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The Economic Value of Electricity Reliability

Seyedmajid Hashemi
Clemson University, majid.hashemi.86@gmail.com

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THE ECONOMIC VALUE OF ELECTRICITY RELIABILITY

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Economics

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by
Seyedmajid Hashemi
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Accepted by:
Dr. William Dougan, Committee Chair
Dr. Robert Fleck
Dr. Andrew Hanssen
Dr. Glenn Jenkins
Reed Watson, J.D.

ABSTRACT

Unreliable access to electricity is the norm rather than the exception in many developing countries. This dissertation analyzes the causes and consequences of outages and evaluates the economic benefits of addressing them. The first chapter investigates how the demand for electricity reliability can be estimated in the absence of markets for it. Employing two complementary pieces of information from a nationally representative sample of grid-connected consumers in Nepal - coping behavior and stated willingness to pay (WTP) - demand electricity reliability is estimated. The results indicate substantial heterogeneity in ex-ante demand for reliability and ex-post increase in electricity consumption levels, even within the same tariff categories. For policy-making purposes, the findings highlight the importance of conducting a detailed analysis of information on households' preferences and firms' opportunity costs when evaluating the benefits from reliability investments.

Chapter two focuses on evaluating the economic benefits of mitigating the risk of unplanned outages in overloaded electric networks. Although electric utilities meter the amount of electricity consumed by individual customers, the physical structure of electricity distribution networks creates a shared level of reliability. The question that arises here is whether the shared nature of electric networks makes them susceptible to the common-pool resource (CPR) problem. Using firm- and substation-level data from a nationally representative sample of Nepalese firms, the findings indicate that the CPR problem would be largely solved if private firms were allowed to own and operate substations. The cost-benefit analysis presented in this chapter demonstrates that the annual gain from eliminating this restriction would be on the order of 0.32 USD million.

The third chapter estimates the extent to which electricity consumers of different income levels would increase their use of high-load appliances in response to improvements in grid reliability. The results indicate that although grid-connected households are counted in the electrification statistics, unreliable electricity service significantly constrains their electric appliance ownership and, consequently, electricity consumption. Putting this paper’s findings into Sustainable Development Goal 7’s perspective, a connection to the grid by itself does not necessarily translate to realized benefits from electricity consumption. The availability and reliability of the service play a critical role for households at all income levels.

DEDICATION

To Neda.

There aren’t any words to express the depth of my love.

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I would like to thank my parents for all the sacrifices they have made to support me to be where I am today. Also, I would like to thank my sister for her endless love and support.

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CHAPTER 1

THE ECONOMIC VALUE OF UNSUPPLIED ELECTRICITY: EVIDENCE FROM NEPAL

1.1 Introduction

During the past decade, extending access to electricity has been a priority for many governments and international development organizations. As of 2018, significant progress has been made in this regard: the world's population living without electricity has decreased from 1.2 billion in 2010 to 789 million people in 2018 (World Bank, 2020). However, these electrification rates do not adequately capture the degree of usability of available electricity for "electrified" consumers. There are many instances in which households and business enterprises receive electricity with frequent and long interruptions. Unreliable electricity service adds coping expenditures to electricity utility bills and reduces electricity consumption levels, leading to an overall reduction in the potential benefits of having uninterrupted access to electricity (Bhatia and Angelou, 2015)[1].

On the supply side, upgrading the generation capacity and maintaining the electricity supply infrastructure can improve reliability, but it requires capital investments. The costs of such investments are expected to be covered, at least partly, by revenues for the electric utility to remain financially sustainable. Thus, understanding consumers' willingness to pay for improved reliability provides critical information to utility managers, policymakers, and investors when assessing investments' costs-recovery potential. On the

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[1] In this paper, reliability refers to the ability of the power system to maintain the delivery of uninterrupted electric service to customers in the face of uncertainty in operating conditions.

demand side, the first step is to clarify why some consumers value electricity reliability more than others. In energy-poor contexts, a concrete step towards understanding drivers of the demand for electricity reliability and uptake of off-grid backup sources is an analysis of associations between household- and firm-level characteristics and electricity consumption.

Due to the lack of market mechanisms to allocate electricity reliability in many developing countries, the economic value of electricity reliability cannot be directly observed. Previous studies have used two approaches to measure the demand for reliability: the stated preference approach and the revealed preference approach (Carlsson and Martinsson 2008; Reichl et al., 2013; Ozbafli and Jenkins, 2015; Ozbafli and Jenkins, 2016; Oseni, 2017; Morrissey et al., 2018; Carlsson et al., 2020; Niroomand and Jenkins 2020a; Niroomand and Jenkins 2020b)[2]. Depending on data availability and the plausibility of a model's assumptions in a given setting, revealed or stated preference approaches had been used interchangeably (Klytchnikova and Lokshin, 2009). Given that each of these approaches provides a different subset of insights about how different categories of consumers value electricity reliability and what characteristics explain different valuations for reliability, it would be informative to analyze the results generated by the two approaches simultaneously. However, there is no such empirical evidence in the existing literature of electricity reliability.

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[2] The stated preference approach elicits willingness to pay for improvements directly through a contingent valuation or a choice experiment survey, while the revealed preference approach uses data derived from the actual choices consumers make to cope with unreliable service and the real expenditures associated with these choices.

This paper fills this gap by investigating two distinct demand-related variables, revealed coping behavior and stated WTP, using a rich nationally-representative sample of 1,800 residential and 590 non-residential electricity customers in Nepal[3]. In principle, coping behavior to deal with power outages and stated WTP for reliability improvements related manifestation of the same underlying preferences for electricity reliability. Nonetheless, there are essential differences between the two: coping expenditures represent the economic value of non-incremental benefits from direct resource cost-saving, i.e., a lower bound for WTP for a well-functioning grid (Devicienti et al., 2004). Stated WTP values, on the other hand, reflect the economic value of incremental benefits (i.e., additional consumption) in terms of additional induced demand due to supply availability.

The findings indicate that although those in higher quartiles of residential electricity bills invest substantially more in coping equipment than those in lower quartiles, the stated WTP for reliability improvements diminishes as one moves from lower quartiles to higher quartiles. The coping behavior of non-residential consumers shows a similar pattern to residential ones, but their stated WTP values do not: industrial consumers state WTP values for improvements two and four times of WTP stated by domestic and commercial consumers, respectively. A closer look at the adoption pattern of coping equipment reveals that these differences can be explained by the substitutability of electricity service provided by the coping equipment.

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[3] The survey used in this study is conducted by the Millennium Challenge Corporation in partnership with the government of Nepal. For more information visit https://data.mcc.gov/evaluations/index.php/catalog/194/study-description.

Moreover, the obtained ex-ante WTP values indicate that consumers under the industrial electricity tariff category have the highest demand for electricity reliability, followed by those under commercial and domestic tariff categories. Nepal has managed to eliminate seasonal shortages in its hydropower generation since 2017 by increasing its electricity imports from India. This change is used to compare the ex-ante predictions to the ex-post electricity consumption levels. As predicted by ex-ante WTP estimates, industrial consumers show the highest increase in electricity consumption after improvements.

This study contributes to the previous literature in several ways. First, it uses a nationally representative sample of electricity customers compromising of both residential and business customers. Earlier studies on the microeconomics of electricity reliability in developing countries have focused only on either residential or business customers, and they have been limited to small samples of customers with the number of observations limited to a few hundred[4]. The only exception at the time of this study is Deutschmann et al. (2019) that evaluates the willingness to pay for reliable electricity for a nationally-representative sample of Senegalese households and firms. Consistent with Deutschmann et al. (2019), this paper's findings highlight that the costs of unsupplied electricity and consumers' behavioral changes after reliability improvements are widely different across and within various consumers' categories.

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[4] For instance, Ghosh et al. (2017) uses a sample of 260 small-scale firms in Hyderabad, India. Similarly, Oseni (2017) uses a sample of 835 Nigerian households from only two regions, Lagos and Osun.

Second, previous studies have only analyzed the ex-ante predicted demand for electricity reliability, and there is no empirical evidence on how consumers actually respond to reliability improvements ex-post. This paper provides the first empirical evidence on how responses vary across and within different categories of consumers. Understanding which category of consumers is most likely to benefit from reliability improvements can help policymakers to better target reliability investments and allocate resources where they are needed the most.

Third, given the chronic nature of electricity reliability in low-income countries, this study's findings would be relevant to policymakers in these countries. Without understanding the current and future demand for electricity, making socially optimal investment decisions and effective planning for sustained supply of electricity is impossible (De Nooij et al., 2007). While some consumers have high latent demand for fully reliable electricity service (such as industrial consumers with heavy equipment), others have lower demand levels (e.g., low-income households with demand only for lighting purposes). In the absence of markets for electricity reliability, the value of unsupplied electricity should be assessed carefully depending on the consumer mix in a given region to avoid under- or over-estimating WTP values (Sullivan et al., 2010). Otherwise, the outcome will be increasing electricity provision to those who do not seek it, leading to a less efficient allocation of electricity.

The remainder of the paper is organized as follows. Section 1.2 reviews the previous literature on the unreliability of electricity supply. Section 1.3 describes the data and methodology, followed by the theoretical model's description in Section 1.4. The empirical results are then discussed in Section 1.5. The robustness of estimated WTPs is tested in Section 1.6. Section 1.7 lists the conclusions of the paper.

1.2 Related literature on unreliable electricity supply

For many countries in South Asia and Sub-Saharan Africa, an unreliable electricity supply is a norm rather than the exception. Public electric utilities in these countries are severely capital-rationed, and electricity rates are heavily regulated. Electricity rates are not only maintained below the long-run cost of generation plus transmission and distribution, but they also cannot be adjusted when seasonal shortages exist. The consequence of this practice is a deterioration of the electricity reliability that imposes costs and inconvenience on electricity consumers. Previous literature documents that intermittent electricity service results in revenue losses for firms due to under-utilization of production capacity and inconvenience for households due to inability to utilize their desired energy services (Steinbuks and Foster 2010; Alby et al., 2012; Chakravorty et al., 2014; Fisher-Vanden et al., 2015; Allcott et al., 2016; Samad and Zhang, 2016; Falentina and Resosudarmo, 2019; Bajo-Buenestado, 2020).

When electricity is an essential input for a firm’s operation, empirical evidence suggests that an unreliable supply can adversely affect its productivity. Allcott et al. (2016) analyze the impact of electricity shortages caused by the seasonality of hydropower availability on large manufacturing firms in India. Their findings reveal that India’s electricity shortages have reduced the average firm’s revenues by 5 to 10 percent. Similarly, Grainger and Zhang (2019) evaluate the cost of electricity shortages for manufacturing firms in Pakistan. They estimate that an additional average daily hour of unexpected power outages decreases a firm's annual revenues by 10 percent, decreases annual value-added at the firm level by 20 percent, and increases the labor share of output. These impacts highlight the significant role of having access to reliable power infrastructure on economic growth (Andersen and Dalgaard, 2013).

The opportunity cost of unsupplied electricity for firms can be measured by the value of forgone production per kWh of unsupplied electricity. An accurate estimation of opportunity cost requires access to detailed operating accounts of business enterprises (Hashemi et al., 2018). In the absence of such data, the stated WTP values can approximate a firm's actual WTP value for a reliable electricity supply. By analyzing the relationship between the estimated WTP and observable characteristics of firms, we can better understand firms' decision-making when it comes to coping with the unreliable supply of electricity.

The welfare impacts of intermittent electricity supply are not limited only to non-residential consumers. Ozbafli and Jenkins (2016) use the choice experiment method to evaluate households' WTP for improved electricity service in North Cyprus. Their findings show that households are willing to pay premia of 3.6 percent and 13.9 percent of their current electricity bills for summer and winter, respectively, to get uninterrupted service. Similarly, Oseni (2017) estimates the WTP of a sample of Nigerian households for improved reliability of grid-supplied electricity. The findings indicate that households are willing to pay more on top of their monthly bills for reliable service, and WTP is significantly higher for those households who have already adopted backup diesel generators.

After identifying the causes and impacts of unreliability, the next challenge is to evaluate potential solutions. Various responses are available to electric utility companies and policymakers (Gertler et al., 2017). In the long run, investments in generation, transmission, and distribution capacities, as well as institutional reforms, can ensure that the electric grid satisfies the increasing demand for reliable electricity. In the short run, pricing mechanisms can help manage demand by adjusting electricity prices when load curtailment is required. Time-of-day tariffs (also known as peak-load pricing) can shift consumption during peak times toward users with the highest marginal benefits. Interruptible electricity contracts provide rebates to users that choose to accept outages during periods of peak demand. Finally, quantity rationing can be employed through load shedding programs, a system in which the power supply is interrupted to different areas for non-overlapping periods.

In Nepal, the electricity utility company is a state-owned vertically-integrated monopoly with regulated electricity tariffs. Quantity rationing (also known as load shedding) has been the method of dealing with seasonal electricity shortages. The efficient energy allocation to ration this excess demand is to provide the available energy to those valuing it the most, those with the highest opportunity cost of unsupplied power. With no system for identifying the value placed by individual customers on each unit of energy received, however, the utility company curtails power arbitrarily to different groups of consumers or makes a judgment by its own priority system of where the energy is least valued. Timilsina et al. (2018) estimate the economy-wide costs of load shedding Nepal faced using a computable general equilibrium model. Their findings indicate that annual gross domestic product would have been 7 percent higher than it was during 2008–16 if there had been no load shedding.

