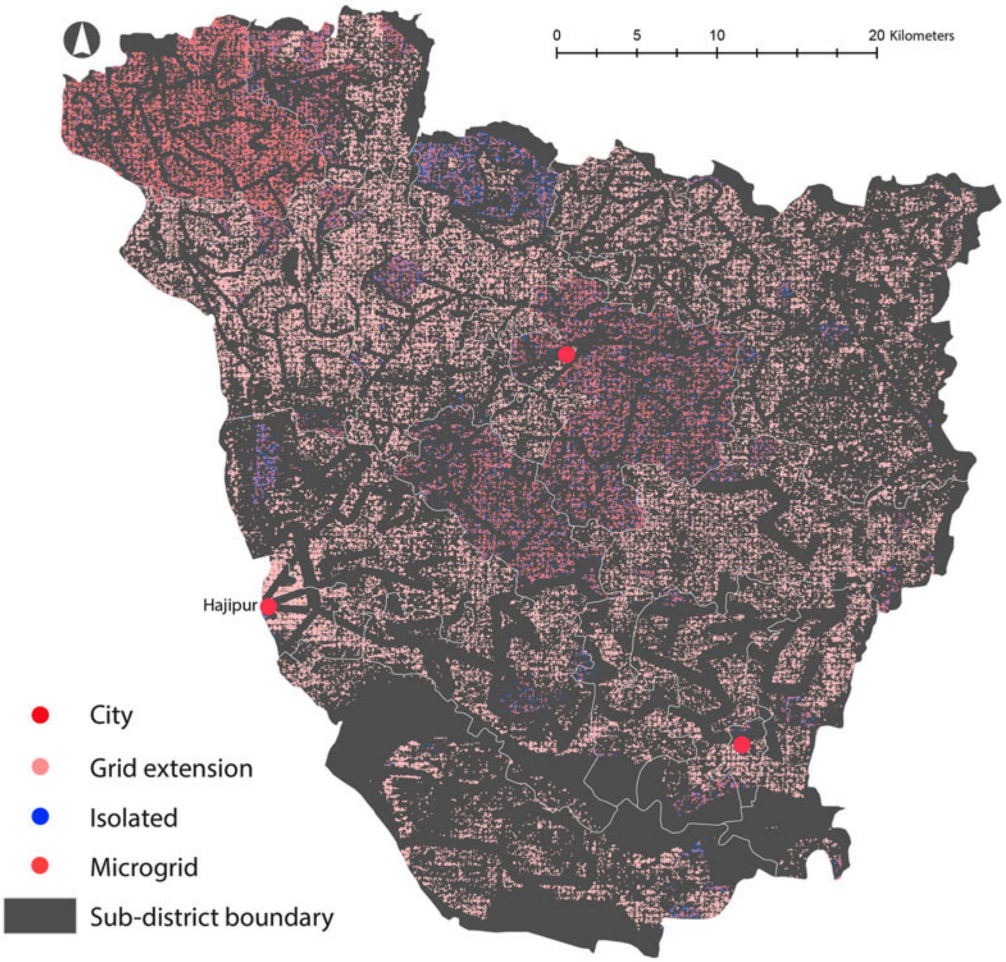
FIGURE 4.10 Microgrid locations by number of people connected to each system in the Demand Growth scenario



4.2.4.C MORE BUILDINGS SCENARIO

A total of 554,080 buildings were considered in the More Buildings scenario. The largest percentage of buildings, 72%, were assigned to grid extension, while 24% were assigned to microgrids. The remaining 4% were left unelectrified. No buildings were assigned to an individual home system (as in the Baseline).

FIGURE 4.11 More Buildings scenario results by customer



The average annual financial cost of grid connection per building was \$40.92 (st. dev = \$7.64) while the average cost per kWh of demand served was \$0.42 (st. dev = \$0.07). On average, the grid served about 40% of demand (st. dev = 0.05%) and the average annual CNSE per building was \$130.33 (st. dev = \$0.93).

Microgrids were similar in size to the Baseline scenario, with 14 customers connected to a single system, on average (st. dev = 28). The average financial annual cost of a microgrid connection per building was $82.62 (st. dev = $30.34) and the average cost per kWh of demand served was $0.75 (st. dev = $0.09). Meanwhile, microgrids served about 43% of demand (st. dev = 22%), on average, and average annual CNSE per building was $111.11 (st. dev = $51.53).

Figure 4.12 shows the distribution of microgrids of different sizes throughout Vaishali in this scenario (a breakdown of this map by microgrid size is provided in Appendix H).

FIGURE 4.12 Microgrid locations by number of people connected to each system in the More Buildings scenario

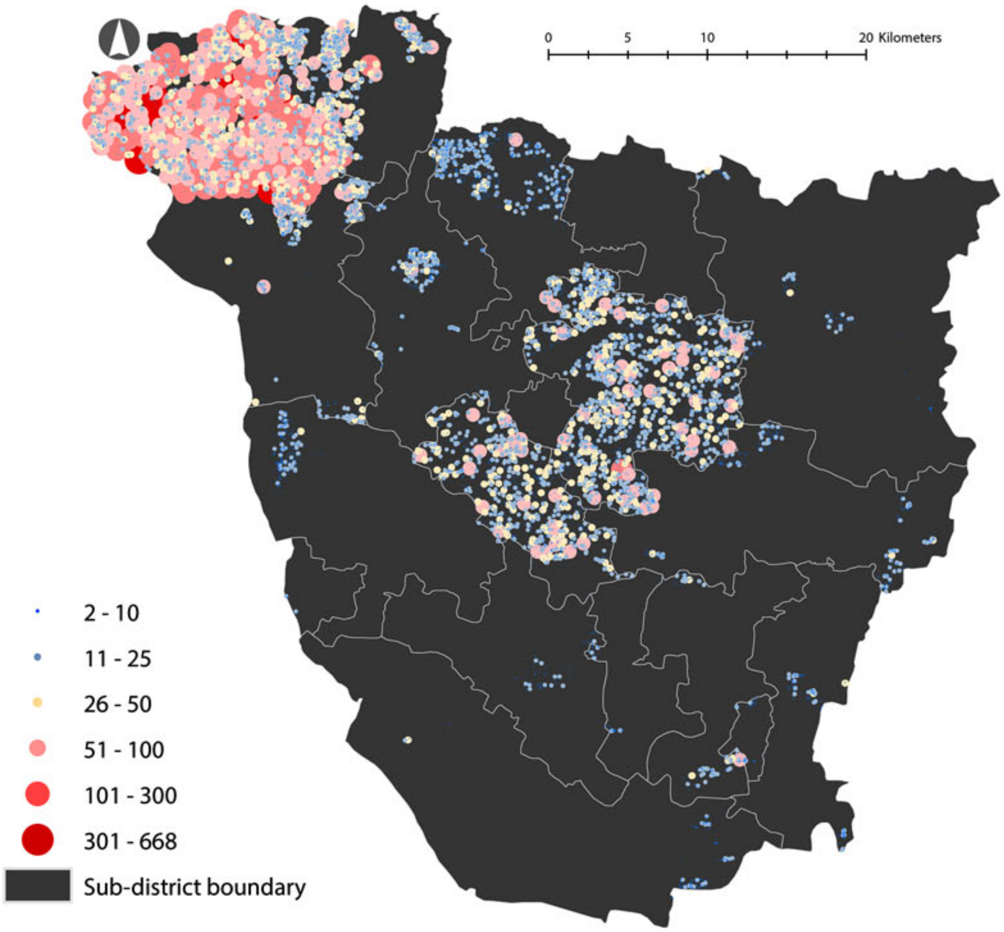


TABLE 4.11 Summary results from all three scenarios

	Scenario					
	Baseline		Demand Growth		More Buildings	
System	Customer Assignments	% of Total	Customer Assignments	% of Total	Customer Assignments	% of Total
Grid Extension	173,394	34.7	302,308	60.5	397,015	71.7
Microgrid	290,852	58.2	178,000	35.6	134,969	24.4
Isolated	35,676	7.1	19,614	3.9	22,096	4.0
Home Systems	*0*	*0.0*	*1,202*	*0.2*	*0*	*0.0*
Total	499,922	100.0	499,922	100.0	554,080	100.0

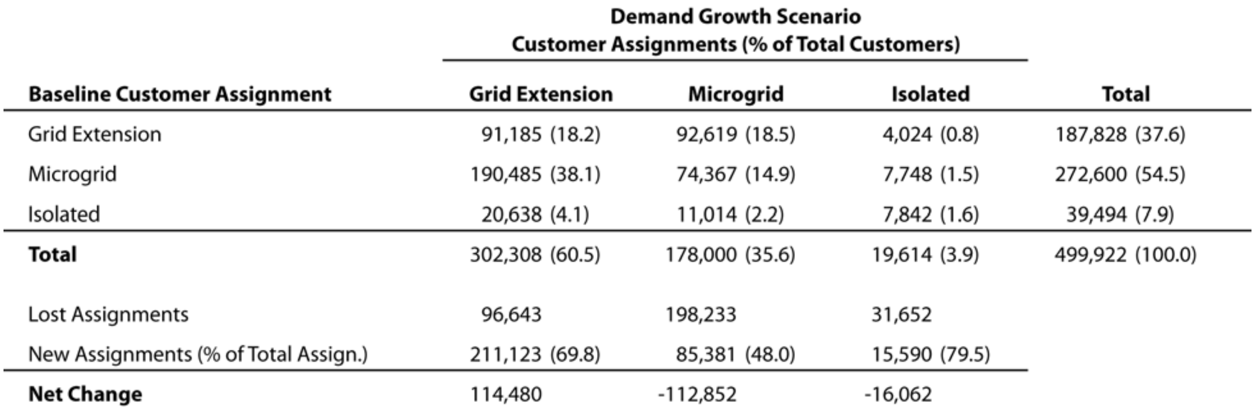
TABLE 4.12 Summary of cost and performance results by system for all three scenarios

	Scenario					
	Baseline		Demand Growth		More Buildings	
System	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Grid Extension						
Annual Financial Cost per Building	$44.61	$6.63	$72.62	$16.03	$40.92	$7.64
Cost of Non-Served Energy per Building	$130.02	$0.50	$227.27	$1.11	$130.33	$0.93
Percentage of Demand Served	39.6%	0.0%	39.6%	0.0%	39.6%	0.0%
Cost per KWh	$0.42	$0.06	$0.40	$0.09	$0.42	$0.07
Microgrid						
Number of Building Connections per Microgrid	16	23	8	11	14	28
Annual Financial Cost per Building	$87.55	$30.26	$172.56	$57.02	$82.62	$30.34
Cost of Non-Served Energy per Building	$101.28	$54.28	$151.66	$92.84	$111.11	$51.53
Percentage of Demand Served	47.7%	23.8%	54.7%	25.3%	43.2%	21.7%
Cost per KWh	$0.73	$0.10	$0.72	$0.11	$0.75	$0.09
Isolated Home Systems						
Annual Financial Cost per Building	Not applicable		$28.80	$0.00	Not applicable	
Cost of Non-Served Energy per Building	Not applicable		$352.54	$0.00	Not applicable	
Percentage of Demand Served	Not applicable		5.8%	0.0%	Not applicable	
Cost per KWh	Not applicable		$1.08	$0.00	Not applicable	

4.2.4.D COMPARISON BY CUSTOMER

Under the Baseline scenario, the largest percentage of consumers were assigned to microgrids (58%), however in both the Demand Growth scenario and the More Buildings scenario the majority of customers were assigned to grid extensions (60% and 72%, respectively). Table 4.14 shows the comparison of percentage of technology decisions by customer between the Baseline and the Demand Growth scenarios.

TABLE 4.13 Comparison of technology decisions between the Baseline and Demand Growth scenarios



	Demand Growth Scenario Customer Assignments (% of Total Customers)			
Baseline Customer Assignment	**Grid Extension**	**Microgrid**	**Isolated**	**Total**
Grid Extension	91,185 (18.2)	92,619 (18.5)	4,024 (0.8)	187,828 (37.6)
Microgrid	190,485 (38.1)	74,367 (14.9)	7,748 (1.5)	272,600 (54.5)
Isolated	20,638 (4.1)	11,014 (2.2)	7,842 (1.6)	39,494 (7.9)
Total	302,308 (60.5)	178,000 (35.6)	19,614 (3.9)	499,922 (100.0)
Lost Assignments	96,643	198,233	31,652	
New Assignments (% of Total Assign.)	211,123 (69.8)	85,381 (48.0)	15,590 (79.5)	
Net Change	114,480	-112,852	-16,062	

The same set of extracted and randomly generated buildings were used in both the Baseline and Demand Growth scenarios making it possible to see how different assumptions about demand changed the technology decision (or not) for any given household. It was not possible to compare either the Baseline or Demand Growth scenario with the More Buildings scenario because of the way in which the buildings were randomly generated to produce the third scenario.

Under the Demand Growth scenario, 62% of customers were assigned a different system than the one they were originally assigned under the Baseline scenario. Of those assigned to a different system, 38% of those assigned to a microgrid and 4% of those assigned to be isolated under the Baseline scenario were assigned to grid extension under the Demand Growth scenario. In total, more than 200,000 customers were re-assigned to the grid under the Demand Growth scenario, while 91,185 (18%) remained connected to the grid. While this is in no way conclusive evidence, this pattern fits with the hypothesis that assuming a higher level of electricity demand might make it more cost effective to connect people to the centralized grid. In the maps in Figure 4.13-4.15, system changes by building are displayed broken out by the original technology assignment made in the Baseline scenario. Buildings are colored according to the technology assignment made under the Demand Growth scenario.