1.3 Data and methodology

1.3.1 Electricity Supply in Nepal

Hydropower represents 90 percent of the total installed generation capacity in Nepal, mostly run-of-the-river type. With river flow being governed by the monsoon and dry seasons, Nepal experiences significant generation declines during the dry season[5]. Figure 1.1 depicts the variation in total hydroelectricity generation during 2016, the year in which the survey data used in this paper were collected. The average monthly rainfall drops significantly between the two seasons (Panel A), leading to a sharp drop in hydropower generation (Panel B). The installed capacity in 2016 was 856 MW, whereas peak demand amounted to 1,385 MW. This resulted in a 534 MW of power deficit with daily outages of up to 11 hours during the dry season. Figure 1.2 shows the hydroelectricity generation pattern during the five years before 2016, confirming that this pattern is not unique to 2016.

In response to low hydropower generation levels during the dry season, Nepal Electricity Authority (NEA), the central government-owned generator, grid operator, and distributor, curtails power supply to all customers through a rationing program known as

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[5] Only 14% of the total installed capacity is in the form of dam storage-type hydropower installations. These dams can store water for long periods and use it to continue full generation during the dry season when run-of-river types reduce output due to lower river flows. However, most of the hydropower projects in Nepal as of the time of this study are run-of-river types because storage-type dams are significantly costlier at least for two reasons: (a) storage-type dams require substantial submergence of forest and agricultural land; and, (b) Himalayan rivers in Nepal contain large quantities of sediment with hard abrasive particles that reduce the lifespan of reservoirs by decreasing storage capacity (Thapa et al., 2005).

load shedding. This program assigns all grid-connected consumers to different groups and cuts their electricity during specific hours of the day that are announced ahead of time. To reduce the extent of the load shedding, Nepal has relied on electricity imports from India[6]. Electricity imports have increased threefold since 2010, from 638 GWh in 2010 to 1,777 GWh in 2016 (NEA, 2017). Due to insufficient cross-border transmission capacity, Nepal has not fully benefited from India's electricity trade to eliminate its domestic power deficits[7].

1.3.2 Household data

The household sample used in this study contains 1,800 grid-connected households across Nepal. The survey design team took various measures to ensure that households' data were selected randomly and nationally representative (see Appendix A for more detail about national-representativeness). First, to avoid selection bias against the most remote rural areas, a GIS-based household selection was followed in rural areas. Similarly, a GIS-

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[6] An alternative for imports would be developing domestic storage-type hydropower projects. The cost of electricity imports from India is projected to range from NPR 5 to 9 per kWh, but the projected cost of electricity generated by domestic storage projects is more than NPR 10 per kWh from (World Bank, 2019a). This is why developing domestic storage projects are not economically feasible at the current level of demand in Nepal despite the high potential of hydropower capacity. Moreover, another advantage of power trades with India is that Nepal will be able to export its surplus capacity to India during the rainy season.

[7] In 2011, the construction of Nepal-India Electricity Transmission and Trade Project (NIETTP) started with financing from the World Bank and a group of international development organizations. The main aim of this project was to increase the cross-border transmission capacity between India and Nepal to facilitate electricity trade between the two countries. Nepal will be able to export its surplus power to India during the monsoon season and to import from India during the dry season in order to eliminate load shedding. In the results section, this project is used to investigate whether the estimated WTP values among electricity consumers for reliability improvements would map into changes in electricity consumption after improvements by NIETTP.

based Random Start or Fanning method was used in the urban areas, based on a sample frame obtained from the NEA.

Also, to ensure that the sample is nationally representative, the same sampling strategy used by Nepal's bureau of statistics and the World Bank is employed. Geographically, Nepal is divided into three ecological regions: Mountain, Hill, and southern flat land called Terai (see Figure 1.3). The Mountain region accounts for 35 percent of the country's total land area, while Hills and Terai accounting for 42 percent and 23 percent, respectively. The Terai zone contains 50 percent of the total population, while Hill and Mountain have 43 percent and 7 percent, respectively.

Any ward belonging to a Village Development Committee (VDC) as per the 2011 census (the latest available at the time of the survey) was treated as a rural location, and any ward belonging to a Municipality/Sub-metropolitan/Metropolitan city as an urban ward. The final sample is achieved by splitting the country into four strata: Rural Hills, Rural Terai, Urban wards outside Kathmandu Valley, and Urban Kathmandu Valley[8]. A sample of 400 households is allocated for each stratum except for the urban locations outside Kathmandu Valley, where a sample of 600 households is allocated (i.e., a total of 1,800 interviews)[9].

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[8] Kathmandu Valley comprises urban areas in the districts of Kathmandu (the capital city), Lalitpur and Bhaktapur. Outside Kathmandu comprises all other urban areas – municipalities (cities and towns) – located outside of the Kathmandu Valley.

[9] Outside-Kathmandu Valley stratum had been oversampled to ensure a sufficient sample allowing for any differences in electricity consumption within the urban locations across Nepal other than urban areas in Kathmandu Valley.

Table 1.1 reports the descriptive statistics of the households' sample[10]. All of the surveyed households were connected to the national electricity grid at the time of the survey[11]. Urban households constitute 56 percent of the sample, with 22 percent residing within the Kathmandu Valley. Of the 44 percent of the rural population, exactly half reside in Terai, with the other half residing in mountainous regions. Survey enumerators collected information about the average monthly electricity bills of households by observing the electricity bills. The survey also collected information about possible demand-shifting sociodemographic characteristics of households such as income, education of the household head, number of household members, number of rooms in the house, number of children of school age (6-14 years old), and ownership of TVs, radios, and computers.

Unscheduled interruptions in electric service and fluctuations in voltage constrain the use of high-voltage appliances (such as refrigerators, televisions, and computers) and result in a malfunction of appliances. The survey finds that households engage in various coping behaviors when electricity from the grid is not available or when there are fluctuations in the voltage of electricity drawn from the grid.

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[10] Tables 1.1 and 1.2 do not report the descriptive statistics of respondents' stated WTP. Later in the paper, Tables 1.3 and 1.4 represent descriptive statistics of stated WTPs for the household sample and the firm sample, respectively.

[11] By 2016, 72% of Nepalese households were connected to the national grid, whereas 23% are connected to off-grid sources (such as solar), and 5% of the households have no access to electricity in any form (World Bank, 2019b).

In addition to the descriptive statistics for the whole sample, Table 1.1 also reports the descriptive statistics by quartiles of the electricity bills[12]. Those data indicate that households are mostly rural in the lower quartiles while most households in the higher quartiles are urban. Also, income varies within all quartiles of electricity bills; energy-poor households are not necessarily income-poor.

Another interesting pattern in Table 1.1 is the adoption of alternative power sources across quartiles of electricity bills. Solar panels, solar lanterns, torch lights, emergency lights, and candles show a similar uptake pattern across all electricity-bill quartiles. However, there is a distinct uptake pattern for inverters and kerosene: kerosene is mostly adopted by the first and second quartiles of electricity bills. In contrast, inverters are the preferred backup technology among consumers in the third and fourth quartiles.

1.3.3 Firms data

Similar measures were taken to ensure the quality of data collected from business enterprises. The sample frame for business enterprises is provided by Nepal's Inland Revenue Department (IRD), segregated into service and manufacturing/industrial firms. The same definition of businesses used by the IRD is used: "small" businesses have an annual turnover (gross sales) of less than NPR 50 million (USD 0.47 million); and "medium" businesses have an annual turnover between NPR 50 million and NPR 400

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[12] Using the electricity tariffs published in 2016 annual report by NEA, the KWh of electricity consumed by each quartile of electricity bills can be approximated. The average monthly consumption is less than 30KWh, 31-150 KWh, 151-400 KWh, and more than 400 KWh for the 1st, 2nd, 3rd and 4th quartiles, respectively.

million (USD 0.47-3.8 million). Firms with an annual turnover greater than NPR 400 million (USD 3.8 million) are categorized as "large."

The achieved sample size is 590 businesses: 340 industrial or manufacturing firms and 250 service-oriented firms, with 46, 38, and 16 percent of firms being small, medium, and large, respectively (see Table 1.2). As in the household sample, the descriptive statistics for the firms' sample are reported by their electricity consumption intensity. There are three main electricity tariff categories for business enterprises in the sample: domestic, commercial, and industrial. On average, the monthly electricity bills of industrial consumers are 24 times and 50 times more than the average monthly electricity bills of commercial and domestic subscribers, respectively. Firms in the domestic tariff category are mostly small and medium firms active in the service-oriented sectors.

Adopting coping technology among firms is different from households due to their different demand for electricity. Firms often use electricity for purposes other than lighting, such as running different equipment types, which is why we observe a higher adoption rate of inverters and diesel generators among firms. The opportunity cost of unsupplied electricity to most firms is so high that they self-generate electricity when the grid is down, even though self-generated electricity is costlier and inferior to grid electricity in terms of load (Burgess et al. 2019)[13]. The adoption rate of diesel generators increases as we go from

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[13] Some firms (those which are not operating 24 hours) might have the option of making up some fraction of lost production time by working overtime and extra shifts (Wing and Rose, 2020). In most cases, however, it is unlikely that a profit-maximizing firm would have an economic incentive to engage in overtime production, unless the firm is constrained by contractual obligations (Munasinghe and Gellerson, 1979). Also, it might be argued that firms can plan ahead of time by keeping inventories during the dry season. Since the dry season lasts for a few months in Nepal,

the domestic tariff category toward the industrial tariff category. It is also observed that the adoption of voltage stabilizers is more prevalent among firms than households, most likely because firms have expensive equipment that is more sensitive to voltage fluctuations. Some firms also use solar panels to cope with the unreliable supply of grid electricity, but firms mostly use them in the domestic tariff category with low electricity demand.

1.3.4 Contingent valuation survey design, limitations, and potential biases

In a contingent valuation framework, two electricity reliability improvement scenarios were proposed to the respondents. Respondents were asked to state how much they were willing to pay on top of their current electricity bills for (i) 50 percent reduction in the planned outages; (ii) 100 percent reduction in the planned outages[14]. The survey design provided a bidding process to elicit the respondents' WTP for each proposed improvement in a double-bounded dichotomous choice format. Using the answers and bids, the mean WTP can be estimated by applying a double-bounded model (also known as interval data model).

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most firms would not be able to make required investments in physical planning or operate profitably by keeping high stakes of inventories.

[14] Interruptions in electricity service are mainly categorized into planned and unplanned outages. Scheduled or planned outages occur due to lack of capacity in generation and/or transmission segments of electricity supply chain. Unplanned outages happen at the distribution level due to different factors such as overloaded transformers and non-technical losses (such as theft and illegal connections). While planned outages can be totally eliminated countrywide by upgrading the upstream (generation and transmission) capacities, unplanned outages often require local solutions. Identifying the type of outages without detailed data from the electric utility is an empirical challenge. In Nepal, however, all electricity consumers can clearly distinguish planned outages from unplanned ones because load shedding program has been a part of their lives for more than a decade.

The initial bid offer was generated as a random amount in NPR from zero to a hundred percent of the respondent's average monthly grid electricity bill. If the respondent agreed that they would pay this initial amount (a "yes" response), then they would be asked if they were willing to increase their payment in steps of 10 percent until the response was "no". If the response to the initial random bid was a "no", then this initial bid was decreased in steps of 10 percent of the respondent's electricity bill until the respondent said "yes" to the proposed amount.

Before starting the bidding process, a few quality measures are taken to reduce biases that can be potentially introduced during a contingent valuation survey. A cheap-talk script was read to the respondents about hypothetical bias, and respondents were asked to state their WTP for the proposed policies "as if" those proposals would be implemented (see Box B1 in Appendix B). Moreover, the script includes consequential features intended to convey to respondents that their responses were of consequence and could eventually result in real policy changes: "*...if you value electricity enough, the government may decide to invest more in electricity, and your tariff may have to increase to pay for the investment."*[15]

Moreover, previous studies show that the payment vehicle — how respondents are asked to pay for the reliability improvements — is also an important design issue in contingent valuation surveys. If respondents do not believe the credibility of payment vehicle, their responses may be biased (Gunatilake et al., 2007; Whittington and Pagiola,

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[15] There is some evidence that cheap-talk and consequential scripts effectively reduce the magnitude of hypothetical bias in the contingent valuation surveys (Cummings and Taylor, 1999).

2012). The valuation questions in this survey are designed to be asked from an ex-ante perspective in the form of increments to current electricity bills. The questions target the premium the respondent would be willing to pay in addition to current monthly bills to have an improved electricity service. Given that all the surveyed households and firms are already connected to the grid and are familiar with electricity bills as the payment vehicle, this should not be of great concern.

Despite the application of contingent surveys in eliciting WTP values, the validity of estimates by this method has been subject to criticism. This study tests the validity of the results to the extent possible. For instance, one major concern with contingent valuation studies is that they measure ex-ante demands based on hypothetical proposed situations. Previous studies have pointed out that this hypothetical nature can lead to overestimating the real WTP (Blumenschein et al., 1998; Penn and Hu, 2018). Although the possibility of such bias cannot be ruled out in this analysis, it should not be of significant concern. Respondents in the sample not only have experienced load shedding schedules announcing planned outages for several years proceeding to the survey, but they also have a clear understanding of how improvements in the reliability of electricity service would be. The first proposed improvement is a 50 percent reduction in outages. This can be related to when the dry season is coming to an end, and the load shedding schedule starts to disappear. Similarly, the second proposed improvement is a total elimination of planned outages, which is the electricity supply status during the wet season when there is no load shedding[16].

Another concern is how accurately contingent valuation surveys reveal respondents' "true" preferences and costs. In this study, to encourage respondents to focus on the marginal benefits and costs, the survey questions were designed very carefully. The questions asked, "how much additional to the current bill" customers would be willing to pay instead of "how much of a tariff" they would be willing to pay for a reduction of planned outages. This difference provides a set of comparable relative costs and benefits and results in more reliable WTP estimates, expressing customers' preferences and costs more accurately (Ghosh et al., 2017).

The application of stated preference methods has also been associated with concerns about ordering effects (Bateman et al., 2004). Although the possibility of this bias cannot be completely ruled out in this analysis, the survey was designed and implemented in a way that mitigated ordering effects bias to some extent. The respondents were aware that a series of questions would be asked regarding their WTP. This process, known as advanced disclosure, is shown to be an effective design factor in mitigating ordering effects (Bateman et al., 2004; Aravena et al., 2012; Day et al., 2012).

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[16] The possibility of delivering the proposed project and familiarity of respondents with the proposed improvements do not necessarily translate into the elimination of hypothetical bias. The main idea here is to highlight that respondents are very well familiar with the nature of planned outages and can refer to their actual experiences when evaluating the proposed improvements.

Finally, construct validity can be used to evaluate the accuracy of WTP responses generated by the contingent valuation survey[17]. In this paper, a set of regressions is used to examine the relationship between a respondent's WTP and the observable characteristics that are pointed out by economic theory as the plausible determinants of the WTP.

1.3.5 Empirical strategy

Given that respondents are presented with two bid levels, the second bid is contingent upon a response to an initial bid (B_i). If the response to the initial bid is yes, the second bid is higher (B_H); otherwise, it is lower (B_L). Thus, there are four possible outcomes: yes-yes, no-no, yes-no, and no-yes. The likelihoods of these outcomes are denoted by π^{yy}, π^{nn}, π^{yn}, and π^{ny} , respectively,

$$\begin{aligned}\pi^{yy}(B_i, B_H) &= \Pr(B_i \leq WTP^* \; and \; B_H \leq WTP^*) = \Pr(B_H \leq WTP^*) \\ &= 1 - G_{WTP^*}(B_H; \theta)\end{aligned} \tag{1}$$

$$\begin{aligned}\pi^{nn}(B_i, B_L) &= \Pr(B_i \geq WTP^* \; and \; B_L \geq WTP^*) = \Pr(B_L \geq WTP^*) \\ &= G_{WTP^*}(B_L; \theta)\end{aligned} \tag{2}$$

$$\pi^{yn}(B_i, B_H) = \Pr(B_i \leq WTP^* \leq \; B_H) = G_{WTP^*}(B_H; \theta) - G_{WTP^*}(B_i; \theta) \tag{3}$$

$$\pi^{ny}(B_i, B_L) = \Pr(B_i \geq WTP^* \geq \; B_L) = G_{WTP^*}(B_i; \theta) - G_{WTP^*}(B_L; \theta). \tag{4}$$

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[17] Construct validity refers to how well the measurement is predicted by factors that one would expect to be predictive a-priori, i.e. the consistency of survey results with the predictions of economic theory.

$G_{WTP^*}(.)$ is the cumulative distribution function of the WTP^*. Given a sample of n respondents and the bids B_i, B_L, and B_H, the log-likelihood function of the double-bounded model takes the following form,

$$\ln L\,(\theta) = \sum_{i=1}^{n} \{ l_i^{yy} ln\pi^{yy}(B_i, B_H) + l_i^{nn} ln\pi^{nn}(B_i, B_L) + l_i^{yn} ln\pi^{yn}(B_i, B_H) + l_i^{ny} ln\pi^{ny}(B_i, B_L)\}, \tag{5}$$

where $\mathrm{l_i^{yy}}$, $\mathrm{l_i^{nn}}$, $\mathrm{l_i^{yn}}$ and $\mathrm{l_i^{ny}}$ are binary variables and θ is a vector of parameters of interest. In the double-bounded model, the maximum likelihood estimation directly estimates the parameters of interest. Once the estimated parameters are obtained, we can estimate households' WTP[18].

1.4 Theoretical model

Suppose there are two types of electricity consumers, low demanders, and high demanders; and, two states of the world, dry season with a frequency of planned outages φ and monsoon season without planned outages. High demanders are those consumers whose WTP for uninterrupted electricity service justifies investments in high-quality backup sources such as diesel generators and inverters. Low demanders are those consumers whose WTP only justifies adopting low-quality backup services such as kerosene and candles when the grid is down.

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[18] The *doubleb* Stata command developed by Lopez-Feldman (2012) is used for estimation.

The question is to what extent consumers are willing to pay for incremental electric system reliability improvements that eliminate seasonal outages. Panel A in Figure 1.4 shows the situation for a high demander. When the supply is unconstrained (i.e., during monsoon season), sufficient generation capacity allows consumers to buy all their needed power from the electricity utility company ($\mathrm{Q_u}$) at the regulated electricity tariff (P_R). When supply becomes constrained (i.e., during dry season), however, consumers can only buy electricity from the utility company during non-load-shedding hours (Q_c). Although high demanders supplement the grid-supplied electricity with backup generators, the cost of self-generation is greater than the utility company's tariff. So, these consumers self-generate only up to a point ($\mathrm{Q_{c\,+\,self}}$) that is less than what they would have purchased from the grid without any constraint ($\mathrm{Q_u}$). If the reliability were improved, high demanders would be willing to pay approximately the area $(A + B + C + E)$ multiplied by φ. In other words, the WTP value will increase until a 100 percent reduction in outages is achieved.

For low demanders, depicted in Panel B of Figure 1.4, the situation is different. The marginal cost of self-generation is sufficiently high that this group cannot justify investments in generators. These consumers tend to use coping equipment other than generators. However, the question is how they would respond to improvements. Assuming that the initial frequency of planned outages is φ_0, a partial improvement in the availability of electricity service $(-\Delta\varphi < \varphi_0)$ is associated with a surplus gain of approximately $(-\Delta\varphi) \times (A + C)$. Total elimination of planned outages $(-\Delta\varphi = \varphi_0)$ will result in even a higher gain in consumer surplus because of the income effect from improved electricity service (demand curve rotates outward from D_0 to D_1). Practically, improved reliability results in savings in the expected monetary costs of injuries by low-quality backup and reduced leisure. The gross WTP for total elimination can, therefore, be approximated by $\varphi_0 \times (A + C + G + H + I)$. This implies that this type also puts a higher value on the quality of the additional improvement that eliminates the uncertainty associated with power outages.

The theoretical model suggests that respondents are expected to state higher WTP for electricity reliability improvements until full reliability is achieved. This behavior is consistent with the real-world observation of consumers' behavior when coping with unreliable public electricity provision. When the national grid is down, consumers lack equivalent perfect substitutes. Provision of electricity is different from other public domains such as water supply. Installing home water treatments when the water supply is unreliable may be sufficient to solve consumers' water problems. In that case, the substantial sunk costs may alter the consumer's behavior regarding the provision of an improved water supply. Therefore, the consumer may not be willing to pay for improvements (Devicienti et al., 2004).

However, in the case of electricity supply, although consumers invest in alternative power sources, they do so to the equivalent of electricity autarky (off-grid alternative sources of power), with costs far more than grid electricity (due to scale economies in grid supply) and with power loads less than a well-functioning grid (Burgess et al., 2019). Therefore, those who invested in coping equipment may be willing to pay even more than those who have not.

1.5 Empirical results

Table 1.3 reports the mean estimated WTP of households in the sample. The results show that households incur on average a premium almost as much as their average monthly grid-electricity bills (95 percent) in the form of coping expenditures. Looking at the estimated WTP values based on the quartiles of electricity bills, it is apparent that such expenditures are relatively higher for households with lower consumption levels: those in the first quartile incur coping expenditures 1.6 times more than their electricity bills, whereas those in the fourth quartile report expenditures 0.4 times of their bills.

While the magnitude of estimates is different, the stated WTP estimates for 50 percent and total elimination of outages show a similar pattern to the revealed WTP estimates across quartiles[19]. An interesting pattern reveals when looking at the breakdown of total WTP values. Although a 50 percent reduction in outages in each step theoretically provides equal units of electricity, households value the second increment differently. The incremental WTP for 100 percent reduction varies across different quartiles of bills (row 2b in Table 1.3). Households in the first quartile are willing to pay a further 74 percent of their current electricity bills, while those in the fourth quartile are willing to pay only an additional 40 percent.

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[19] In the sample of households, 4 percent of respondents (72 respondents) stated zero willingness to pay for service improvements. Looking at the observable characteristics of this group, it is clear that zero bids are stated by those at lower income categories. So, it is assumed here that these bidders represent valid zero bids rather than protest zeros, which would arise if respondents have stated a zero WTP even though their true valuation was positive.

The same exercise is repeated for the firms' sample (see Table 1.4)[20]. The average coping expenditures for a representative firm amounts to a premium of 79 percent on the electricity bill. Once the sample is split by electricity tariff categories, a pattern of scale economies in off-grid coping expenditures is observable among firms, with the relative coping expenditures of industrial firms being less than domestic and commercial firms'. The stated WTP for a 50 percent reduction in outages by firms suggests a similar pattern to the revealed WTP estimates among firms. However, the stated WTP for the total elimination of planned outages indicates a change in the opposite direction: the average WTP stated by firms with industrial tariffs is 50 and 30 percent greater than the WTP by firms with domestic and commercial tariffs, respectively.

These obtained WTP estimates provide two insights about the cost of interruptions to electricity consumers. First, the sustained availability of electricity is valued heterogeneously between residential and non-residential consumers. Second, even within the same category of consumers, the reliability of electricity service is valued differently. The next step is to test the associations between the obtained WTP values and observable

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[20] In the firms' sample, two percent of respondents (15 firms) stated zero willingness to pay for the proposed improvements. Previous studies suggest that zero bids (also known as protest bids) should be considered legitimate WTP bids when respondents value a proposed policy, as opposed to when they value a commodity (McGuirk, Stephenson and Taylor, 1989; Oseni, 2017). Moreover, as Carlsson and Martinsson (2007) argue, if there is no further information about the protest, they should be treated as true zeros since we cannot rule out a WTP equal to zero. Following these arguments, I included zero WTP responses by firms. The estimated WTP without zero responses are, on average, 11 percent, 18 percent, and 15 percent lower for firms under domestic, commercial, and industrial electricity tariffs, respectively. Moreover, I tested the robustness of the regression coefficients represented in Table 1.7 by estimating a Tobit model. The Tobit model's results indicate that while the sizes of the coefficients change slightly, their signs do not show any sensitivity to the regression model's choice.

characteristics of respondents to see what observable characteristics of electricity consumers should be taken into account to avoid the increased provision of energy to those who do not seek it.

Panels A and B in Figure 1.5 depict the regression coefficients by quartiles of households' electricity bills and firms' electricity tariff categories, respectively. The absolute value of stated WTP by households in higher quartiles of electricity bills does not significantly differ from those in lower quartiles. The relative WTP values, however, decrease significantly from lower to higher quartiles. At first glance, this might imply that households in higher quartiles put a lower value on improvements in the electricity system reliability. However, this counterintuitive finding can be explained by a closer look at the resale value of coping equipment and the coping equipment's adoption patterns across quartiles.

Households in higher quartiles of electricity bills are more likely to invest in inverters and voltage stabilizers (see Table 1.6). Among available backup technologies, only inverters have enough capacity to power large-load appliances (e.g., refrigerators and washing machines) beyond lights, radios, and mobile phone chargers. Also, voltage stabilizers can insure the large-load sensitive electric appliances against voltage fluctuations. With such complementary off-grid equipment, high-demand households are able to consume almost as much as electricity units they desire even without proposed improvements. For them, the inconvenience may be simply rescheduling power-consuming activities. These technologies are also associated with high sunk investment costs and most likely have a low ratio of resale value to purchase value. A fully reliable grid, however, provides a reliability level above and beyond any equipment. Thus, higher quartile households are willing to pay a positive but smaller fraction of their current bill to reduce outages further.

On the other hand, given the low demand for electricity services among lower quartiles of bills, their WTP for reliable electricity is insufficient to cover the high upfront and routine maintenance costs of inverters and voltage stabilizers. Hence, it is not surprising that lower quartile households are more likely to use kerosene to cope with unreliable electricity service (see Table 1.6). However, kerosene provides low-quality lighting with an expected possibility of burn injuries for household members (Daltrop and Mulqueeny, 2010). Also, they cannot turn on the radio or TV or charge their mobile phones during blackouts. Therefore, they might be willing to pay a relatively higher fraction of their current bill to eliminate outages' risks and inconvenience.