FIGURES 4.13 – 4.15 Technology assignment under the Demand Growth scenario by original assignment in the Baseline scenario

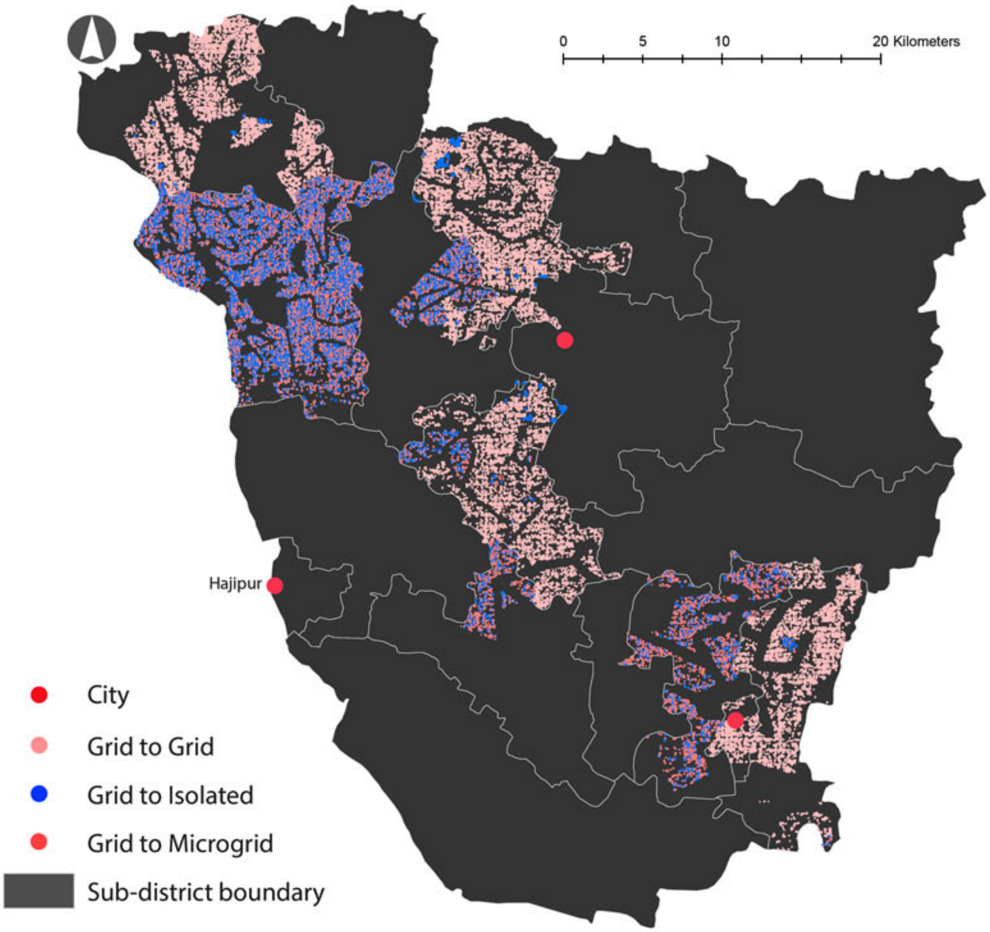


FIGURE 4.14

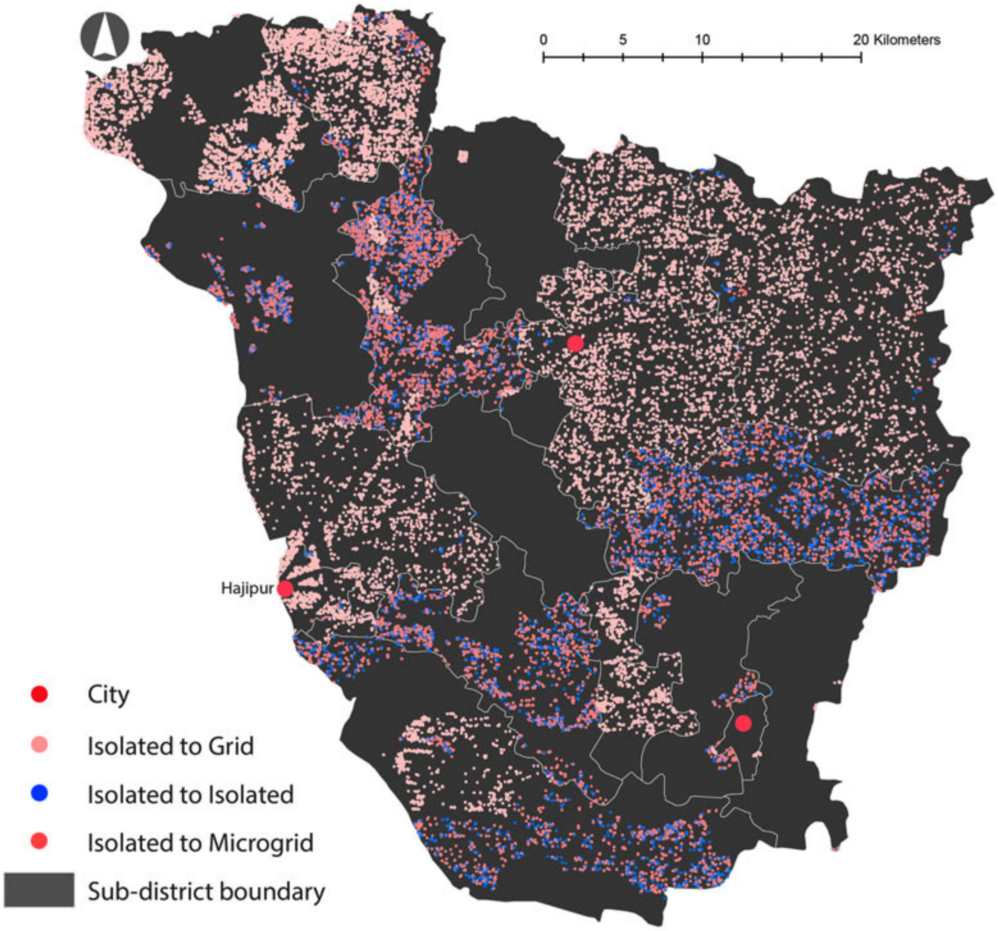
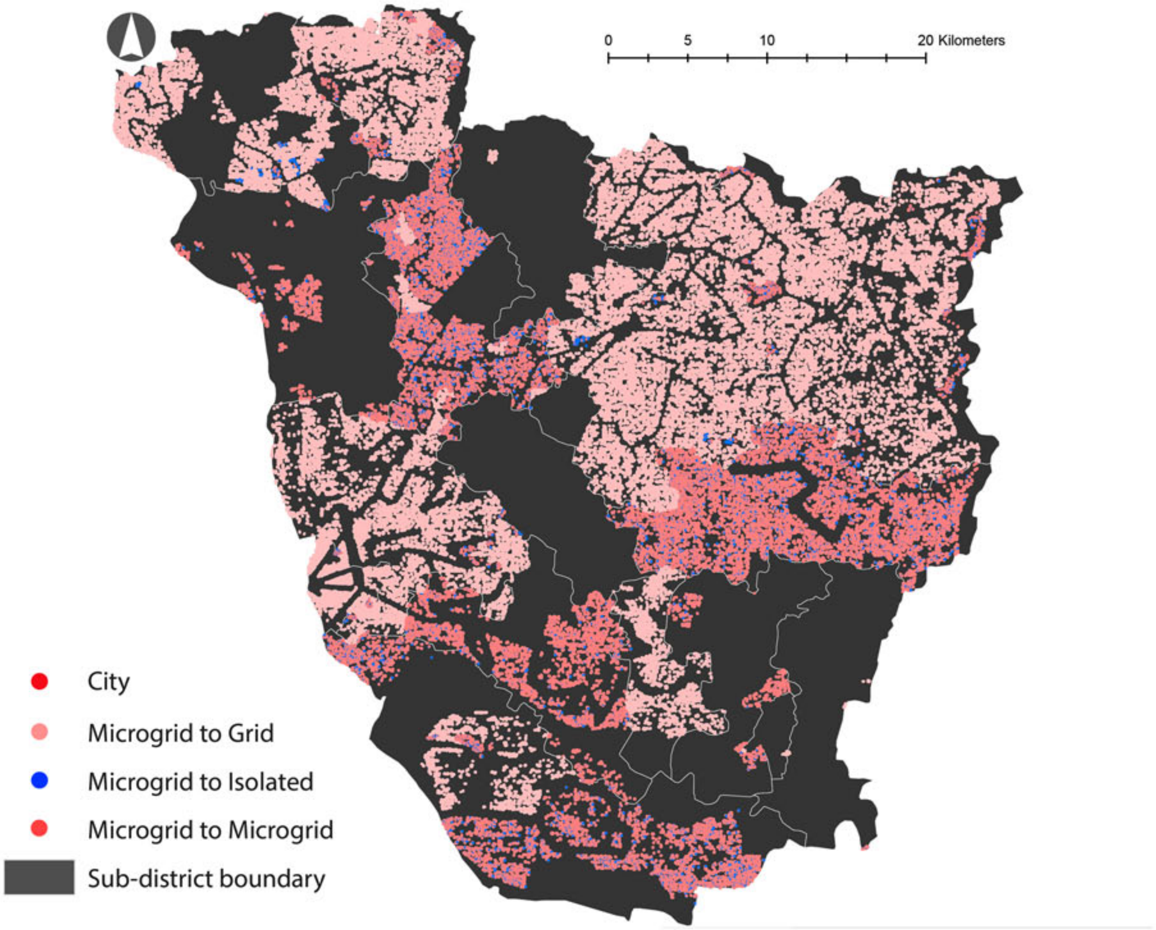

0
5
10
20 Kilometers
Hajipur
City
Isolated to Grid
Isolated to Isolated
Isolated to Microgrid
Sub-district boundary

FIGURE 4.15



Interestingly, 2% of customers initially assigned to the grid and another 2% initially assigned to a microgrid (a total of 15,590 customers) were left unelectrified or assigned to an individual home system in the Demand Growth scenario. While this seems strange, it is possible that these results may be linked to random differences in the REM pre-clustering stage (see description in Chapter 3), which is slightly different every time the model is run, even if the set of buildings data remains the same.

4.2.5 DISCUSSION

Demand is a tricky variable when it comes to planning for rural electrification. These scenarios highlight why assessing demand for unelectrified households is both quantifiable and yet unknowable at the same time. It is quantifiable in the sense that it is possible to gather sufficient data about demand to produce (or predict) a reasonably plausible demand profile for a newly electrified household or to gather data about demand directly from electrified buildings using surveys or meters. Demand is unquantifiable in the sense that there is no way to really know what an unelectrified household will consume once they have a grid connection. The discussion of demand earlier in this chapter emphasizes the various factors that could influence a household's electricity demand, not to mention the rate at which that demand could change over time.

REM's utility in the planning process, particularly when it comes to demand, is that it allows the planner, policymaker, or project developer to ask questions about demand in a variety of ways and get a sense of how different demand assumptions affect broad planning goals. For example, more knowledge about how demand varies spatially in Vaishali could result in very different technology decision for urban versus rural versus peri-urban residents. Furthermore, more information about different types of demand, such as commercial, industrial, or agricultural demand, could lead to substantially different technology decisions and system configurations that would be relevant to budget or business model constraints.

4.2.5.A OTHER MAJOR LIMITATIONS

Although a statistical analysis of these results is outside the scope of this thesis, statistical correlation is not necessary to know that demand is not the only variable influencing technology decisions in these scenarios. There are several modeling issues to point out that not only produce oddities in the patterns revealed by the visual results, but also produce oddities in the cost comparison process. I will briefly discuss these limitations as they are important to know about in order to understand the potential role of REM in any future planning process. They are also interesting fodder for future research.

THE LIMITS OF CLUSTERING AND THE MODIFIABLE AREAL UNIT PROBLEM (MAUP)

The clustering process discussed in Chapter 3 groups buildings together at two levels. First, buildings are divided into Vaishali's sub-districts so that no system can cross over administrative boundaries. Second, buildings are clustered into groups called analysis regions, for which technology costs are evaluated and system decisions are made. These analysis regions, however, are not fixed. They can vary from scenario to scenario such that any given house may not always belong to the same analysis region in every run of REM even if all of the data is the same. This artifact of the modeling logic can produce changes in technology decisions that have little do with the assumptions about demand. In other words, the results are vulnerable to the modifiable areal unit problem (O'Sullivan and Unwin 2010), which affects point-based results such that they are at least partially driven by the arbitrary boundaries around the points.

Arbitrary, however, is too strong a word for the phenomenon here. Administrative boundaries, for example, may or may not be arbitrary depending on the governance structure in any given sub-district, since it may not be legally or politically feasible to design systems (particularly microgrids) that cross boundaries. In other words, just because distinctions look arbitrary at the regional level, does not mean they are politically arbitrary at the local level.