In Panel B of Figure 1.5, it is shown that an incremental improvement in reliability from 50 percent to 100 percent is valued more by both commercial and industrial firms, but only statistically significant for industrial firms. This behavior among firms can be explained by the nature of coping behavior among industrial firms. As shown in Table 1.8, industrial firms invest in backup generators and voltage stabilizers because of their needs for higher loads and their equipment's high sensitivity to voltage fluctuations. The reliability level that these consumers require cannot be provided by other off-grid equipment such as intermittent solar panels. However, the cost of running backup generators is so high that these firms cannot operate 24 hours (as they usually do to avoid ramp-up times or to meet manufacturing requirements) if they decide to self-generate all their required electricity.

When a 50 percent reduction in outages is proposed, these firms still need to keep their installed backup capacity, but they save partially in generator’s operating costs (fuel for generators). Given that industrial firms benefit from the economies of scale in self-generation, their savings in operating costs after service improvements are relatively less than commercial and domestic categories. On the other hand, when outages due to electricity shortages are entirely eliminated, firms may decide to remove all or a large fraction of their installed backup capacity. In other words, they are not only able to save all the operating costs, but they are also able to save substantially on the fixed capital costs as well as high routine maintenance costs. These savings add up to potential increases in revenues from higher utilization rates due to increased consumption of electricity services. The value of these gains ranks industrial consumers first, with the highest WTP for outage-free electricity service.

The impacts of other household-level characteristics on WTP values are listed in Table 1.5. Household income is expected to correlate with electricity demand (Sievert and Steinbuks, 2020) positively. Column 1 of Table 1.5 shows a positive correlation between households’ electricity bills and income levels. This is most likely driven by the ownership of high-power electric appliances (such as refrigerators and washing machines) that higher-income households use to do household chores. The relationship between income and WTP for reliability follows the same pattern as the relationship between income and electricity consumption.

Also, households with at least one kid at school stated a higher WTP for reliability improvements. As the household head's educational attainment increases, the WTP for the total elimination of outages increases. Lee et al. (2020) argue that the impact of electrification is a direct function of a household's ability to make complementary investments to realize the potential benefits of electrification. Parents with school kids and household heads with higher education attainment put a higher value on reliability because more electricity reliability can increase their expected benefits from the investments they have made in their kids and their education.

Similarly, other firm-level characteristics are expected to affect their current and future electricity demand once reliability is improved. As represented in Table 1.7, firms under commercial and industrial electricity tariff categories currently consume significantly more electric power than domestic ones. Firm size is a predictor of current electricity demand and absolute WTP for improvements. And, firms located in rural areas state a significantly higher WTP for the total elimination of outages, both in absolute and relative terms.

1.6 Comparing ex-post electricity consumption with predictions of ex-ante WTP estimates

The Nepal-India Electricity Transmission and Trade Project (NIETTP) was proposed in 2011 to expand cross-border transmission capacity between India and Nepal. With the development of different phases of NIETTP, Nepal has been able to import additional power from India from 2017. NEA has been able to serve the residential consumers without any load shedding since 2017. Non-residential load shedding, however, continued partially until early 2018, when the project became fully operational. The survey used in this study is conducted right before this project came into service. The WTP estimates predict that industrial consumers put the highest value on the sustained supply of electricity. The validity of this prediction can be tested by ex-post changes in electricity consumption levels after 2016.

In 2016, NEA served 3,257,812 customers, 93.8 percent under domestic tariff, 0.6 percent under commercial tariff, and 1.4 percent under industrial electricity tariff[21]. Sales to these three categories were more than 88 percent of total MWh sold by NEA, totaling USD 0.4 billion of revenues. Domestic consumers comprise 42 percent of these revenues, followed by industrial and commercial consumers with 35 and 11 percent, respectively.

Figure 1.6 depicts the electricity consumption growth index for domestic, commercial, and industrial customers from 2010 through 2018, with 2016 as the base year[22]. Each year's index value is constructed as the ratio of GWh of electricity sold to each consumer category in that year to GWh of electricity sold to that category in 2016. The index is also adjusted for the growth rate in the number of consumers to ensure that it represents the average change in consumption level for each category over time. Industrial customers have the highest ex-post increase in electricity consumption, as predicted by the ex-ante WTP. This finding is consistent with previous studies' findings that grid expansion has an aggregate

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[21] The other 4.2 percent included supply of power for public usage such as street lights, temples, irrigation and water supply.

[22] 2018 annual report is the latest available electricity utility report as of the time this study is being conducted.

impact on industrial development (Kassem, 2018; Khanna and Rowe, 2020; Fried and Lagakos, 2020; Perez-Sebastian et al., 2020; Fiszbein et al., 2020).

1.7 Conclusion

This study contributes to the growing discussions of how increased electricity availability from new generation capacity or power imports can improve electrification policies' effectiveness in low-income, energy-poor contexts. These upstream energy interventions can facilitate moving beneficiaries to relatively higher electricity consumption tiers since the shortfall in electricity availability has locked them into a lower tier of access despite being connected to the grid (Bhatia and Angelou, 2015). Using a representative sample of electricity customers in Nepal, I find substantial heterogeneity in ex-ante demand for an improved electricity supply and an ex-post increase in electricity consumption levels, even within the same tariff categories.

The estimates reported in this paper indicate that focusing only on aggregate coping expenditures or stated WTP for proposed improvement may lead to under- or over-estimation demand for reliability among different categories of consumers. While energy supplied by off-grid backup technologies can be used during periods of supply interruptions, there is still inconvenience among electricity consumers caused by public infrastructure's insufficiency. Households need to reschedule their routine activities, and firms cannot utilize their full capacity. The value of this remaining inconvenience is not reflected in consumers' coping expenditures and shows up only in the stated WTP values when the survey respondents are asked to state their WTP for the additional increments to reliability.

For policy-making purposes, the findings highlight the importance of understanding which categories of electricity customers will most likely benefit from electricity reliability improvements. An unreliable supply of electricity from the grid can be expected to impose varying levels of welfare cost depending on the household's socioeconomic characteristics. Similarly, business enterprises may be affected differently based on their opportunity costs of unsupplied power. Thus, a detailed analysis of households' preferences and firms' opportunity costs is necessary for electricity utilities and policymakers to evaluate the benefits from reliability investments properly. Even if investments cannot be made and rationing has to be done, such information allows the decision making process for utilities by ranking customer groups based on their costs of per kWh unserved when the electric system load has to be shed, rather than making arbitrary allocations.

Table 1.1: Descriptive statistics for households' sample

Variable	Whole sample (n=1,800)	Quartiles of electricity bills 1st (n=450)	2nd (n=482)	3rd (n=418)	4th (n=450)
Monthly grid electricity bill					
USD	5.73	0.76	1.93	4.59	15.82
	(8.13)	(0.14)	(0.59)	(1.14)	(10.95)
Household characteristics					
Number of household members	5.14	4.91	4.89	5.22	5.58
	(2.42)	(2.30)	(2.23)	(2.26)	(2.71)
Number of rooms in the house	5.59	4.15	5.00	5.50	7.75
	(3.15)	(2.08)	(2.62)	(2.94)	(3.60)
Have at least one school kid (aged 6-14)	0.57	0.59	0.58	0.57	0.53
Owns a TV/radio	0.85	0.64	0.86	0.94	0.98
Owns a computer	0.35	0.08	0.28	0.38	0.68
Educational attainment of the household head					
No formal education	0.20	0.29	0.25	0.17	0.09
Less than School Leaving Certificate (SLC*)	0.44	0.47	0.45	0.44	0.39
SLC	0.13	0.12	0.12	0.12	0.17
More than SLC	0.23	0.12	0.18	0.27	0.35
Household income					
Category 1: Less than NPR 10K (USD 95)	0.07	0.16	0.05	0.03	0.01
Category 2: Between NPR 10K to 20K (USD 95 to 190)	0.23	0.35	0.27	0.21	0.09
Category 3: Between NPR 20K to 40K (USD 190 to 381)	0.37	0.30	0.42	0.40	0.35
Category 4: Between NPR 40K to 60K (USD 381 to 571)	0.21	0.11	0.18	0.23	0.31
Category 5: More than NPR 60K to 80K (USD 571)	0.12	0.07	0.07	0.11	0.22
Urban/rural status and ecological zones					
Urban – Kathmandu	0.22	0.02	0.18	0.23	0.45
Urban – Outside Kathmandu	0.34	0.24	0.27	0.44	0.39
Rural – Terai	0.22	0.27	0.32	0.22	0.06
Rural – Mountain	0.22	0.46	0.23	0.10	0.09
Coping technology					
Inverters	0.19	0.02	0.09	0.18	0.47
Solar panel	0.16	0.17	0.14	0.19	0.16
Solar lantern	0.01	0.02	-	0.01	-
Voltage stabilizer	0.11	0.02	0.05	0.13	0.23
Torch lights	0.47	0.51	0.47	0.48	0.43
Emergency lights	0.48	0.42	0.54	0.51	0.43
Candle	0.20	0.19	0.24	0.22	0.15
Kerosene	0.13	0.27	0.13	0.09	0.03

Standard deviation in parentheses.

* School Leaving Certificate (SLC) is the certificate given to those who pass a national exam at the end of grade 10.

Table 1.2: Descriptive statistics for firms' sample

Variables	Whole sample (n = 589)	Electricity Tariff Category		
		Domestic (n = 144)	Commercial (n = 153)	Industrial (n = 292)
Monthly grid electricity bill				
USD	2,539	82	175	4,164
	(6,122)	(168)	(5,272)	(7,432)
Firm size (based on annual gross sales)				
Small	0.46	0.67	0.58	0.29
Medium	0.38	0.31	0.33	0.43
Large	0.16	0.02	0.09	0.28
Firm location				
Urban	0.81	0.95	0.89	0.06
Rural	0.19	0.05	0.11	0.84
Adoption of coping technology				
Inverter	0.72	0.79	0.81	0.65
Diesel generators	0.68	0.24	0.78	0.84
Voltage stabilizer	0.34	0.19	0.34	0.42
Solar panel	0.09	0.18	0.11	0.04

Standard deviation in parentheses.

Table 1.3: Estimated WTP values for households (percentage of monthly electricity bill)

Approach		Method	Whole sample	Quartiles of monthly electricity bills			
				1st	2nd	3rd	4th
Stated preference		Contingent valuation					
	(1)	WTP for 50% reduction in planned outages*	39.91	43.55	41.85	42.27	32.56
			(1.09)	(3.06)	(2.09)	(2.03)	(1.79)
	(2)	Incremental WTP for 100% reduction in planned outages**	54.57	75.30	57.10	49.55	39.61
			(1.07)	(3.29)	(2.08)	(1.80)	(1.44)
	(3)	Total WTP for elimination of planned outages	94.48	118.86	98.97	91.83	72.18
			(2.08)	(6.67)	(4.29)	(3.44)	(2.76)

Figures in parentheses are standard deviations.

Notes:
* If a respondent chooses to pay an additional amount for 50% fewer outages, the base figure is calculated as the current bill multiplied by the accepted offered value (the final accepted bid). For instance, if the current bill is USD 50 and the respondent's final accepted bid is 30%, the WTP value for 50% reduction in outages is recorded as USD 15, or 30% of the current electricity bill (reported in row 1).

** If the respondent chooses to pay an additional amount for no outages in the follow-up question, then the base figure is recorded as the current bill multiplied by random offered value plus recorded WTP for 50% fewer outages. For instance, if the current bill is USD 50 and the final accepted bid for the total elimination of outages is 60%, the WTP value for the total elimination of outages is recorded as USD 30 + USD 15 = USD 45, or 90% of the current electricity bill (reported in row 3). The incremental WTP for 100% reduction in outages is the difference between WTP values for 50% and 100% reduction in outages (reported in row 2).

Table 1.4: Estimated WTP values for firms (percentage of monthly electricity bill)

Approach		Method	Whole sample	Electricity Tariff Category		
				Domestic	Commercial	Industrial
Stated preference		Contingent valuation				
	(1)	WTP for 50% reduction in planned outages	37.23	41.56	37.20	34.27
			(1.87)	(3.21)	(3.70)	(2.83)
	(2)	Incremental WTP for 100% reduction in planned outages	71.97	53.68	66.60	84.83
			(2.45)	(2.94)	(4.68)	(4.11)
	(3)	Total WTP for elimination of planned outages	109.21	95.25	103.81	119.10
			(4.96)	(4.93)	(9.29)	(8.73)

Figures in parentheses are standard deviations.

Table 1.5: Determinants of current and future demand for electricity – households' sample

Variables	Current demand	Absolute WTP – log(WTP)		Relative WTP (% of current bill)	
	Log (current electricity bill)	50% reduction in outages	100% reduction in outages	50% reduction in outages	100% reduction in outages
	(1)	(2)	(3)	(4)	(5)
Distribution of grid electricity bills					
2nd quartile		- 0.58	0.11	- 0.14***	- 0.21***
		(0.37)	(0.18)	(0.03)	(0.03)
3rd quartile		- 0.09	0.29	- 0.20***	- 0.31***
		(0.40)	(0.20)	(0.03)	(0.03)
4th quartile		- 1.20***	0.26	- 0.38***	- 0.48***
		(0.45)	(0.22)	(0.03)	(0.03)
Household monthly income					
Category 2 (between USD 95 to 190)	0.19**	1.88***	0.90***	0.16***	0.13***
	(0.08)	(0.53)	(0.26)	(0.04)	(0.04)
Category 3 (between USD 190 to 381)	0.25***	2.29***	1.42***	0.22***	0.24***
	(0.08)	(0.53)	(0.26)	(0.04)	(0.04)
Category 4 (between USD 381 to 571)	0.43***	2.82***	1.71***	0.26***	0.28***
	(0.09)	(0.57)	(0.28)	(0.04)	(0.04)
Category 5 (more than USD 571)	0.48***	2.35***	2.08***	0.25***	0.36***
	(0.10)	(0.63)	(0.31)	(0.05)	(0.05)
Urban/Rural status					
Urban – Outside Kathmandu	- 0.15**	- 1.96***	- 0.96***	- 0.15***	- 0.10***
	(0.06)	(0.38)	(0.19)	(0.03)	(0.03)
Rural – Terai	- 0.59***	- 1.84***	- 0.34	- 0.19***	- 0.05
	(0.07)	(0.46)	(0.23)	(0.03)	(0.03)
Rural – Mountain	- 0.83***	- 5.68***	- 1.24***	- 0.46***	- 0.16***
	(0.06)	(0.44)	(0.22)	(0.03)	(0.03)
Household characteristics					
Number of household members	0.06***	0.01	0.01	- 0.0005	- 0.0007
	(0.01)	(0.05)	(0.02)	(0.0048)	(0.0046)
Number of rooms in the house	0.07***	0.13***	0.04*	0.009**	0.005
	(0.01)	(0.05)	(0.02)	(0.004)	(0.003)
Have at least one school kid (aged 6-14)	- 0.03	0.45*	0.17	0.04*	0.05**
	(0.04)	(0.27)	(0.13)	(0.02)	(0.02)
Ownership of TV/Radio	0.44***	0.11	0.22	- 0.02	- 0.0006
	(0.06)	(0.38)	(0.19)	(0.03)	(0.03)
Ownership of computer	0.48***	0.30	0.25	0.01	0.02
	(0.05)	(0.32)	(0.16)	(0.02)	(0.02)
Educational attainment of the household head					
Less than SLC	0.07	0.19	0.31*	0.03	0.06**
	(0.05)	(0.33)	(0.16)	(0.02)	(0.03)
SLC	0.09	0.22	0.27	0.01	0.03
	(0.07)	(0.48)	(0.22)	(0.03)	(0.03)
More than SLC	0.08	- 0.20	0.59***	- 0.01	0.11***
	(0.06)	(0.41)	(0.20)	(0.03)	(0.03)
Observations	1,800	1,800	1,800	1,800	1,800

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Figures in parentheses are standard errors.

Table 1.6: Adoption pattern of coping equipment by quartiles of electricity bills (Probit model)

Variable	Coping equipment				
	Inverter (1)	Voltage stabilizer (2)	Solar panel / solar lantern (3)	Torch/emergency light/candle (4)	Kerosene (5)
Quartiles of electricity bills					
2nd quartile	0.06*	0.04	- 0.04*	0.02	- 0.07***
	(0.03)	(0.02)	(0.02)	(0.02)	(0.01)
3rd quartile	0.11***	0.10***	0.004	- 0.01	- 0.08***
	(0.03)	(0.02)	(0.02)	(0.03)	(0.02)
4th quartile	0.20***	0.14***	- 0.03	- 0.06**	- 0.12***
	(0.03)	(0.02)	(0.03)	(0.03)	(0.02)
Controls	YES	YES	YES	YES	YES
Observations	1,800	1,800	1,800	1,800	1,800

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Figures in parentheses are standard errors. Average marginal effects of Probit model are reported.

Controls include household monthly income categories, urban-rural and ecological status, household characteristics, and household head educational attainment.

Table 1.7: Determinants of current and future demand for electricity – firms' sample

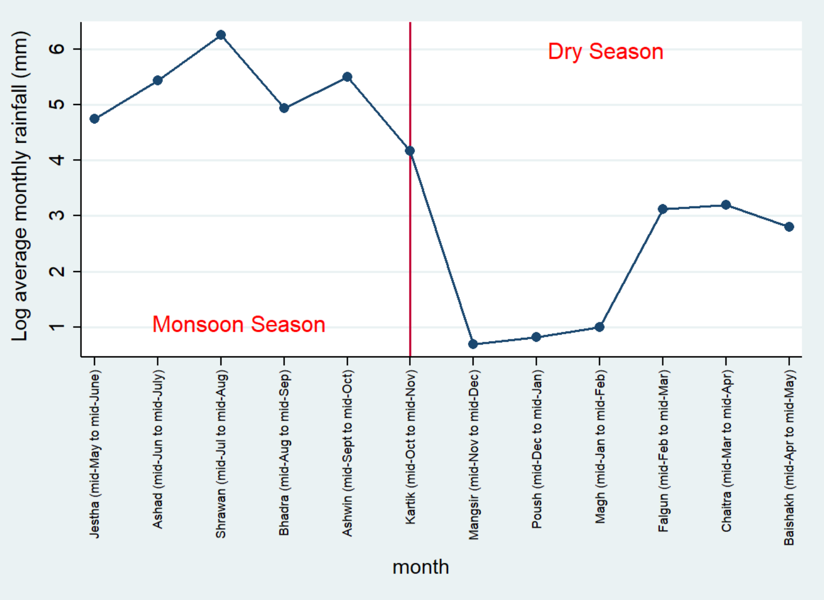
Variable	Current demand	Absolute WTP, log(WTP)		Relative WTP, % of the current bill	
	Log (current electricity bills)	50% reduction in outages	100% reduction in outages	50% reduction in outages	100% reduction in outages
	(1)	(2)	(3)	(4)	(5)
Electricity Tariff category					
Commercial	1.92***	0.54	2.06***	- 7.27	7.35
	(0.15)	(0.74)	(0.30)	(5.18)	(6.53)
Industrial	3.31***	1.17**	3.84***	- 13.15**	19.27***
	(0.15)	(0.73)	(0.30)	(5.96)	(6.49)
Firm size					
Medium	0.67***	1.89***	0.92***	8.93**	1.75
	(0.13)	(0.60)	(0.25)	(4.16)	(5.36)
Large	1.96***	3.25***	1.88***	14.96**	- 6.29
	(0.17)	(0.82)	(0.34)	(5.72)	(7.35)
Rural	- 0.14	- 1.34*	1.02***	- 3.47	21.98***
	(0.15)	(0.71)	(0.31)	(4.96)	(6.63)
Observations	589	589	589	589	589

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Note: Figures in parentheses are standard errors.

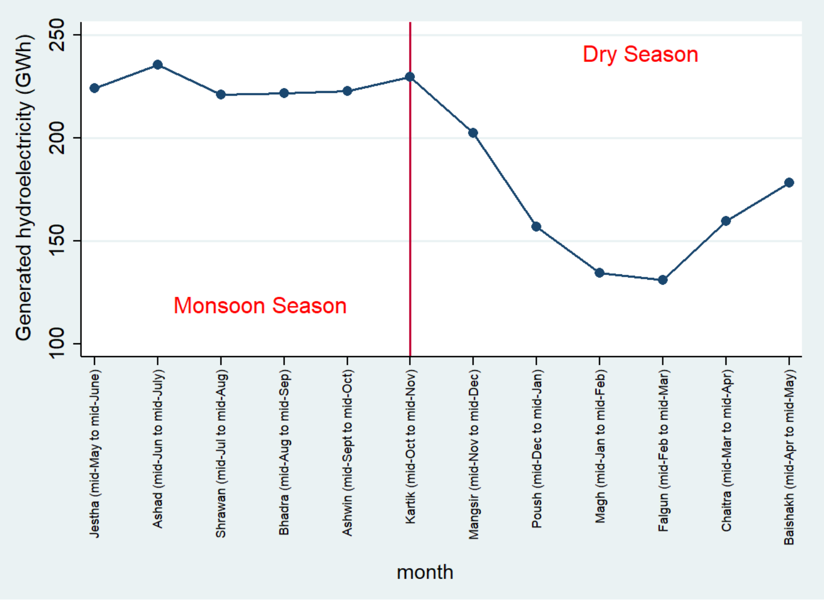
Table 1.8: Adoption pattern of coping equipment by firms (Probit model)

Variable	Coping equipment			
	Diesel generator	Voltage stabilizer	Inverter	Solar panel
	(1)	(2)	(3)	(4)
Electricity tariff category				
Commercial	0.36***	0.16***	0.03	- 0.04
	(0.03)	(0.05)	(0.05)	(0.03)
Industrial	0.36***	0.22***	- 0.12**	- 0.12***
	(0.03)	(0.05)	(0.05)	(0.03)
Firm size				
Medium	0.12***	0.09**	0.02	0.04
	(0.03)	(0.04)	(0.04)	(0.02)
Large	0.22***	0.03	0.03	0.001
	(0.05)	(0.05)	(0.05)	(0.03)
Firm location				
Rural	0.07	- 0.04	- 0.04	- 0.04
	(0.05)	(0.05)	(0.05)	(0.04)
Observations	589	589	589	589

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Figures in parentheses are standard errors. Average marginal effects of Probit model are reported.



Panel A: Variation in average monthly rainfall in 2016



Panel B: Variation in hydroelectricity generation in 2016

Figure 1.1: Seasonal variations in average rainfall and hydroelectricity generation in 2016

Note: Months are categorized into monsoon and dry months. The first six months represent the monsoon season (Jestha through Kartik in Nepalese calendar, mid-May through mid-Nov), and the second six months refer to the dry season (Kartik through Baishakh in Nepalese calendar, mid-Nov through mid-May). Data sources: The rainfall data are from the World Bank Climate Change Knowledge Portal. Monthly generation values are from Annual reports of the Nepal Electricity Authority.

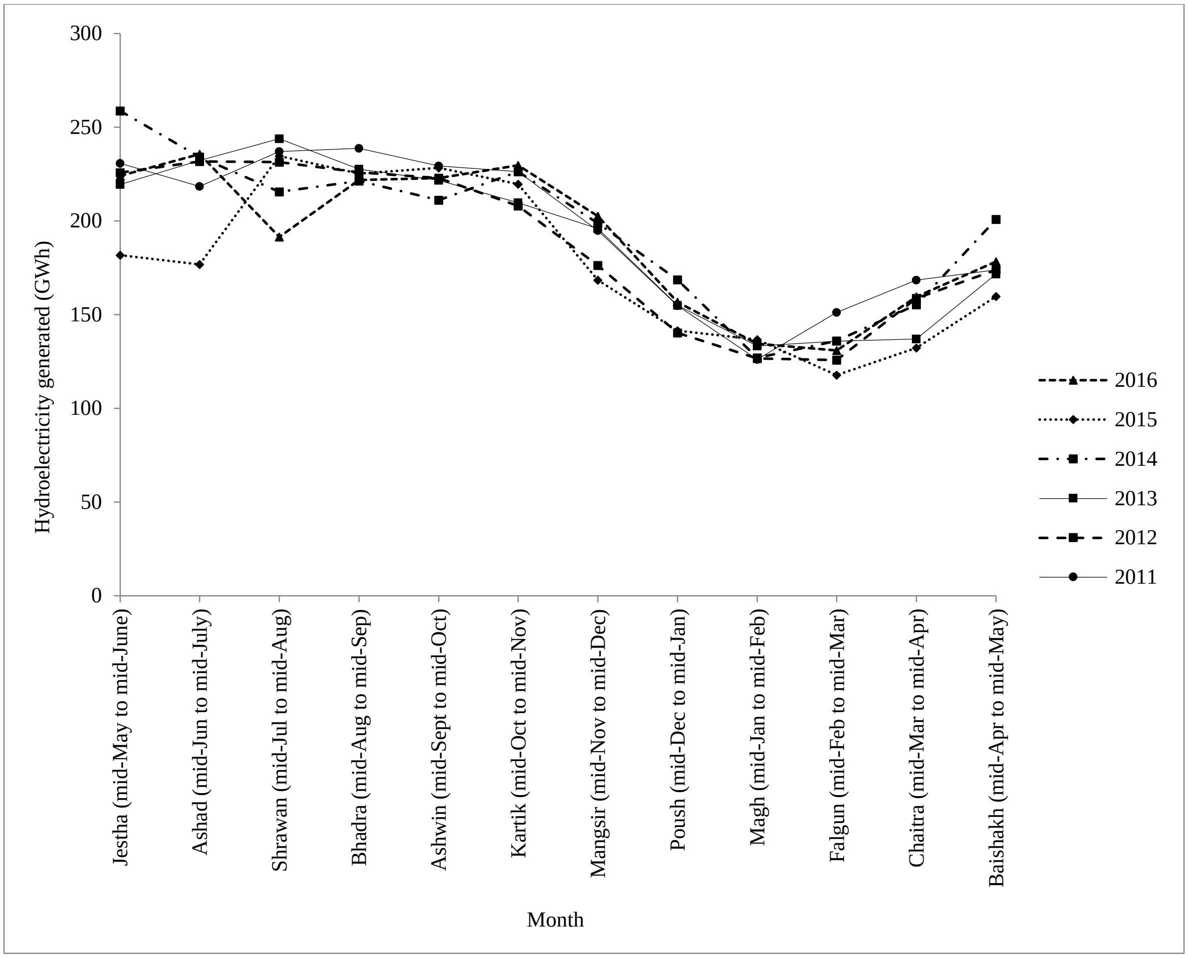


Figure 1.2: Hydroelectricity generation in Nepal during 2011-2016

Source: Annual reports of Nepal Electricity Authority (https://www.nea.org.np/annual_report)