That said, this phenomenon does help explain why groups of customers assigned to different types of systems appear to follow sub-district boundaries very closely in some cases.

ASSUMPTIONS ABOUT THE COST OF NON-SERVED ENERGY

As I mentioned in the comparison between the Baseline and the Demand Growth scenario, some houses were assigned to grid extension in the Baseline that were assigned to a microgrid or left unelectrified in the Demand Growth scenario. Practically, this result is confusing since one would expect that a building connected to the grid at low demand would still need to be served by the grid at a higher level of demand. From a modeling perspective, this may be partially explained by the clustering limitation discussed above, but it could also be compounded by cost assumptions. Since the cost comparison is a function of both the annual financial cost of a system and the annual CNSE, even slight variations in CNSE could tip the balance toward one technology option or another, though perhaps either would be cost-effective from a rational technoeconomic perspective.

Further investigation into the cost comparisons between analysis regions that determine technology decisions and sensitivity analysis might reveal more insight about how assumptions about CNSE influence the model results. That said, there are also other, ways to model account for unreliability that do not require making assumptions about the value of an hour without electricity to a given consumer. One way to do this would be to impose a reliability or quality of service target, which would force technology choices that could meet this threshold of service (Perez-Arriaga 2013). In all likelihood, a future version of the model will constrain reliability in this way.

CONCLUSION

India is facing an enormous rural electrification challenge, but calling it purely a rural problem is not quite fair. The implications of rural electricity access (or the continued lack thereof) will have ripple effects on many aspects of the economy, including people living in urban areas. This problem undoubtedly requires effective planning by both public and private stakeholders, but defining the problem and the planning approach are just as much of a priority as achieving the end goal. The process, not just the outcome, has implications for rural electrification policy as well as for the off-grid electrification market.

Like many so-called wicked problems, the problem with rural electrification remains difficult to define: there is little agreement on what constitutes energy poverty or energy access. As a result, planners from different schools of thought disagree on the best way to ensure access to electricity for all in India, and in other developing countries. These obstacles are further compounded by limited access to information about the people who need electricity services.

Technoeconomic models can help make large-scale technology decisions between different electrification modes, but cannot account for a variety of sociotechnical, socioeconomic, socio-political, social, and political factors that are difficult or impossible to quantify. They also impose a planning perspective that is heavily removed from the people actually being served. Those who unquestioningly use the results of these models to inform policymaking run the risk of designing policies and programs that may seem cost-effective, but do not meet the needs of real people.

Communicative planning approaches, on the other hand, emphasize defining the problem from the perspective of every stakeholder involved on both the supply and demand side. These approaches attempt to design solutions based on local needs and preferences, however, they are generally considered too difficult to implement quickly for a large number of people. As a result, policymakers may easily write them off as inefficient.

Planning to achieve universal access to electricity in India will require a combination of planning approaches that target different aspects of this systemic issue. My research group aspires to develop a planning methodology for India that can accomplish exactly this complex task. It involves the development of a technoeconomic regional planning model called the Reference Electrification Model (REM) as well as a focus on exploring methods to better understand factors that are not quantifiable and create other types of non-financial costs. This thesis represents the first attempt, in that broader effort, to highlight the various issues that influence rural electrification planning and to demonstrate ways to better understand those issues by combining insight from both the technocratic planning paradigm and the communicative planning paradigm.

Multiple factors influence the planning process and those factors take on different nuances depending on the lens through which you view them. As a means of focus in the qualitative analysis, I consider factors that a group of planners report are most influential to the success of rural electrification efforts and draw on insights from many more stakeholders to illuminate the complexity of the social acceptance of electrification technologies. I specifically focus on factors that fit within a framework of social acceptance because consumer perceptions are difficult to quantify. Thus, planners often overlook them until it is too late and both time and money have already been invested in a project or a government program. These technology adoption and perception issues are also personally interesting because they are so deeply connected to the interaction between humans and technology.

In many ways, it is not surprising that issues related to consumer perception and technology adoption were most salient to the planners surveyed, once overall importance ("critically important" and/or "important") was taken into account. In my experience, superficial conversations with planners (as well as several reports) focused first on technoeconomic factors, but longer conversations and interviews frequently revealed many non-technical issues that complicated typical technoeconomic questions. Similarly, in the survey, issues that could belong in both the technoeconomic and at least one other non-technical category received the highest percentage of "critically important" ratings (though agreement on any one factor was inconsistent), however ranking factors by overall importance revealed that less obvious issues had much stronger agreement. Further research should expand on the pilot survey instrument used in this thesis to gain further insight along this theme since more rigorous evidence of this finding could have important implications for how policymakers and entrepreneurs think about the financial and transactional costs associated with rural electrification.

For the quantitative component, I analyze electricity demand, a particularly tricky factor that is both technoeconomic and not, depending on your perspective. I use scenario analysis to demonstrate how three different assumptions a planner might make about demand affect the technology decisions produced by REM. What emerges is a clear indication that the way in which a planner chooses to represent a complex factor like demand can have observable differences in the least-cost technical solution. Clear limitations to the modeling approach emerge that raise important questions about modeling CNSE and reliability, related factors that also span the divide between technoeconomic factors and non-technoeconomic factors. These questions revolve around how to determine the value of CNSE, whether attempting to determine this value is a useful pursuit, and how to understand the influence of unreliability on electrification technology decisions. They each pose topics for future research.

The scenario analysis also reveals how practical computing limitations ultimately could have an influence on REM results. These limitations, in combination with the many assumptions made in order to model demand (building locations, costs, etc.), raise very important questions about how to know when to “trust” model results as a rural electrification planner.

Taking these two methodologies together, there are clear opportunities to use the insights from the qualitative analysis to inform the specification of scenarios to run using REM. Future research could derive more focused insight by implementing the qualitative methods specifically in the particular region being studied — in this case, Vaishali District. Such work would certainly yield more specific policy recommendations for Vaishali.

Still, the goal of melding (or transcending) these two opposite planning visions is far from complete. Over the course of this research, much of the time spent studying the non-technoeconomic factors in detail occurred alongside the development of REM. In fact, from our very first exploratory research trip to India, we were both seeking to understand the rural electrification problem in India and trying to vet our idea that a planning model would help planners make technology decisions more quickly and more systematically. This project structure made sense given the two-year timeline and limited time we had to spend in the field, however, it means that many decisions were made about REM before we fully understood the extent and the depth of the non-technoeconomic factors. The version of REM used to model the scenarios presented in this thesis could reasonably be referred to as version 1.0 — the earliest completely functioning version of the model — and so could change substantially subject to more research into the dynamics of the non-technoeconomic factors. By the same token, the overall planning methodology presented here, including the qualitative approach, should be considered version 1.0. As much as I aspired to create something transdisciplinary, the structure of my thesis, itself, maintains a disciplinary divide — revealing the extent to which this methodology is still very much a work in progress.

So, the inevitable question: how should a policymaker, planner, or off-grid entrepreneur approach rural electrification planning? What should they *do*? In the absence of our final planning methodology, three opportunities emerge for various types of planners. Taken together, the three analyses revealed that consumer perception and demand represent two broad types of issues that stakeholders engaged in this project encountered and struggled with. This finding is an indication that planners may be able to improve outcomes for otherwise technoeconomically sound projects in a few ways (though there might have been more if all 39 original factors had been considered). One idea is that regulators could create and enforce quality standards through regulation that mandates closer monitoring of off-grid businesses. These standards should ensure that off-grid systems are reliable, easy to maintain, and offer the sort of electricity service that customers value. Standards could help reduce skepticism about solar-powered microgrids and home systems, assuming consumers are involved in the standards development process and are convinced that they are not being swindled. Another idea would be for electrification planners to demonstrate the functioning of various electrification technologies and engage potential customers in awareness programs that help them learn about the trade offs between different electrification technologies relative to their own assessment of their electrification needs. A third idea is for planners to use previous studies from locations similar to where they work to estimate potential transaction costs associated with altering preconceived attitudes towards certain electrification technologies that may otherwise meet electricity needs effectively.

In India, the recent political shift heralded by Prime Minister Narendra Modi has brought hopes of a regulatory shift (i.e., specific off-grid electrification regulation) and a policy shift (i.e., an amendment to the National Electricity Act of 2003) that has the potential to substantially alter the off-grid electrification environment. Future work must also focus on understanding these dynamics in order to expand on the methodological skeleton presented in thesis in a way that is robust to whatever new political, policy, or regulatory order (or disorder) emerges. Such work should also drive an ongoing discussion about our research group's role in the off-grid electrification space and continued questioning about whether we are solving the right problem. Only if we are constantly returning to the definition of the problem and our ideas for solving it can we truly hope to develop an adaptive, robust, transdisciplinary approach to electricity service delivery in India and elsewhere.

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APPENDIX

APPENDIX A: RECORD OF INTERVIEWS, PERSONAL COMMUNICATIONS, AND SITE VISITS

INTERVIEWS

[1] Ananth Aravamudan (Senior Technical Manager, SELCO) in discussion with the author, March 2015.

[2] Bharath Jairaj (Senior Associate, World Resources Institute) in discussion with the author, February 2015.

[3] Mrinmoy Chattaraj (Independent Consultant) in discussion with the author, February 2015.

[4] Sushanta Chatterjee (Joint Chief, Regulatory Affairs, Central Electricity Regulatory Commission) in discussion with the author, February 2015.

[5] Emily Rains (Associate, IDInsight) in discussion with the author, February 2015.

[6] Sanjoy Sanyal (Country Director, New Ventures India) in discussion with the author, February 2015.

PERSONAL COMMUNICATIONS

[8] Gajendra Haldea (National Planning Commission), meeting with author and research team, July 29, 2013.

[9] Akanksha Chaurey (CEO, IT Power Consulting Private Ltd.) and Rakesh Kacker (former Minister of Food Processing), meeting with author and research team, July 29, 2013.

[10] Alok Jindal (Fellow and Area Convenor, TERI) meeting with author and research team, July 30, 2013.

[11] Anil K Varshney and Veena Sinha (Ministry of New and Renewable Energy) meeting with author and research team, July 31, 2013.

[12] Ratan Watal and staff (Secretary, Ministry of New and Renewable Energy) meeting with author and research team, July 31, 2013.

[13] BK Chaturvedi (Member, National Planning Commission) meeting with author and research team, August 1, 2013.

[14] Jairam Ramesh (Minister, Ministry of Rural Development) meeting with author and research team, August 1, 2013.

[15] Luke Jordan (Private Sector Development Specialist, India, World Bank) meeting with author and research team, August 1, 2013.

[16] Harish Hande and SELCO staff, meeting with author and research team, August 5, 2013.

[17] SELCO staff, meeting with author and research team, August 6, 2013.

[18] SELCO staff, meeting with author and research team, August 7, 2013.

[19] Simpa Networks, call with author and research team, September 5, 2013.

[20] Akanksha Chaurey (CEO, IT Power Consulting Pvt. Ltd.) meeting with author and research team, January 15, 2014.

[21] Amit Gupta and Sandeep Singal (Tata DoCoMo) meeting with author and research team, January 16, 2014.

[22] Jacob Dickinson (CTO, Gram Power) and Yashraj Khaitan (CEO, Gram Power) meeting with author and research team, January 2014.

[23] Jyoti Dar (Director, Kuvam Energy) and Abhijit Halder (Project Lead, Kuvam Energy), meeting with research teammate, Brian Spatocco, January 2014.

[24] Praveen Bhasin (NextGenTech, Minda Group) meeting with author and research team, January 17, 2014.

[25] Dinesh Gupta and Shri Har (OMC Power) meeting with author and research team, January 17, 2014.

[26] Ananth Aravamudan and Jon Basset (SELCO) meeting with author and research team, January 2014.

[27] Ganesh Das (Head of Group – Strategy, Tata Power Delhi Distribution Limited), Arunabha Basu (Chief of Technology and Systems, TPDDL), and Praveer Sinha (Chief Executive Director, TPDDL) meeting with author and research team, January 17, 2014.

[28] Govinda Raju (Director, HESCOM) and Shri P. Ravikumar (Energy Secretary, Karnataka) meeting with author and research team, July 14, 2014.

[29] Bharath Jairaj (World Resources Institute), Anjana Agarwal (World Resources Institute), and Pamli Deka (New Ventures India), meeting with author and research team, July 14, 2014.

[30] Ananth Aravamudan (Associate Director, SELCO) meeting with author and research team, July 15, 2014.

[31] Umesh Narayan Panjiar (Chairman, Bihar Electricity Regulatory Commission) meeting with author and research team, July 16, 2014.

[32] Colonel Singh (HUSK Power) meeting with author and research team, July 17, 2014.

[33] Pratayaya Amrit (Chairman and Managing Director, Bihar Energy Department/State Power Holding Company) and Abhijeet Kumar (Technical Secretary, Bihar Energy Department) meeting with author and research team, July 17, 2014.

[34] Subha Sharma (Secretary, Central Electricity Regulatory Authority) and other CERC members, meeting with author and research team, July 21, 2014.

[35] Akanksha Chaurey (CEO, IT Power Consulting Pvt. Ltd.) meeting with author and research team, July 22, 2014.