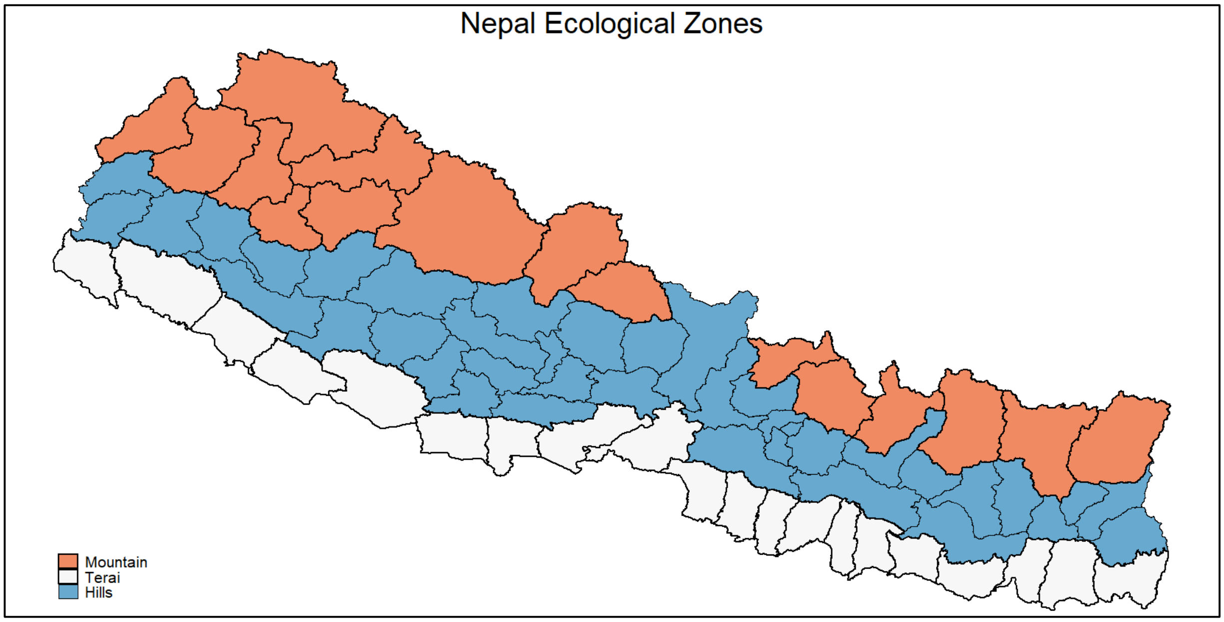
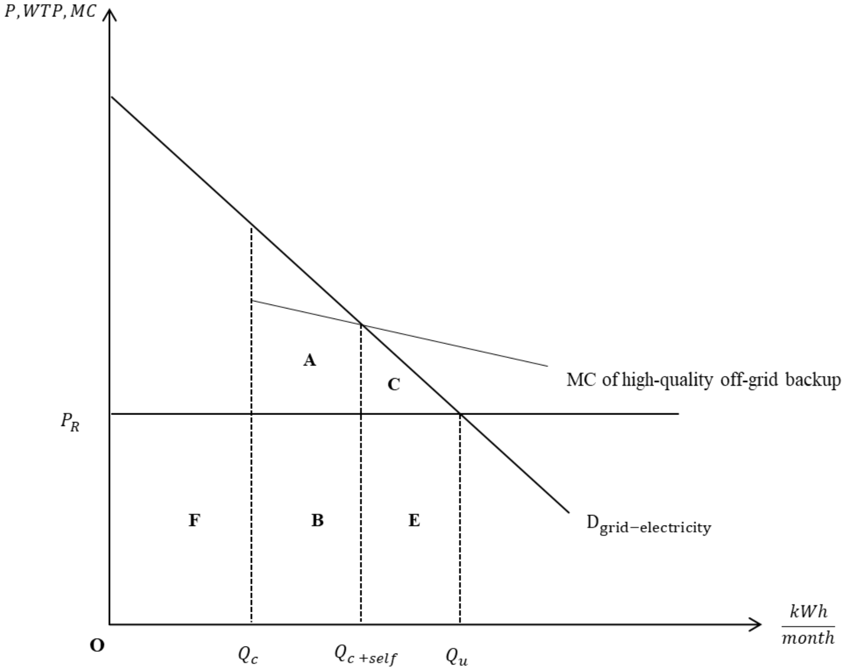
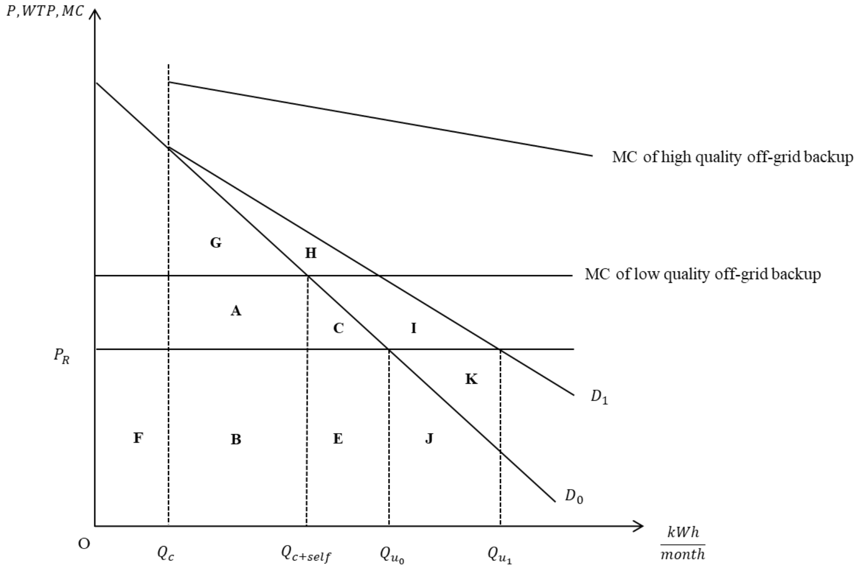


Figure 1.3: Ecological zones used for the sampling

Source: author’s demonstration based on the data from www.arcgis.com

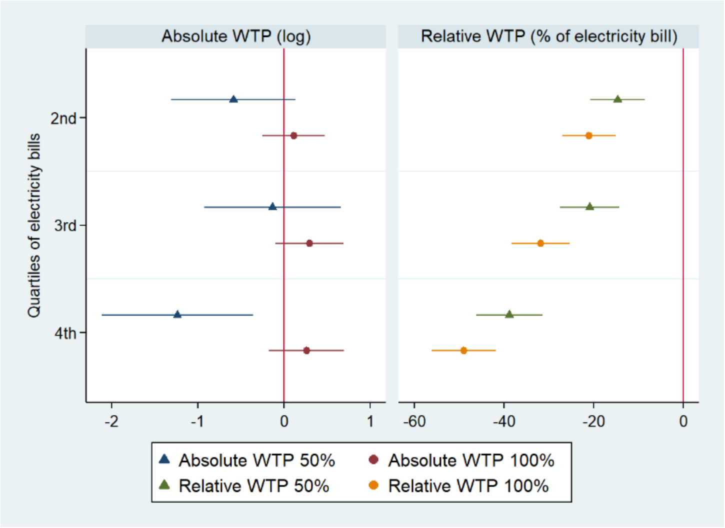


Panel A: High demanders

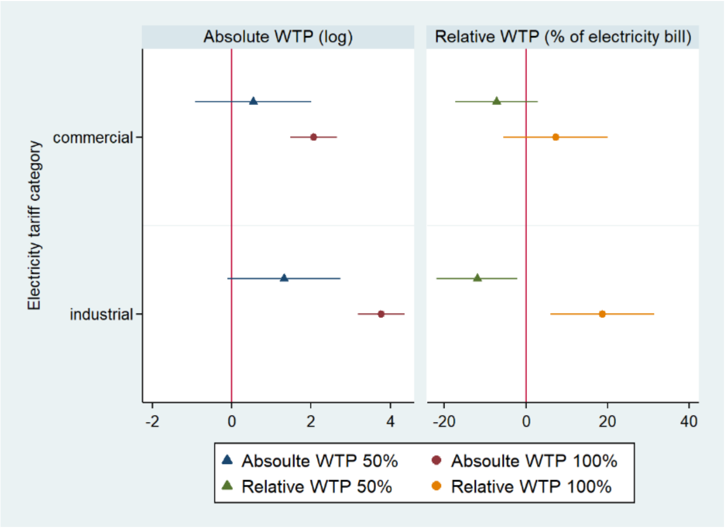


Panel B: Low demanders

Figure 1.4: WTP for improvements in the reliability of the electricity service



Panel A: households' WTP by quartiles of electricity bills (reference category: 1st quartile)



Panel B: Firms' WTP by electricity tariff categories (reference category: domestic)

Figure 1.5: Coefficients plot for households and firms by current consumption levels

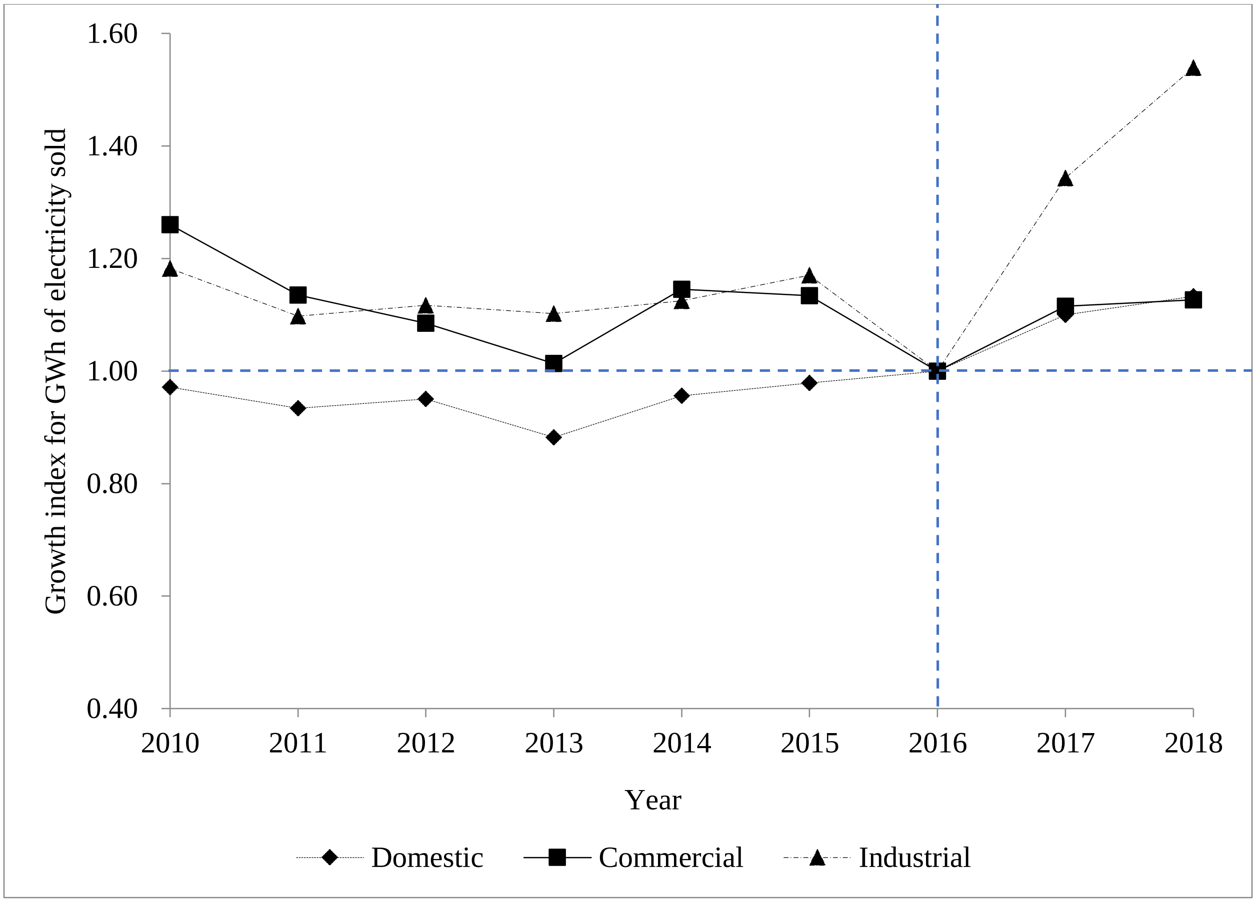


Figure 1.6: GWh of electricity sold over time (adjusted for growth in the number of consumers, base year = 2016)

Note: The base year for growth index is selected as 2016 because: (a) the WTP survey was conducted in 2016; (b) load shedding for domestic consumers and all consumers have been eliminated since 2017 and 2018, respectively.