[36] Ganesh Das (Head of Group – Strategy, Tata Power Delhi Distribution Limited), Tarun Batra (Head of GIS, TPDDL) and others, meeting with author and research team, January 19, 2015.

[37] TK Bosh (Rural Electrification Corporation) meeting with author and research team, January 19, 2015.

[38] Mani Khurana (Energy economist, World Bank) and Julia Bucknall (World Bank), meeting with author and research team, January 20, 2015.

[39] Dr. Tripathi (Division Head, Ministry of New and Renewable Energy), Sanjay Prakash (Central Electricity Regulatory Commission), and Mrinmoy Chattaraj (Independent Consultant), meeting with author and research team, January 21, 2015.

[40] Praveer Sinha (CEO, Tata Power Delhi Distribution Limited), Ganesh Das (TPDDL), Tarun Kapoor (TPDDL), and others, meeting with author and research team, January 21, 2015.

[41] D. Balamurugan (Managing Director, North Bihar Power Distribution Company) and others, meeting with author and research team, January 22, 2015.

[42] Pratayaya Amrit (Chairman and Managing Director, Bihar Energy Department/State Power Holding Company), meeting with author and research team, January 27, 2015.

[43] Vinod Singh Gunjiyal (District Magistrate, Vaishali), meeting with author and research team, January 27, 2015.

[44] K. Pratep (National Planning Commission), meeting with author and research team, July 29, 2013.

[45] Pankaj Kumar (Executive Engineer, Vaishali District, North Bihar Power Distribution Company Ltd.), meeting with author and research team, January 24, 2015.

[46] Akanksha Chaurey (CEO, IT Power Consulting Pvt. Ltd.) meeting with author and research team, January 20, 2015.

SITE VISITS

[47] Husk Power. Korbaddha Pataili Village, Samastipur, Bihar. July 2013.

[48] SELCO. Solar Energy Center in Bangalore Slum, Karnataka, July 2013.

[49] SELCO. Village outside Bangalore, Karnataka, July 2013.

[50] Barefoot College, Tilonia, Rajasthan, January 2014.

[51] Tata Trusts, Three villages near Indore, Madhya Pradesh, January 2014.

[52] MORSEL, Khalepurwa and Parvatpor Khas, Barabanki, Uttar Pradesh, July 2014.

[53] Vaishali District Magistrate Staff, Zafarabad Tok, Raghopur, Vaishali, January 2015.

APPENDIX B: SAMPLE INTERVIEW QUESTIONNAIRE

PURPOSE

The purpose of this document is to serve as a comprehensive list of questions about the factors we hypothesize may affect assumptions made in the creation of electrification plans as well as the factors we hypothesize may cause electrification plans to fail despite best intentions. These questions are designed to test claims about factors that influence rural electrification that we have heard or read in the course of our work in India. We seek to understand how common certain obstacles and issues might be, based on a relatively small sample of stakeholders. We will use the answers to these questions to inform our understanding of how best to improve electrification planning for rural India, specifically within our case study area: Vaishali District, Bihar.

It is important to note that not all of the open-ended questions will be posed to all stakeholders depending on their relevance. Questions may also be modified slightly depending on the interviewee's roles within the landscape of stakeholders in rural electrification. The short survey at the end of the document will be posed to all utility employees, planners, regulators, and entrepreneurs involved in the task of extending electricity access who agree to participate in this research. It is designed to elicit an indication of the top 5 most important non-technical factors that influence the effectiveness of electrification projects.

CURRENT EVENTS

IN THE US, WE SEE A LOT OF ENERGY-RELATED NEWS ANNOUNCING NEW INITIATIVES FROM PRIME MINISTER NARENDRA MODI.

[1] How impactful, in terms of achieving universal electrification in the next decade, do you believe these new initiatives will be? Which announcements and programs do you think will be the most important?

[2] How do these announcements impact plans for your work?

[3] Have these new initiatives influenced how you view the role of renewables as a source of energy? How do you view the economics of solar and other renewables energies as compared to conventional energy sources in the context of rural electrification?

PRIORITIES

[1] When you are considering how to meet electrification targets for your constituents, do you estimate current demand for unelectrified citizens? If so, how do you estimate current demand? If not, how are electrification goals determined?

[2] How much do you take future demand growth into account when formulating plans and allocating budget?

[3] How do you balance decisions between people's current demand, potential future demand once electrified, and the level of service you aim to provide given your budget? In other words, what factors influence service goals?

[4] How much of a concern is theft? How do you take expectations about theft into account?

[5] We have learned that caste and religious tensions can sometimes influence the success of microgrid projects. For you, how much of a concern is caste/religion in electrification planning?

[6] When you consider plans to extend electricity access, how do you plan to collect payment from new customers? Is staff expansion needed every time you expand access? What is the cost per customer of staff expansion?

[7] How important is it for you to know the ability to pay of potential customers who get new connections to electricity? How do you determine ability to pay?

[8] How does the reliability of the existing grid affect electrification planning?

[9] Are plans for generation capacity expansion taken into account when choosing where to extend grid connection? For example, how do you ensure there is enough generation to meet demand?

TECHNOLOGY ISSUES

[1] When designing a microgrid, how important is for you that the microgrid is designed so that it can be connected to the main grid?

[2] Do you see a future in which utilities work effectively with companies like Mera Gao to provide service to off-grid customers if they conform to a grid code.

[3] What generation sources, aside from solar, do you consider to be most viable off-grid electrification?

[4] Does the availability of operations and maintenance expertise influence your perception of various generation technologies?

CONTEXT

[1] What do you perceive to be the types of attitudes rural people have towards different electrification modes (e.g., grid connection versus microgrid connection)?

[2] What do you perceive to be the types of attitudes utility employees have towards off-grid electrification modes like microgrids and solar home systems?

[3] How important are these attitudes when you are considering an electrification plan or project proposal?

REGULATION + POLICY

[1] Through the RGGVY program, the government provides a 90% capital subsidy for rural electrification. How does this subsidy affect your planning and technology decisions?

[2] Do you encounter difficulty in the subsidy application process?

[3] How long does it take, on average, to receive subsidy money from the government once you have submitted your application (assuming it is approved)?

[4] Do you think that the government could spend the money from the 90% capital subsidy in a different way that would be more useful to you and others developing rural electrification projects?

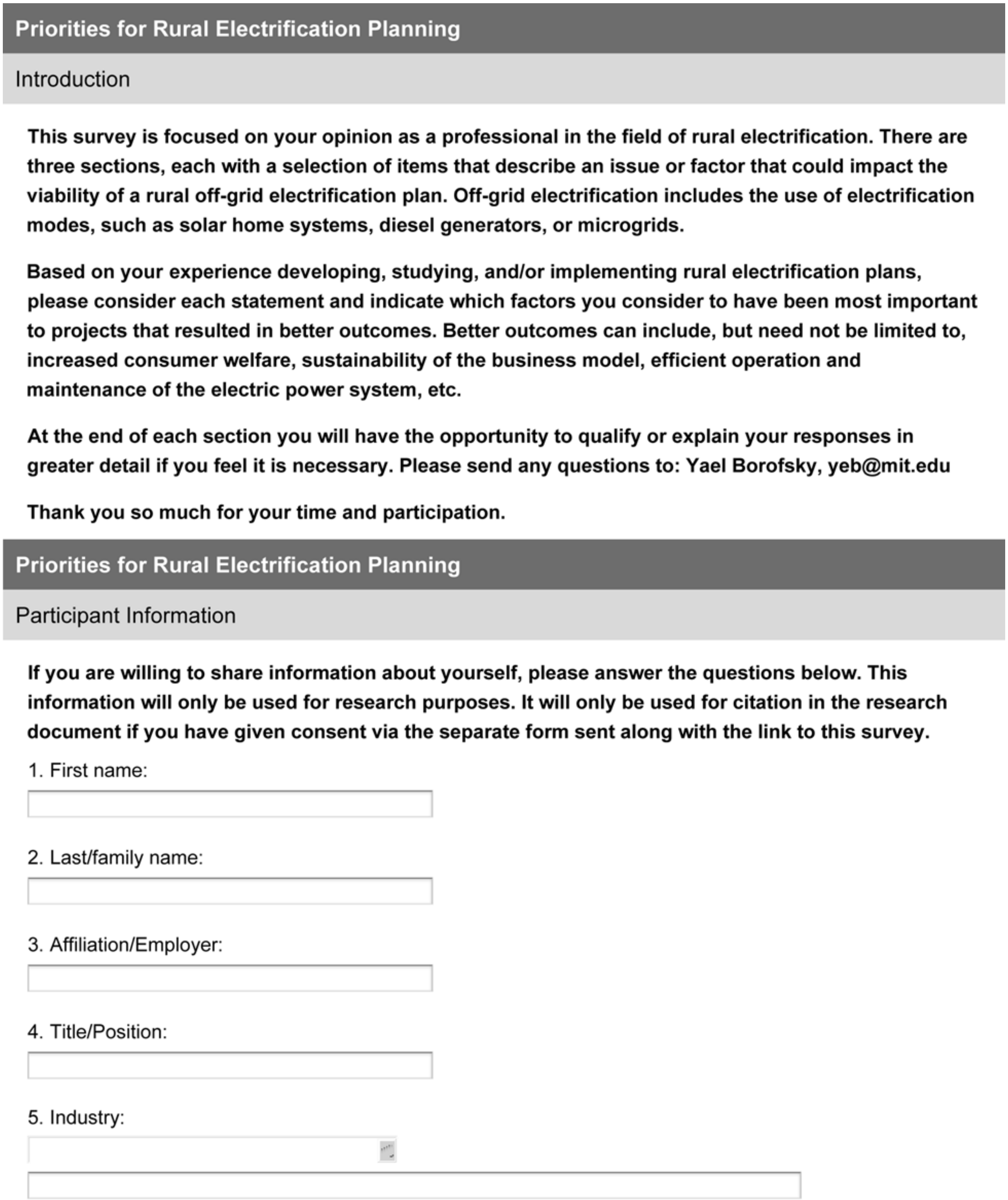
[5] Is the availability of financing a significant concern? If so, what impedes your access to financing?

[7] If regulators required a grid-compatible code for microgrids, do you foresee any obstacles they might face in enforcing this regulation?

[8] How financially sustainable do you think microgrids are?

[9] How might regulation change to better enable the long-term financial sustainability (and profitability) of microgrid electrification?

APPENDIX C:
PILOT SURVEY OF PRIORITIES FOR RURAL ELECTRIFICATION PLANNING



Priorities for Rural Electrification Planning

Introduction

This survey is focused on your opinion as a professional in the field of rural electrification. There are three sections, each with a selection of items that describe an issue or factor that could impact the viability of a rural off-grid electrification plan. Off-grid electrification includes the use of electrification modes, such as solar home systems, diesel generators, or microgrids.

Based on your experience developing, studying, and/or implementing rural electrification plans, please consider each statement and indicate which factors you consider to have been most important to projects that resulted in better outcomes. Better outcomes can include, but need not be limited to, increased consumer welfare, sustainability of the business model, efficient operation and maintenance of the electric power system, etc.

At the end of each section you will have the opportunity to qualify or explain your responses in greater detail if you feel it is necessary. Please send any questions to: Yael Borofsky, yeb@mit.edu

Thank you so much for your time and participation.

Priorities for Rural Electrification Planning

Participant Information

If you are willing to share information about yourself, please answer the questions below. This information will only be used for research purposes. It will only be used for citation in the research document if you have given consent via the separate form sent along with the link to this survey.

1. First name:

2. Last/family name:

3. Affiliation/Employer:

4. Title/Position:

5. Industry:

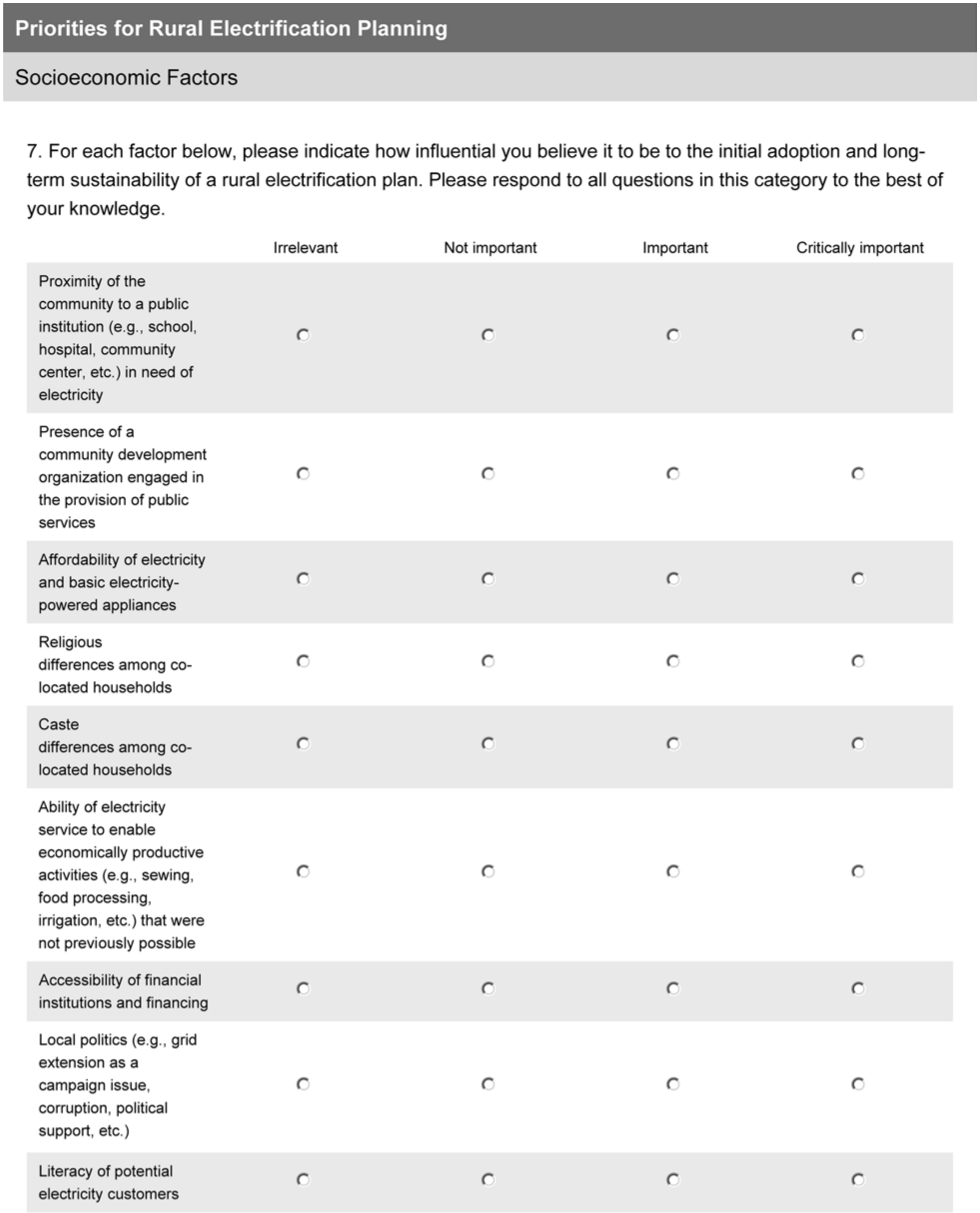
Priorities for Rural Electrification Planning

Technology Factors

6. For each factor below, please indicate how influential you believe it to be to the initial adoption and long-term sustainability of a rural electrification plan. Please respond to all questions in this category to the best of your knowledge.

	Irrelevant	Not important	Important	Critically important
Ability to provide electricity to meet a level of demand that is beyond the most basic service (i.e., two lights and a mobile phone charger)	○	○	○	○
Local attitudes towards different rural electrification modes (e.g., perceiving solar-powered rural electrification modes to be a second-class option)	○	○	○	○
Convenience of procuring, storing, and preventing theft of diesel fuel	○	○	○	○
Consumer perception that quality of light provided by the rural electrification mode is superior to kerosene-powered light	○	○	○	○
Reliability (number of hours of electricity people consistently receive over a 24-hour period) of nearby existing grid connection	○	○	○	○
Location of the electricity generator (e.g., solar panel, diesel generation set, etc.) in the community (i.e., proximity to homes, places of worship, etc.)	○	○	○	○

Other technology factors (please specify)

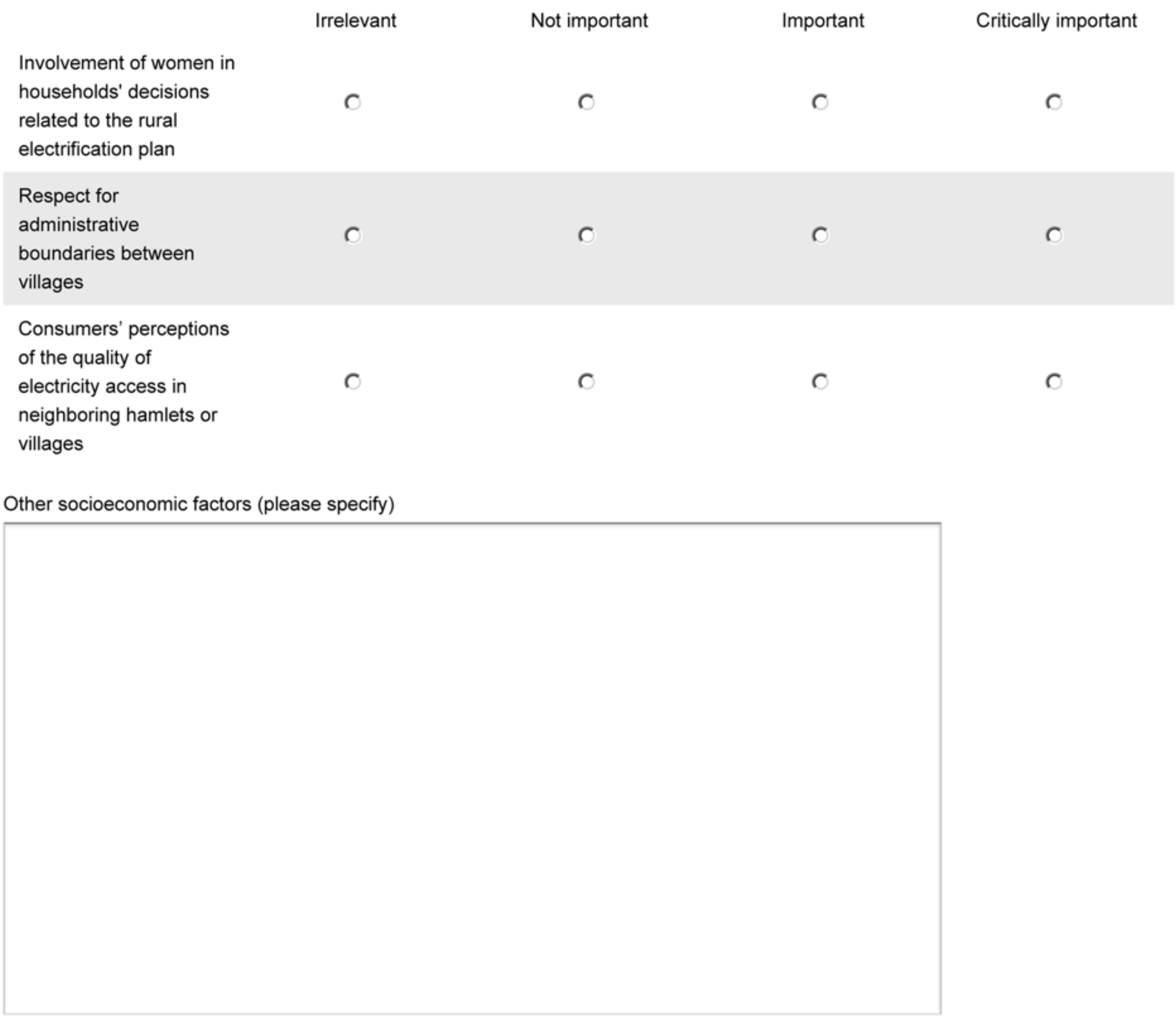


Priorities for Rural Electrification Planning

Socioeconomic Factors

7. For each factor below, please indicate how influential you believe it to be to the initial adoption and long-term sustainability of a rural electrification plan. Please respond to all questions in this category to the best of your knowledge.

	Irrelevant	Not important	Important	Critically important
Proximity of the community to a public institution (e.g., school, hospital, community center, etc.) in need of electricity	○	○	○	○
Presence of a community development organization engaged in the provision of public services	○	○	○	○
Affordability of electricity and basic electricity-powered appliances	○	○	○	○
Religious differences among co-located households	○	○	○	○
Caste differences among co-located households	○	○	○	○
Ability of electricity service to enable economically productive activities (e.g., sewing, food processing, irrigation, etc.) that were not previously possible	○	○	○	○
Accessibility of financial institutions and financing	○	○	○	○
Local politics (e.g., grid extension as a campaign issue, corruption, political support, etc.)	○	○	○	○
Literacy of potential electricity customers	○	○	○	○



	Irrelevant	Not important	Important	Critically important
Involvement of women in households' decisions related to the rural electrification plan	○	○	○	○
Respect for administrative boundaries between villages	○	○	○	○
Consumers' perceptions of the quality of electricity access in neighboring hamlets or villages	○	○	○	○

Other socioeconomic factors (please specify)

Priorities for Rural Electrification Planning

Regulatory Factors

8. For each factor below, please indicate how influential you believe it to be to the initial adoption and long-term sustainability of a rural electrification plan. Please respond to all questions in this category to the best of your knowledge.

	Irrelevant	Not Important	Important	Critically Important
Potential for theft or tampering with electrification mode	○	○	○	○
Convenience of procuring existing government subsidies for project developers/customers	○	○	○	○
Use of government subsidies as part of business model	○	○	○	○
Local tariff charged to rural consumers who purchase electricity from the grid	○	○	○	○
Compatibility of the rural electrification mode with the existing grid code (e.g., use of standard voltages)	○	○	○	○
Compatibility of proposed rural electrification plan with existing rural electrification programs, such as Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY)	○	○	○	○
Engagement with local/regional electric utility	○	○	○	○

Other regulatory factors (please specify)

APPENDIX D:
MIT QUESTIONS FOR BARABANKI MIDLINE SURVEY

CONDUCTED IN COLLABORATION WITH DR. JOHANNES URPELAINEN, DR. MICHAËL AKLIN, AND DR. PATRICK BAYER

1. How many electric lights do you own?

___ Incandescent	___ Typical wattage
___ Fluorescent	___ Typical wattage
___ LED	___ Typical wattage

2. Do you own any other electric appliances:

APPLIANCE ____	Typical Wattage ____
APPLIANCE ____	Typical Wattage ____
APPLIANCE ____	Typical Wattage ____
APPLIANCE ____	Typical Wattage ____

3. Do you use any electric appliances in your business? How much do they contribute to your monthly business income?
   ____ APPLIANCE ____ MONTHLY ESTIMATE OF ADDED INCOME
4. Do you charge your mobile phone at home? 1 Yes 0 No
   IF YES: how frequently? ___ TIMES A WEEK
   8. 5. Other than your home, where do you charge your mobile phone? __________
6. How frequently do you charge your mobile phone somewhere other than your home?
   ____
7. Which of the following do you use for lighting? [Check all that apply]
   a. Electricity
   b. Kerosene
   c. Candles
   d. Battery charged lamps
   e. Solar panel
   f. Off-grid electricity from Mera Gao Power
   Other [SPECIFY]: ______________________________

MIT: USAGE PATTERNS

INSTRUCTIONS: For all daily usage questions, please ask respondent to explain the time of day they most frequently use each appliance with respect to each of the three seasons enumerated in the table. Place a check mark next to each time of day and under each season that applies. If usage does not vary by season, check the appropriate box under "All Year".

1. LIGHTING:
   During what time of day are you most likely to use light inside or outside your home [insert each season]?

	Winter	Spring	Rainy Season	All Year
Morning: 6am - 12pm				
Midday: 12pm - 3pm				
Afternoon: 3pm - 7pm				
Evening: 7pm - 9:30pm				
Night: 9:30pm - 6am				

2. IF THE HOUSEHOLD OWNS A TV:

2.a. How many televisions do you own? ____ COUNT

2.b. During what time of day are you most likely to watch TV?

	Winter	Spring	Rainy Season	All Year
Morning: 6am - 12pm				
Midday: 12pm - 3pm				
Afternoon: 3pm - 7pm				
Evening: 7pm - 9:30pm				
Night: 9:30pm - 6am				

2.c Do you use an electric outlet in your home to power it/them? 1 Yes 0 No

IF YES: What do you do during power outage if someone wants to watch television?
SPECIFY: ____

IF NO: Do you use batteries to power it/them?1 Yes 0 No

I F YES: Monthly cost? ___ RUPEES

3. IF THE HOUSEHOLD OWNS A RADIO:

3.a. How many radios do you own? ___ COUNT

3.b. During what time of day are you most likely to listen to radio?

	Winter	Spring	Rainy Season	All Year
Morning: 6am - 12pm				
Midday: 12pm - 3pm				
Afternoon: 3pm - 7pm				
Evening: 7pm - 9:30pm				
Night: 9:30pm - 6am				

3.c. Do you use an electric outlet to charge it/them? 1 Yes 0 No

IF YES: What do you do during power outage if someone wants to listen to radio?
SPECIFY:____

IF NO: Do you use batteries to charge it/them? 1 Yes 0 No

IF YES: Monthly cost? ___ RUPEES

4. IF THE HOUSEHOLD OWNS A FAN OR OTHER COOLING DEVICE:

4.a How many fans do you own? ___ COUNT

4.b. During what time of day are you most likely to use your fan for cooling [insert each season]?

	Winter	Spring	Rainy Season	All Year
Morning: 6am - 12pm				
Midday: 12pm - 3pm				
Afternoon: 3pm - 7pm				
Evening: 7pm - 9:30pm				
Night: 9:30pm - 6am				

4.c. Do you use an electric outlet in your home to power it/them? 1 Yes 0 No

IF YES: What do you do if electricity is not available, but you want to use a fan? ___ SPECIFY

IF NO: Do you use batteries to charge them? 1 Yes 0 No

IF YES: Monthly cost? ___ RUPEES

4.d. Do you use any other cooling methods? 1 Yes 0 No

IF YES: Specify___

IF YES: Monthly cost? ___ RUPEES

5. IF THE HOUSEHOLD OWNS SOME KIND OF A SPACE HEATER:

5.a. How many space heaters do you own? ___ COUNT

5.b. During what time of day are you most likely to use an appliance for heating [insert each season]?