CHAPTER 2

THE ECONOMIC BENEFITS OF MITIGATING UNPLANNED OUTAGES IN OVERLOADED ELECTRIC DISTRIBUTION NETWORKS

2.1 Introduction

In many developing countries, insufficient investments or seasonal shortages in the upstream segments of the electricity supply chain (generation and transmission) result in long hours of electricity service unavailability (Zhang, 2018). Electric utilities in these countries typically allocate the constrained supply of electricity among customers through rationing programs (also known as load shedding programs). Outages caused by these programs are called planned outages, and previous studies show that there is often a significant willingness to pay among consumers to eliminate planned outages (Ozbafli & Jenkins, 2016; Carlsson et al., 2020; Niroomand & Jenkins, 2020; Hashemi, 2021).

There are, in addition, situations where sufficient electricity is generated and transmitted to distribution networks (the downstream segment of the electricity supply chain), but frequent unplanned outages remain. Local substation failure due to capacity overload is the most common cause of unplanned outages[23]. Electric utilities upgrade substation capacities to keep up with growing demand over time and to prevent or reduce

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[23] A distribution substation is the last part of the electricity distribution network that ensures electric power is adequately converted to a usable service voltage for the daily operations of consumers. Each substation is designed for a specific maximum capacity, and the installed protection devices automatically shut down the substation in the occurrence of an overload, leaving all consumers connected to that substation without power. Thus, the frequency with which unplanned power outages occur in a locality is a function of how much overloaded the distribution substations are in that locality.

overloading. The cost of such investments is recovered from adjustments to retail electricity prices (EIA, 2017).

There is political pressure against higher electricity prices in many developing countries' electricity markets, and the situation gets worse where access to electricity is increasingly viewed as a right. Unaccounted electricity usage (electricity theft) through illegal connections and unpaid electricity bills becomes an accepted part of the system (Burgess et al., 2020). Consequently, electric utilities' cash flows deteriorate, and they postpone essential investments to maintain service reliability (Gertler et al., 2017).

Distribution substations are not only essential parts of power distribution from an electrical engineering perspective, but they also play a critical role in the economics of power distribution. When reliability concerns are significant, the electric power drawn from a substation has common-pool resource (CPR) aspects (Pless & Fell, 2017). Once consumers are connected to the electric network, although their kWh consumption can be individually metered it is impossible to precisely monitor their individual contributions to overloading. The CPR problem arises when individual users draw electricity from a substation without paying a market price that reflects the marginal cost of technical or economic sustainability.

While CPR problems have gained significant attention in the management of natural resources such as fishery, grazing areas, and forestry, research on electricity infrastructure as a CPR has mainly been conceptual (Künneke & Finger, 2009) and rarely informed by empirical evidence. This study uses a nationally representative sample of Nepalese firms to investigate the extent to which electricity distribution networks face commons problems.

The ownership boundaries of substation configurations are used to identify how CPR problems at local distribution substations affect the aggregate level of reliability, and to estimate the extent to which private ownership of a substation enables a firm to mitigate those problems.

The data analyzed in this paper indicate that firms with captive substations are less likely to experience unplanned outages[24]. In particular, firms with private substations are less likely than firms with shared substations to report the occurrence of unplanned power outages. If these firms report unplanned outages, they are less frequent and have shorter durations than those experienced by firms without their own substations. These findings are then used to study the feasibility of investing in a captive substation for a firm (or a group of firms) as a mitigation strategy to address outages caused by overloaded substations. Estimates of the firms' willingness to pay to reduce unplanned outages are used to estimate the potential economic gains from deregulation of private substation provision. I estimate that the benefits from deregulation of substation ownership would generate substantial economic gains to Nepal's economy, up to 18.17 USD billion as of 2016.

Understanding the heterogeneous impacts of outages and proposing practical solutions to address them is useful to decision-makers when designing policies to address distribution networks' reliability issues. While expanding upstream generation and transmission capacities can effectively eliminate *planned* outages, the situation for

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[24] A captive substation is a distribution substation used and managed by an industrial or commercial electricity consumer for their own electricity consumption.

addressing *unplanned* outages in the downstream segment is a fundamentally different problem. The localized nature of these outages implies that the potential solutions should also be local. Private investment in distribution substations by a firm or a group of firms is a possible solution to the problems caused by local overloads.

2.2 Literature review: electricity reliability as a common-pool resource

Electricity distribution networks can be viewed as rivalrous but non-excludable resources for at least three reasons (Künneke & Finger, 2009). First, electricity distribution infrastructures are often spread over a vast geographical area with difficult-to-monitor access points, making them susceptible to the actions taken by interconnected electricity consumers. An example of such actions is the pilferage of electricity through illegal tapping of the low-voltage distribution lines leaving a substation. Empirical evidence suggests that electricity theft can adversely affect electricity reliability, which is why reducing electricity theft has been recognized as one of the potential solutions for improved electricity reliability (Jamil, 2013; Tang, 2014; PWC, 2016).

Another source of reduced local electricity reliability is present when a new enterprise gains connectivity to a distribution substation that already bears a load equal to its rated capacity. The new connection to an already-at-capacity substation leads to more outages. Such a large new connection can only happen by bribing the electric utility authorities who control access to such substations. The new enterprise will have found the bribe worthwhile to obtain some grid-supplied electricity service of whatever quality given the high cost of self-generated electricity, while the reliability of service is reduced for everyone connected to that substation (Gertler et al., 2017; Pless and Fell, 2017). Energy sector assessment reports by the Asian Development Bank (ADB) highlight corruption as one of the significant issues affecting electricity reliability (ADB, 2007; ADB 2009).

Third, even if grid access could be technically monitored, there might be politically motivated universal-access obligations. Access to electricity is increasingly viewed as a right across the developing world. In such an environment, illegal connections have become an accepted part of the electricity distribution system (Burgess et al., 2020). This social norm will eventually result in reduced reliability of the electricity distributed by the utility. Those who are legally connected will have to pay higher electricity bills in order for the utility to recover the costs of maintaining reliability. If retail electricity tariffs are regulated and there is resistance to higher tariffs, the electric utility's cash flow deteriorates, leading the utility to postpone essential investments to maintain reliability, leading to reduced reliability for all customers (ADB, 2011; Gertler et al., 2017).

Fourth, once users have entered the network, it might be difficult or even impossible to determine the services they appropriate from it. Although individual kWh consumption can be precisely metered, certain critical services to technically balance the electricity network (i.e., load balancing, voltage control, and reactive power) cannot be. This rivalrous nature of reliability is particularly prominent when the network is congested during peak demand periods. There is a need for load management, voltage control, and reactive power provision. However, different use patterns and the technical characteristics of users' applications cause different demands for these services. Individual users extract these services from the system without paying the full cost of their technical and economic sustainability (Künneke, R., & Finger, 2009; Melville et al., 2017).

2.3 Cost-benefit analysis of deregulating distribution substations

Private investments in substations can either be made by an individual firm or by a group of firms. Third parties can also make such investments and serves as intermediaries between the electric utility and firms. For them, it is of great importance to analyze whether the electricity users would find it worthwhile to pay a substation owner a high enough price to turn that substation into a profitable business[25]. In either case, the framework below can be used to quantify the costs and benefits of investments in substations.

2.3.1 Accumulated savings by reducing per kWh charge

Private ownership of a distribution substation is not a new idea. It has been a common practice worldwide for large consumers, especially those with high electricity loads (primarily large commercial and industrial facilities). For instance, in the United States firms can purchase an existing substation from the utility, install a new one themselves, or partner with third-party providers (Interstates, 2020). If a substation is purchased from the utility, a cost estimate is provided by the utility based on factors such as size, age, and condition. If the utility does not make the substation available, or the firm wants to install a new one, the firm may directly request quotes. In a partnership, a third party owns the substation, buys electricity from the utility, and provides it to other firms. This partnership allows the client firms to avoid capital costs while getting the benefits of metering at a higher service voltage. Regardless of the option chosen, insurance coverage for service

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[25] In case of substation privatization, institutional arrangements should be considered in order to avoid the hold-up problem from technological interdependencies in different production stages.

reliability is provided by the firm and the utility for their respective facilities as part of ordinary course of doing business.

The utility often owns and maintains distribution substations. After receiving electricity from transmission lines in high voltages, distribution substations reduce the voltage of supply to desired levels for each category of consumers. Depending on how many voltage-reduction steps the electricity supply passes through, the electric utility charges a higher rate per kWh after each step to recover the ownership costs of distribution substations (see Figure 2.2). If a customer decides to purchase power at a higher voltage, the utility charges a lower per kWh rate. In such cases the customer must install and maintain its own substation to step down the voltage before final use.

For consumers with high demand for electric service, the present value of the cash savings on their electricity bills due to the lower per kWh cost of high voltage electricity is often sufficient to pay off the capital and maintenance costs of a distribution substation over its lifetime. Table 2.1 shows that the differences in NEA’s retail electricity prices by voltage and tariff categories. The average savings after switching to high voltage are 2.76 and 2.24 US cents per kWh for low- and medium-voltage connections, respectively. These savings are equivalent to 28 and 24 percent of the initial tariff rate for low- and medium-voltage consumers. The savings per kWh and the firm’s average annual kWh of electricity consumption are the main determinants of the present value of benefits from tariff savings over a substation’s economic life.

2.3.2 Value of lost production due to power outages

The unexpected nature of unplanned outages combined with their shorter duration makes them more detrimental than planned outages to firms' operations. When a planned outage occurs, firms can take various precautions to reduce the costs of service interruptions (Munasinghe & Gellerson, 1979; Sanghvi, 1982). For instance, proper equipment shutdown prevents damage to equipment and spoilage of production inputs and outputs. Similarly, labor employment can be curtailed if the production stops in a planned manner (Hashemi et al., 2018). However, in the case of an unplanned outage, the degree of losses depends on the flexibility of production inputs (Allcott et al., 2016).

The savings per kWh tariff rates are the lower bound of the substation ownership benefits in a high distribution-loss environment like Nepal. The possibility of reducing power failures by installing a captive substation is also a tangible benefit item for firms in the form of saved production time. The value of forgone production per kWh of unsupplied electricity is the measure for quantifying this benefit category. Contribution-margin analysis is a valuable tool for this purpose, given that firm managers typically use it to compare planned and actual operations (Warren et al., 2013; Galo, 2017). The contribution margin (i.e., the difference between price and average variable cost) is the portion of sales revenues covering fixed costs and earning a profit after direct variable costs are deducted. It is equivalent to a short-run producer surplus. A firm maximizes its profits by maximizing its contribution and continues to conduct its business in the short run as long as the contribution is positive, even during circumstances when profits would be negative in the long run.

Thus, a firm can use contribution-margin analysis to evaluate the opportunity cost of unplanned power outages, since the value of forgone production during the outage period is the contribution margin that would have been realized if the unit had actually been produced.

The contribution margin for firm *i* can be estimated as

$$CM_i = R_i - c_i^m - c_i^e - c_i^{other} \tag{1}$$

where R is sales revenue, c^m is the cost of raw materials, c^e is the cost of electricity, and c^{other} is other direct costs such as maintenance, repairs, and packaging. Due to the unexpected nature of unplanned outages there are often other cost components borne by firms. Most firms do not have a flexible labor force that can be released from work for the outage period to save direct labor costs. In-process material spoilage is another cost component for some firms.

Once these two costs are taken into account, the total cost of power outages for firm i (C_i^{outage}) can be obtained as shown in Equation 4,

$$C_i^{outage} = \sum_{j=1}^{f} \left[d_j + \mu\left(d_j\right)\right] . CM_i + (SV_i - SC_i) \tag{2}$$

where d_j is the outage duration, $\mu\left(d_j\right)$ is the re-start time for an outage duration d_j, f is the frequency of outages per annum, SC_i is the spoilage costs, and SV_i is the salvage value of spoiled material-in-process. Using the total cost of power outages and the number of kWhs not supplied, the levelized cost of power outages can be estimated for each individual firm.

Estimating Equation 2 for firms in the sample requires access to detailed information from firms' operating accounts. Such information is available for a comprehensive set of firms in Nepal from the 2011 National Census of Manufacturing Establishments (latest available for Nepal at the time of this study). The national census collects detailed information about the aggregate value of inputs used and the output produced by different industries. The contribution value per kWh is estimated for a selected list of sectors and reported in Table 2.2. Sales revenues are not directly reported in the census data, but the value of output can be used as an approximation for sale revenues.

Contribution values per kWh range from 0.51 to 2.94USD/kWh. These estimates clearly show that even without accounting for the cost of idle labor and material spoilage contribution values per kWh are significant. The estimated contribution values are in the range of 0.28 to 2.88 USD/kWh reported in Hashemi et al. (2018). They employ three years of hourly data on power outage occurrences for three Nepalese manufacturing firms. Estimates of contribution values indicate that even if the savings in tariff differences would not be sufficient for a firm to justify an investment in a substation, the additional benefits from reducing the value of lost production might make the investment profitable to the firm. The extent to which the avoided loss in production time contributes to substation ownership feasibility depends on the additional power supplied after installing the dedicated substation.