	Winter	Spring	Rainy Season	All Year
Morning: 6am - 12pm				
Midday: 12pm - 3pm				
Afternoon: 3pm - 7pm				
Evening: 7pm - 9:30pm				
Night: 9:30pm - 6am				

5.c. Do you use an electric outlet in your home to power it/them? 1 Yes 0 No

IF YES: What do you do if electricity is not available, but you want heat?
SPECIFY____

I IF NO: Do you use batteries to charge it/them? 1 Yes 0 No

IF YES: Monthly cost? ___ RUPEES

5.d. Do you use any other heating methods? 1 Yes 0 No

IF YES: Specify____

IF YES: Monthly cost? ___ RUPEES

FUTURE DEMAND

INSTRUCTIONS: Please ask the respondent to imagine a future scenario in which they have a grid-connection with electricity available 24 hours per day/7 days per week in their home. Ask them to imaging pay the typical subsidized grid tariff for a rural residential customer for this service. With this in mind, please ask them to answer the following questions:

1. Which electricity-using appliances do you think you would own (continue to use or purchase):

APPLIANCE _________ Count ____

APPLIANCE _________ Count ____

APPLIANCE _________ Count ____

APPLIANCE _________ Count ____

APPLIANCE _________ Count ____

2. Would you use any electricity-using appliances to increase your monthly income? 1 Yes 0 No

   IF YES:

   In which activity could electricity help you make more money? ___________________

   Which appliances would you use? ___________________

   How much additional monthly income do you think you could make with these appliances and a reliable, 24-hour electricity service?

   ___________ RUPEES

INSTRUCTIONS: Under the same scenario described above, please ask the respondent to indicate the time of day and time of year they would be most likely to make use of the energy service categories of appliances they imagined they would purchase or continue to use in their home. Be sure it is clear that the respondent assumes they must purchase the necessary appliances to provide this service. If there is a category in which they do not imagine owning any appliances, there is no need to fill out a usage table for that energy service category.

3. For lighting:

   [If they specified appliances for lighting] You stated you would use ________ for lighting. During which times of day are people in your household most likely to make use of lighting inside or outside your home:

	Winter	**Spring**	**Rainy Season**	**All Year**
Morning: 6am - 12pm				
Midday: 12pm - 3pm				
Afternoon: 3pm - 7pm				
Evening: 7pm - 9:30pm				
Night: 9:30pm – 6am				

4. For mobile phone charging:

   [If they specified appliance for mobile phone charging (e.g., a current or additional handsets)] You stated you would use [quantity of handsets] ______ mobile phones. During which times of day are people in your household most likely to charge mobile phones:

	Winter	Spring	Rainy Season	All Year
Morning: 6am - 12pm				
Midday: 12pm - 3pm				
Afternoon: 3pm - 7pm				
Evening: 7pm - 9:30pm				
Night: 9:30pm – 6am				

5. For entertainment:

   [If they specified appliances for entertainment] You stated you would use ________ for entertainment. During which time of day are people in your household most likely to use a TV, radio, or some other appliance for entertainment:

	Winter	Spring	Rainy Season	All Year
Morning: 6am - 12pm				
Midday: 12pm - 3pm				
Afternoon: 3pm - 7pm				
Evening: 7pm - 9:30pm				
Night: 9:30pm – 6am				

6. [If they specified appliances for cooking] You stated you would use ________ for heating. During which time of day are people in your household most likely to use a cooling appliance (fan etc.):

	Winter	Spring	Rainy Season	All Year
Morning: 6am - 12pm				
Midday: 12pm - 3pm				
Afternoon: 3pm - 7pm				
Evening: 7pm - 9:30pm				
Night: 9:30pm – 6am				

7. [If they specified appliances for heating] You stated you would use ________ for heating. During which time of day are people in your household most likely to use a heating appliance (space heater, etc.):

	Winter	Spring	Rainy Season	All Year
Morning: 6am - 12pm				
Midday: 12pm - 3pm				
Afternoon: 3pm - 7pm				
Evening: 7pm - 9:30pm				
Night: 9:30pm – 6am				

WILLINGNESS TO PAY VIGNETTES

INSTRUCTIONS: Present the respondents the following scenarios and ask them to answer what they would be willing to pay assuming they could have access to the following set of services.

Imagine you were offered the following sets of services. Specify how much you would be willing to pay for each service per month.

These service options include rental of the listed appliances, electricity to use them for some number of hours per day, and choice of which hours per day you'd like to use your electricity service.

Appliances	Hours Per Day	Willingness to Pay (monthly)
2 lights, 1 mobile phone charger	6	
2 lights, 1 mobile phone charger	12	
2 lights, 1 mobile phone charger	24	
2 lights, 1 mobile phone charger, 1 fan	6	
2 lights, 1 mobile phone charger, 1 television	6	
2 lights, 1 mobile phone charger, 1 fan, 1 television	6	

These service options include electricity for some number of hours per day. You could use this electricity at any time you want and for any appliances you want, but you would have to purchase the appliances on your own.

Appliances	Hours Per Day	Willingness to Pay (monthly)
Any	6	
Any	12	
Any	24	

These service options include electricity for some number of hours per day and you can use any appliances that you want (you would still have to purchase or own those appliances). But in this scenario, you cannot control what times of day you can use the electricity: it could be available sporadically or only at certain times of day.

Appliances	Hours Per Day	Willingness to Pay (monthly)
Any	6	
Any	12	

APPENDIX E:
CONTEXT FOR THE CASE STUDY

FIGURE E.1 Map of the state of Bihar (blue) in India (Census of India 2011)

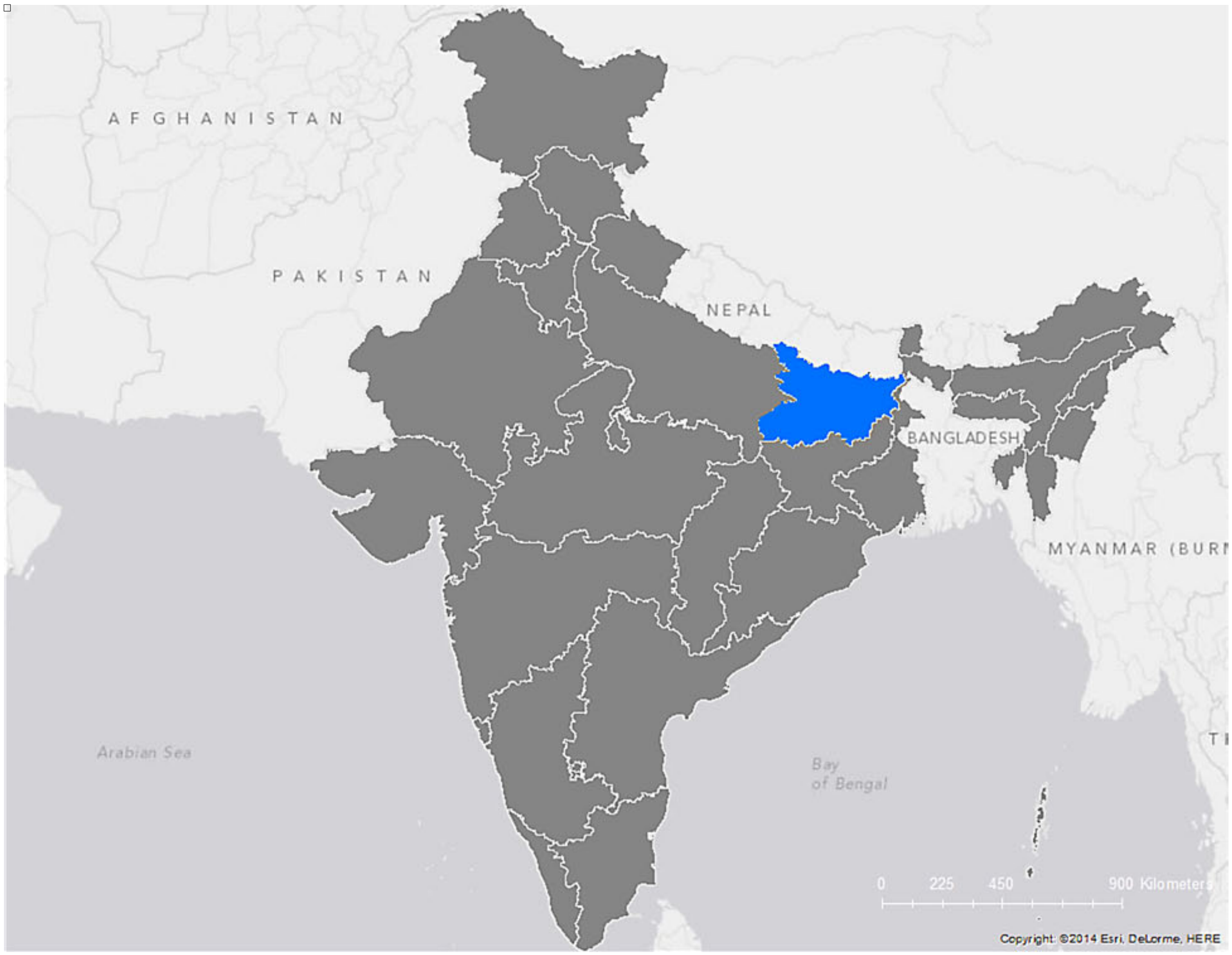
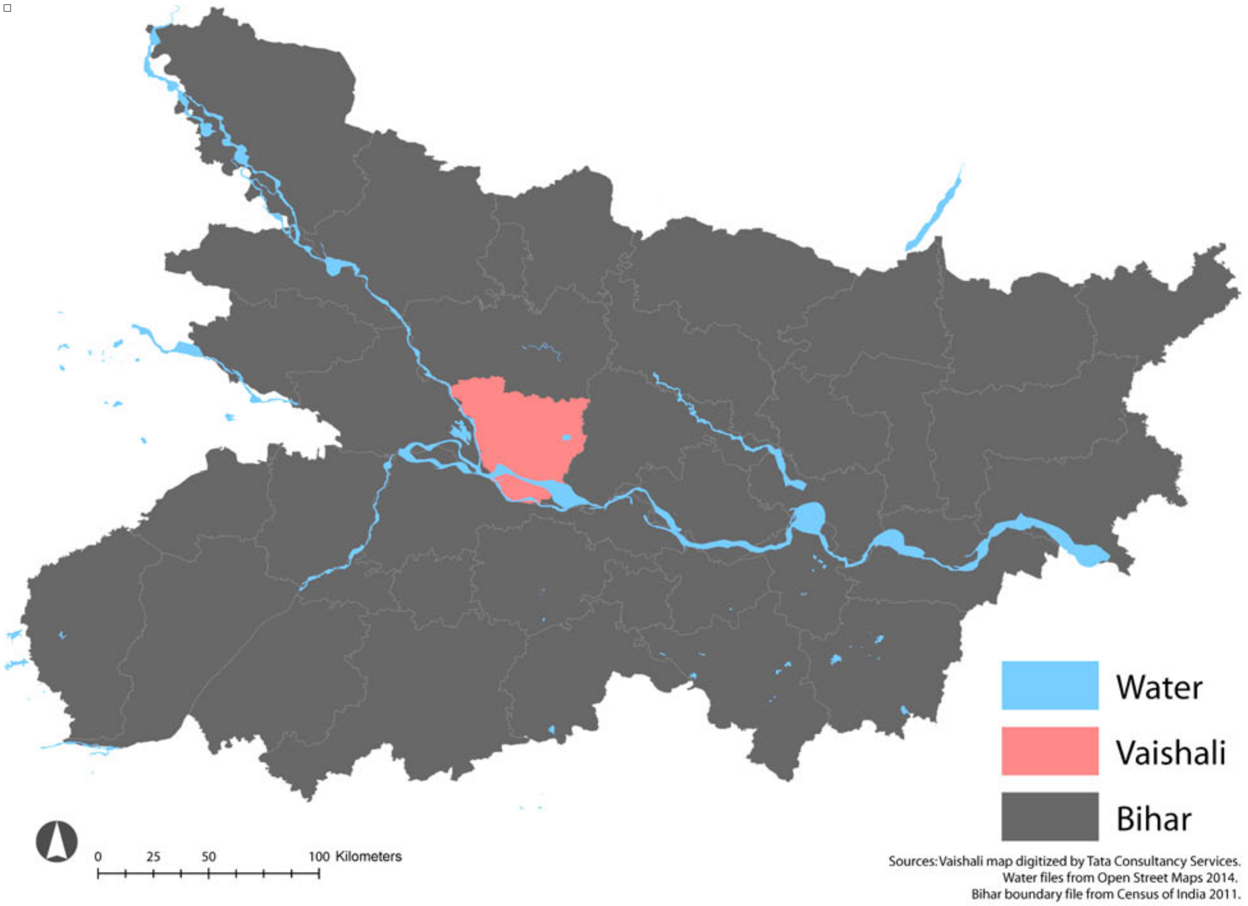


FIGURE E.2 Map of Vaishali District in the state of Bihar



Sources: Vaishali map digitized by Tata Consultancy Services.
Water files from Open Street Maps 2014.
Bihar boundary file from Census of India 2011.

APPENDIX F:
MICROGRID LOCATIONS BROKEN OUT BY NUMBER OF BUILDINGS CONNECTED TO EACH SYSTEM (BASELINE SCENARIO)

FIGURE F.1

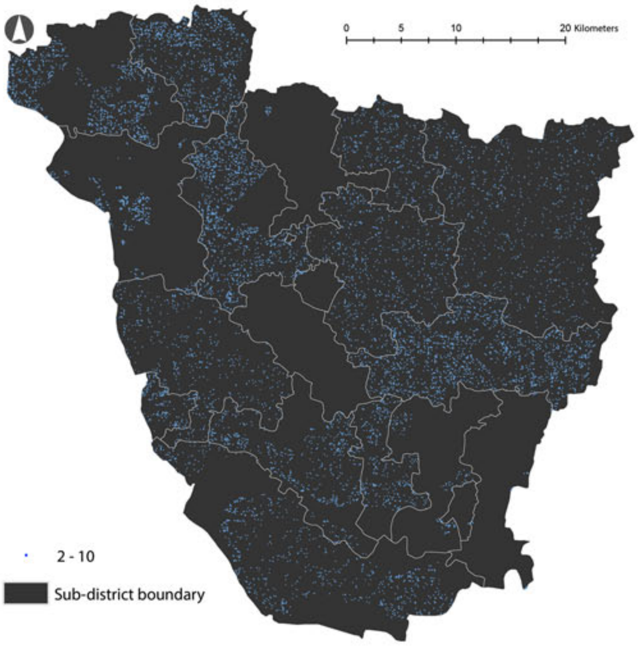


FIGURE F.2

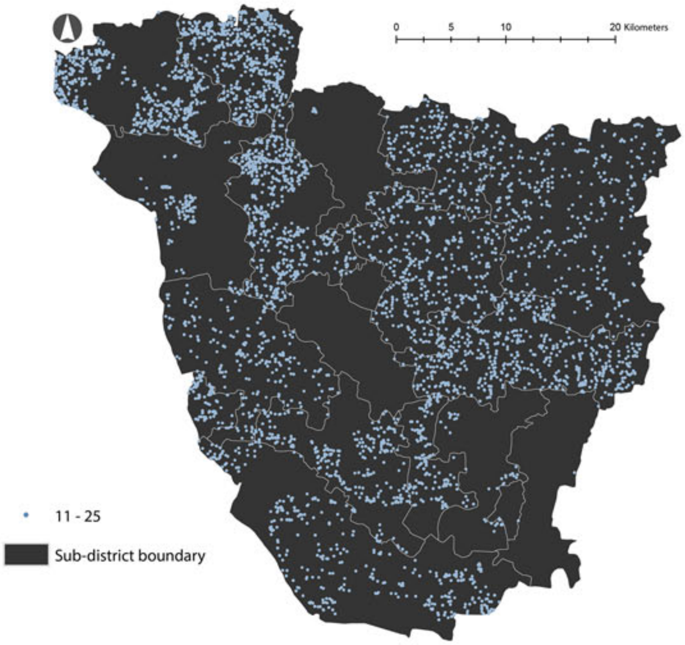


FIGURE F.3

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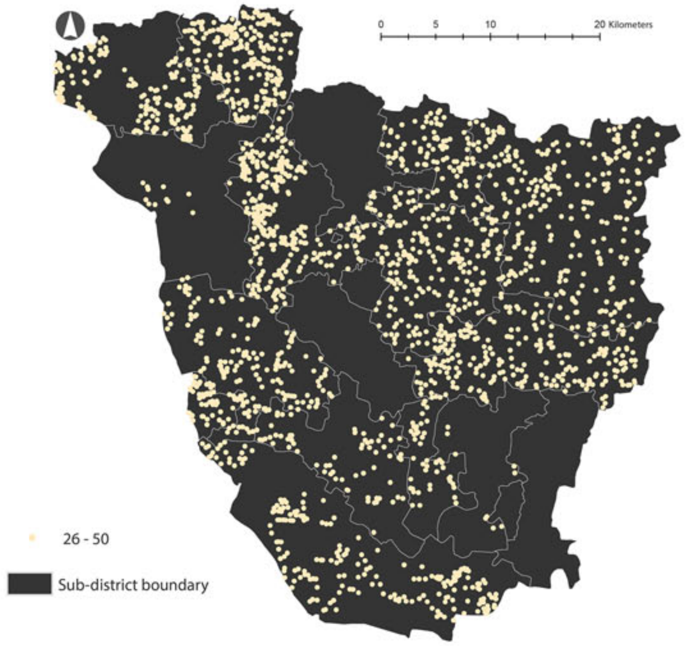

FIGURE F.4

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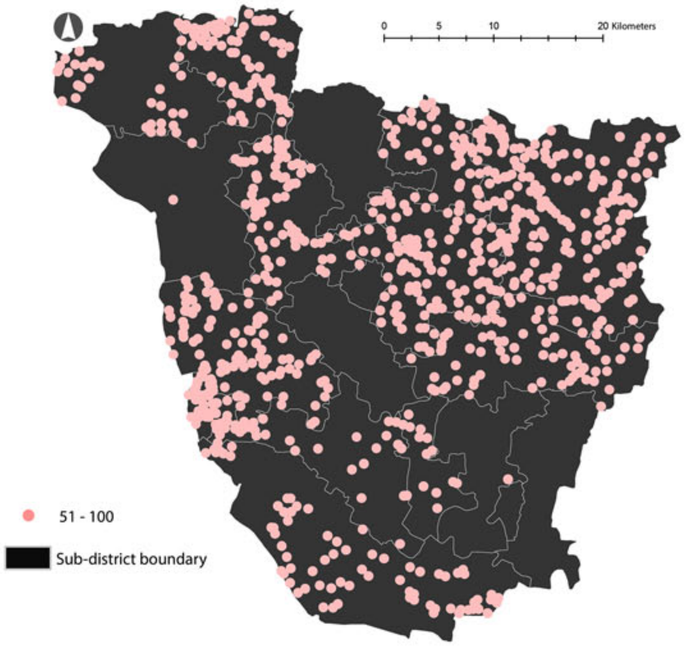

FIGURE F.5

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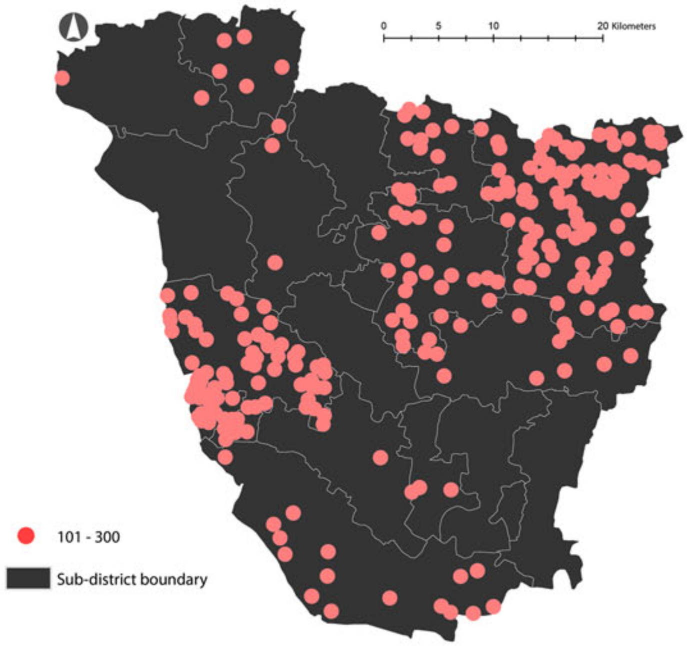

FIGURE F.6

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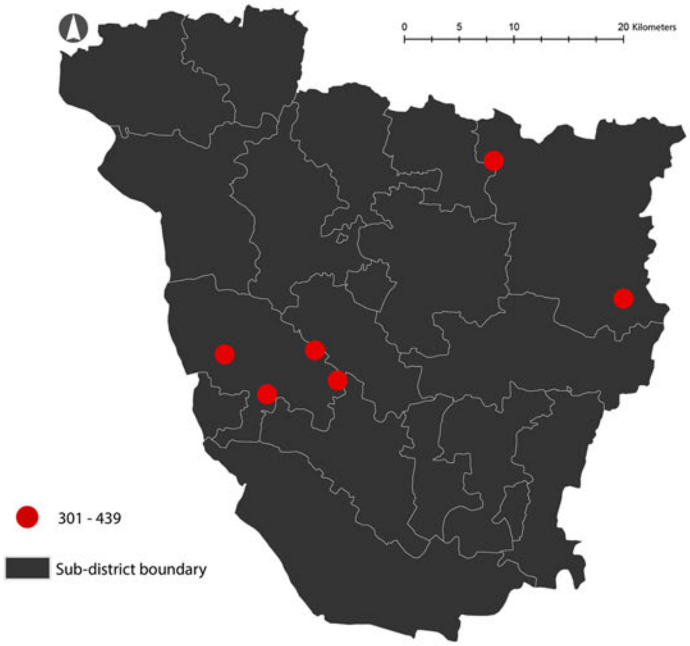


APPENDIX G:
MAPS OF MICROGRID LOCATIONS BROKEN OUT BY NUMBER OF BUILDINGS CONNECTED TO EACH SYSTEM (DEMAND GROWTH SCENARIO)

FIGURE G.1

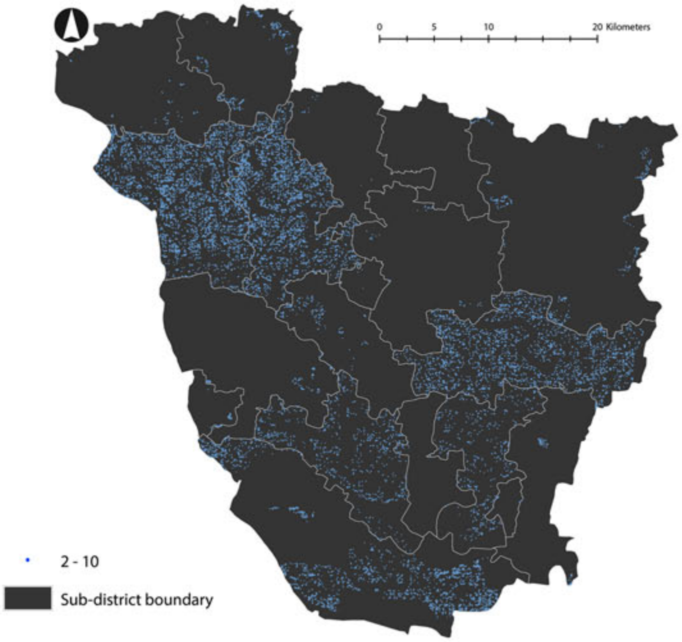


FIGURE G.2

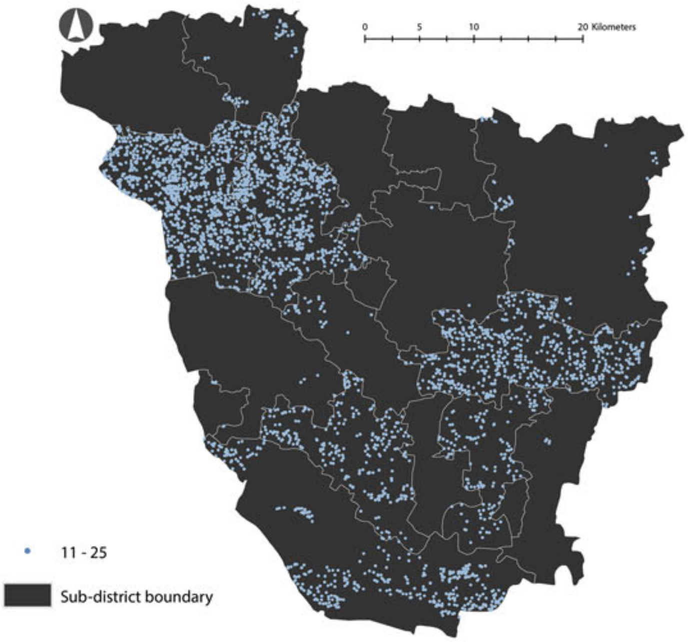


FIGURE G.3

□

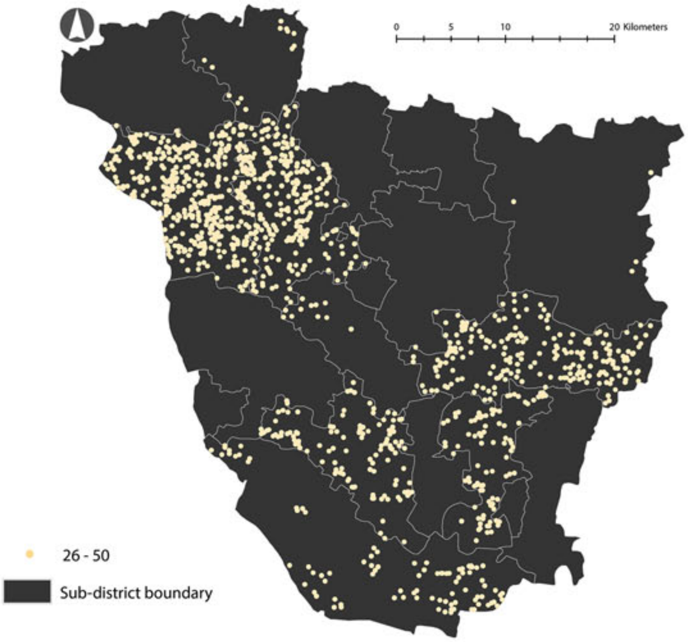


FIGURE G.4

□

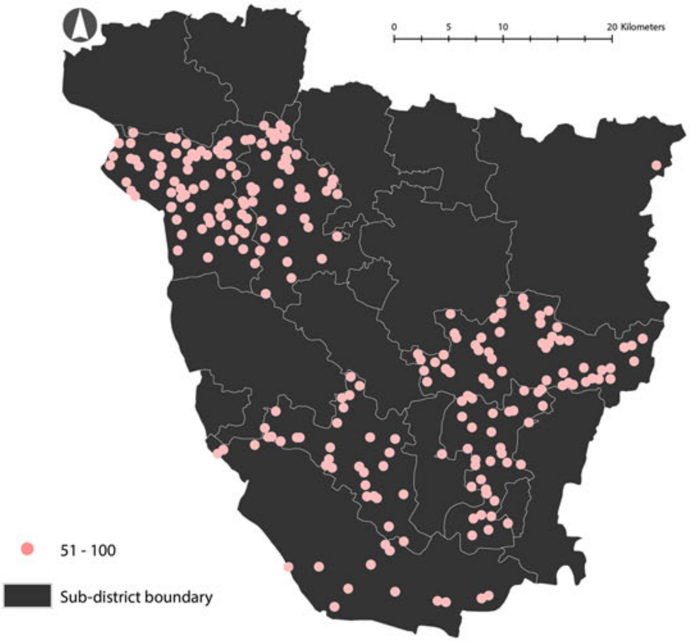
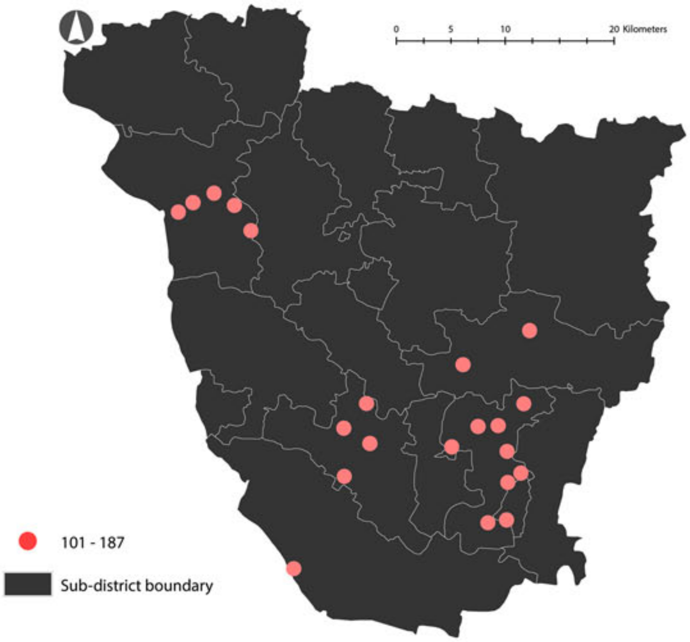


FIGURE G.5

□



APPENDIX H:
MICROGRID LOCATIONS BROKEN OUT BY NUMBER OF BUILDINGS CONNECTED TO EACH SYSTEM (MORE BUILDINGS SCENARIO)

FIGURE H.1

□

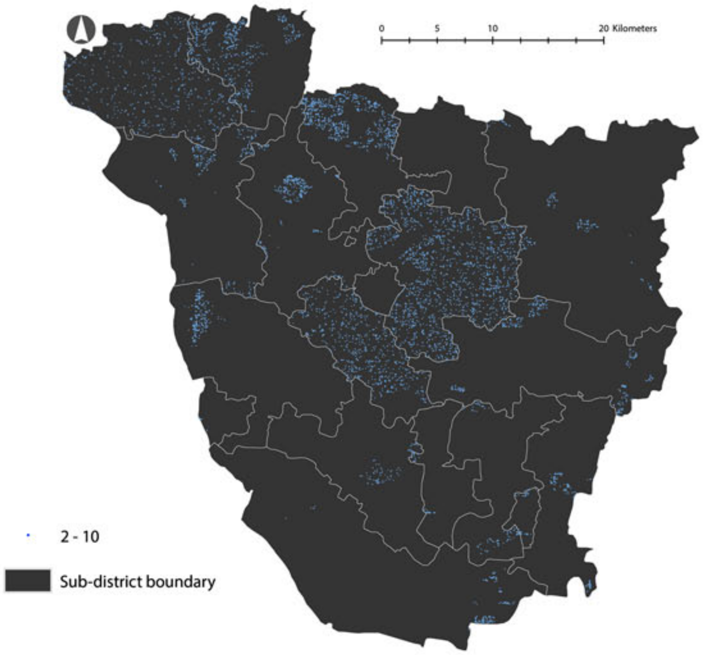


FIGURE H.2

□

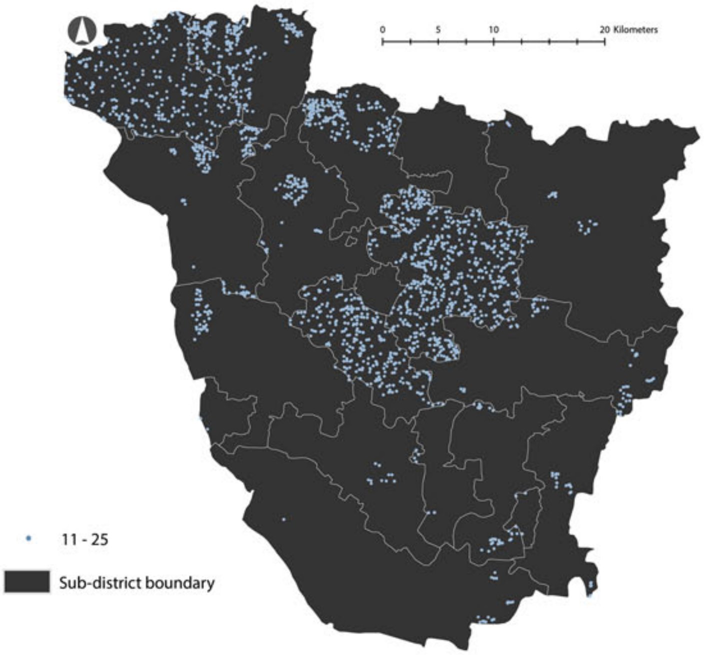


FIGURE H.3

□

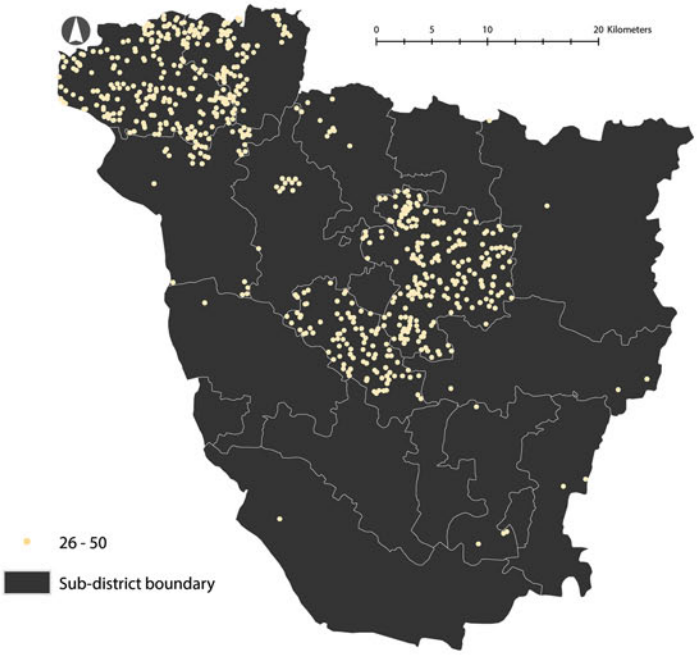


FIGURE H.4

□

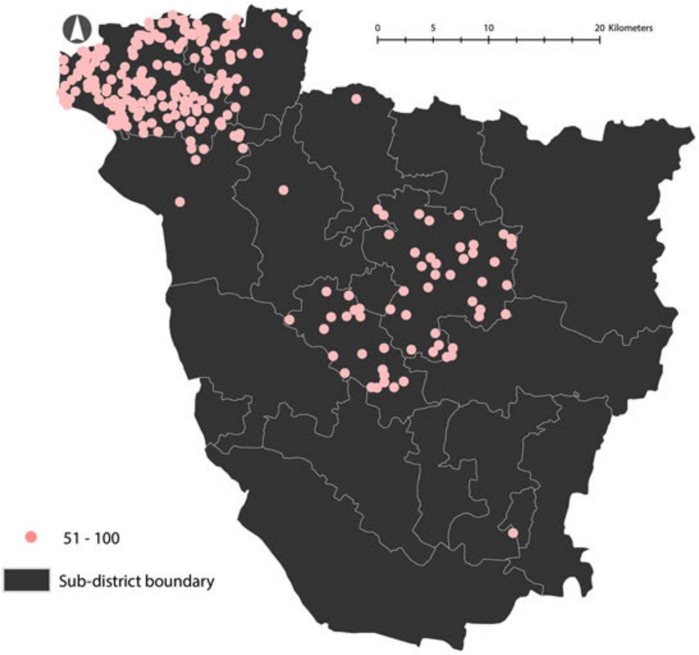


FIGURE H.5

□

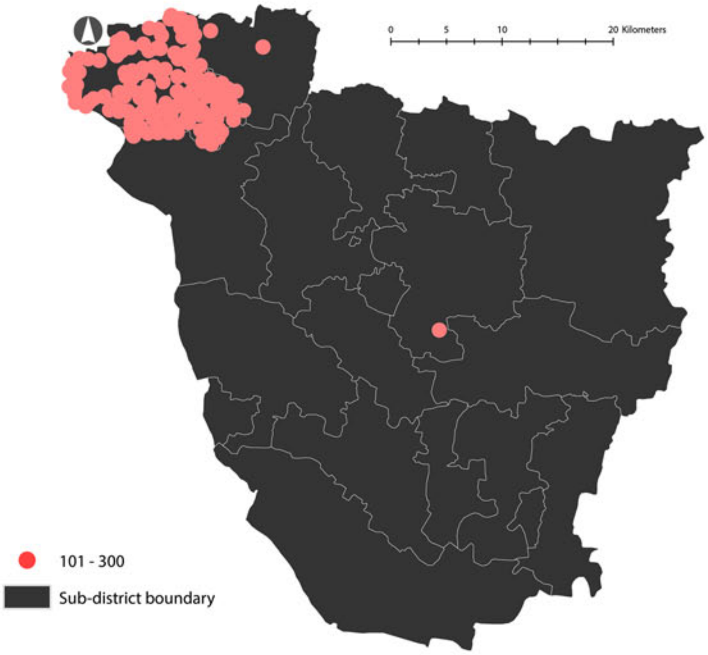


FIGURE H.6

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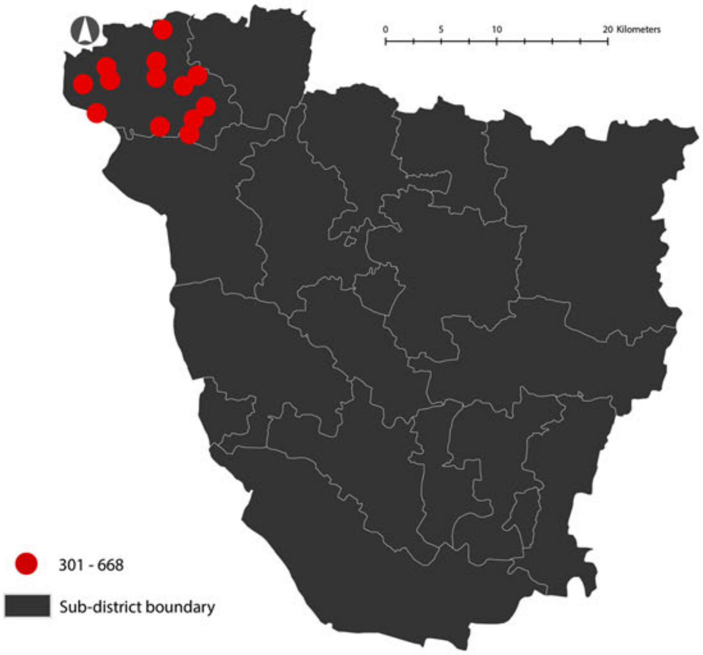

APPENDIX I:
EXISTING MV DISTRIBUTION GRID IN VAISHALI

FIGURE I.1 Hand-drawn map of the existing 11kV grid in Vaishali District given to MIT by the Bihar State Power Holding Company Ltd.