2.3.3 The impact of substation ownership on electricity reliability

The following specification is used to estimate the impact of substation ownership on firm i's experienced level of electricity reliability,

$$Y_i = \beta\ voltage\ of\ connection_i + \alpha_r + \varepsilon_i \tag{3}$$

where Y_i is a measure of electricity reliability for firm i, $voltage\ of\ connection_i$ is the voltage at which firm i receives electricity from the grid (low, medium, or high), α_r are electric utility regional distribution center fixed effects, and ε_i is the error term. The voltage of connection is a proxy for exposure to externalities in the distribution network.

Three different measures of reliability are tested here. The first measure is whether the firm reports frequent unplanned outages (experienced outages daily as opposed to a weekly or monthly basis). The dependent variable equals one if the answer is "Yes" and 0 if "No." The central assumption here is that frequent unplanned outages reported by a firm relative to other firms in the same distribution center imply that the substation from which the firm draws electricity experiences more failures due to overloading, and therefore more outages.

The second measure of electricity reliability is the frequency of unplanned daily outages. Power outages could be due to failures at other segments rather than distribution (e.g., the transmission segment). If a firm reports a higher frequency of unplanned daily outages than other firms being supplied by the same distribution center, that difference is most likely attributable to heterogeneities in reliability at the distribution-substation level.

The third measure of reliability tested is the duration of the most extended unplanned outage. Technical studies show that if a substation is overloaded more frequently, it not only becomes more susceptible to failures over time but it also takes longer for that substation to be brought back online after an outage (ADB, 2020a). It is expected that firms with captive substations would report shorter-duration outages than those with shared substations.

2.3.4 Investment appraisal of a captive substation as a mitigation strategy

The net present value (NPV) of investing in a captive substation for firm i can be expressed as

$$NPV_i = \sum_{t}^{T} (1+r)^{-t} \left[\left(t_{i,t}^{high} - t_{i,t}^{low} \right) \times E_{i,t} \times H_{i,t} \right] + [C_i^{outage} \times E_{i,t} \times h_{i,t}] \quad (4)$$

where r is the discount rate, $t_{i,t}^{high}$ and $t_{i,t}^{low}$ are the tariff rates per kWh charged by the electric utility for high- and low-voltage connections, $E_{i,t}$ is the average kWh of power consumption per hour, $H_{i,t}$is annual hours of power consumption, C_i^{outage} is the levelized cost of outages for firm i, and h is averted hours of power outages for firm i due to having a captive substation[26]. The analysis covers a period of 10 years ($T = 10$), which is the substation's economic life. It is also assumed that the benefits of a captive substation will begin to be realized in the second year of the investment because the construction of the substation and its transmission lines takes one year to be completed.

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[26] It is assumed in the base case that the electricity reliability remains the same for the period of this analysis. Later in this section, an analysis is carried out to identify the breakeven hours of outages below which the investment is not financially feasible for the firm.

2.4 Data and methodology

2.4.1 Nepal's power sector data

Hydropower represents ninety percent of the total installed generation capacity in Nepal, mostly run-of-the-river type. With river flow being governed by the monsoon and dry seasons, Nepal experiences significant generation capacity deficits during the dry season (winter months) when electricity demand is at its peak. In response to low dry-season hydropower generation, the Nepal Electricity Authority (NEA), the central government-owned generator, grid operator and distributor, has used a load curtailment program (known as load shedding).

Insufficient upstream capacity has not been the only challenge in Nepal's electricity sector. NEA's annual reports show that even during the monsoon season with its abundance of hydropower availability, a significant amount of generated and transmitted electricity is lost in the distribution network. Despite NEA's efforts to decrease the distribution losses, an average loss of 17 percent is reported across regional distribution centers in 2016 (NEA, 2016). Technically speaking, a fraction of generated electricity inevitably gets lost in the transmission and distribution systems (known as technical losses). The magnitude of these losses can be minimized by proper design and timely maintenance of distribution substations. For instance, in the United States, it is estimated that only 5 percent of generated electricity was lost in transmission and distribution networks in 2014 through 2018 (IEA, 2019). Three times more losses in Nepal's distribution network than the combined losses in transmission and distribution losses in the United States imply that there factors other than technical factors (non-technical factors) contribute to these substantial losses.

A closer look at Nepal's regional distribution centers reveals a noticeable heterogeneity in their losses. Eight regional centers across Nepal distribute electricity. Each of these centers is responsible for distributing the electricity transmitted by the national grid to a particular group of districts across the country (a total of 77 districts). The total megawatt-hours (MWh) received by each of the eight distribution centers (net of transmission loss) and the total MWhs billed by each center to its customers are extracted from NEA reports. For each center, the ratio of the difference between the two totals over total MWhs of transmitted electricity represents the percentage loss in the distribution network, as shown in Equation 5,

$$Percentage\ loss = \frac{MWhs\ of\ electricity\ billed - MWhs\ received\ by\ distribution\ network}{MWhs\ received\ by\ distribution\ network}. \quad (5)$$

As depicted in Figure 2.2, percentage losses across distribution centers ranged from as low as 10.24 percent to as high as 36.45 percent in 2016, when the firm-level data used in this study was collected. This variation suggests that the sample firms drew electricity from distribution networks with different electricity reliability levels.

2.4.2 Firm-level data

The firm-level data is obtained from a sample of 590 Nepalese firms surveyed in 2016[27]. The survey collected information about the voltage at which each firm purchased

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[27] The survey is conducted by the Millennium Challenge Corporation in partnership with the government of Nepal. For more information visit https://data.mcc.gov/evaluations/i ndex.php/catalog/194/study-description.

electricity from the national electric utility. This rich information facilitates the identification of each firm's substation ownership. If a firm draws electricity from the grid at a primary voltage (i.e., high voltage), it means that the firm has to have a captive substation to step down the voltage before final use. Otherwise, drawing electricity at a secondary voltage (i.e., medium or low voltages), indicating that the firm is connected to a shared utility-owned substation. Although such information may be readily provided by a typical electric utility in a developed country, most electric utilities in developing countries, where unreliable access to electricity is prevalent, do not have detailed information beyond the transmission lines (Wijayatunga, & Siyambalapitiya, 2016).

While each firm in the sample is connected to the same national grid, the voltage at which they receive electricity varies depending on their power needs. For instance, small service-sector firms might use electricity primarily for lighting purposes and powering appliances with low power requirements. Large industrial firms might use electricity as an input of production (such as cooling and heating raw materials or powering heavy equipment and machinery). Low voltage connections provide sufficient electricity for lighting purposes and running small electric appliances, but higher voltage connections are required for industrial purposes. Out of 590 firms in the sample, 435 firms have low-voltage connections, 105 firms have medium-voltage connections, and 50 firms have high-voltage connections.

2.5 Results

Table 2.3 presents the sample's descriptive statistics. There are 50 firms in the sample with captive substations (high voltage connections). While 36 percent of firms with low and medium voltage connections report unplanned outages daily, only 4 percent of firms with high-voltage connections have experienced unplanned daily outages. Also, firms with captive substations report fewer unplanned outages in a day, and they report a shorter duration for those outages. Table 2.3 shows a list of firms' characteristics by voltage of connection. There are firms with different sizes across all voltage categories. Industrial firms mostly use medium and high voltage connections.

Table 2.4 reports the regression results from estimating Equation 3. Firms with captive substations are 30 percent less likely to experience unplanned outages on a daily basis than firms with utility-owned shared substations (see column 1). The reason for this disparity is that firms with captive substations tend to be less exposed to the cumulative effect of distribution-line and substation overloads than firms with shared substations. Compared to captive substations, which provide a dedicated supply to the owner, the distribution lines coming out of a utility-owned substation spread across a vast difficult-to-monitor geographical area. Therefore, firms located further downstream tend to experience more interruptions. More precisely, firms with captive substations report 0.8 fewer outages per day on average than other firms (see column 2).

Unplanned outages also last for a shorter period for high- and medium-voltage firms than for low-voltage firms (see column 3). This finding is consistent with the study by LaCommare and Eto (2006), who find that larger commercial and industrial customers often experience shorter power interruptions than smaller commercial and residential customers. The results indicate that both medium- and high-voltage firms report durations of unplanned outages that are 0.99 and 1.49 hours shorter than those reported by low voltage-firms.

It can be inferred from the empirical results that in the case of a utility-owned substation, service reliability diminishes for all because electricity users fail to internalize the overloading costs that they impose on others. When distribution substations are privately owned, the costs of overloads are borne directly by a profit-maximizing business owner with the proper incentives to protect the substation against overloads. The operational performance of low-voltage networks can be improved by adding new substations to reduce the number of consumers covered by each substation. The investment appraisal of captive substations as a method of mitigating losses from unplanned outages described in Section 2.3.4 is carried out in this section.

The CBA is conducted for a representative firm with an average of 1 MWh electricity consumption per hour. Given its power consumption, this firm requires a substation with a capacity of 2 megavolt amperes (MVA). The investment cost of constructing a 2 MVA substation in Nepal is estimated to be around 0.75 USD million, with annual operating and maintenance costs of 0.016 USD million, at 2016 prices[28].

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[28] The technical requirements and cost estimates listed in this section are provided with consultation of business owners in Nepal who have invested in captive substations. The initial investment cost includes the cost of acquiring land, construction of a building to house switchgears and panels, cost of equipment, transmission line from the substation to the site's power station, and delivery costs. Also, to maintain the quality of service from the substation, there are annual operation and maintenance costs (O&M). The O&M cost is mainly the labor cost and the materials required for substation's efficient operation.

The CBA starts with the saving in tariff rates as the only benefit considered. Using a tariff difference of 2.76 US cents per kWh (the average value of rate difference presented in Table 2.1), the investment has a negative NPV unless the firm operates for 16 hours every day, plans for load growth in the near future, or shares the substation with another firm. This highlights the critical role of a substation's utilization rate in the investment's net value. The utilization rate needs to be sufficiently high to make the investment financially feasible, but not so high as to cause overloading.

Following the discussion in Section 2.3, apart from the savings in electricity expenses a captive substation also provides substantial benefits by reducing losses during power outages. The next step in the analysis is to calculate the opportunity cost of the electricity not supplied due to power outages, using the levelized cost of the electricity lost. The levelized cost can be estimated by taking the present value of the losses in contribution value that would have borne by the firm over the captive substation's life and dividing this value by the present value of the quantity of the electricity supply that would have been lost during this period. The levelized cost is the rate per kWh that would make the NPV of the electricity not supplied equal to the costs inflicted by the power outages. Assuming a levelized cost of 0.50 US cents per kWh and 16 hours of daily operation, the NPV of substation investment by a representative firm amounts to 0.97 USD million at 2016 prices[29].

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[29] To calculate the benefits from the value of lost production saved, one of the main inputs is the additional power supplied by the captive substation ($h_{i,t}$ in Eq. 5). Here, it is assumed that the captive substation mitigates one hour of unplanned outage per day, a cumulative duration of 365 hours per year. Hence, having a captive substation translates into 365 MWh of additional power

A significant risk factor associated with captive substation investments is uncertainty about the future status of the electricity reliability provided by the electric utility. The more reliable the electric utility's service provision becomes, the lower the inflow of benefits from savings in losses due to outages will be. Breakeven analysis is conducted to estimate what fraction of the current frequency of outages (365 hours per year) would make the NPV equal to zero. It appears that even if only 42 percent of power outages (153 hours per year) take place, the investment would still be financially viable.

Because the sample is nationally representative, the economic gains to the whole economy can also be estimated. About 10 percent of the firms in the sample have captive substations, of these firms, 88 percent are industrial or manufacturing. As reported in the National Economic Census (NEC), the total population of manufacturing establishments in Nepal is 104,058. Therefore, a total of 93,652 firms can potentially get connected to newly-built private substations with reforms facilitating private ownership of substations. Assuming that each private substation would probably be relevant for clusters of five firms (to create enough demand to justify a substation), the maximum number of private-sector substations would be 18,730. With 0.97 USD million net economic gains from a representative substation, the total economic gains to Nepal would amount to 18.17 USD billion at 2016 prices.

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supplied. This assumption is reasonable given that the low-voltage firms with shard substations report an average of 1 unplanned outage per day and a median duration of 2 hours for an extended unplanned outage. Moreover, Hashemi et al. (2018) evaluate the cost of outages using hourly data for three manufacturing firms in Nepal. The three-year average of cumulative duration of unplanned outages experienced by the firms per year range from 282 to 409 hours.

The CBA presented above assumes that investors can undertake to build substations, buy high-voltage electricity from the public electric utility, and then sell reliable low-voltage electricity to customers. However, building a captive substation in Nepal is a challenging proposition in the current institutional and governance framework. First, it requires special permissions from the public electric utility, which are subject to bureaucratic procedures. The next challenge is to acquire the land needed for housing the substation. Since a substation must be located close to high-voltage transmission towers, the choice of location is limited. Although regulations allow the land adjacent to roads to be used for this purpose, a transmission line from the substation to the point of consumption must pass through the land belonging to third parties, creating contractual challenges.

2.6 Conclusion

This chapter has investigated the quantitative significance of common-pool resource problems in electric network infrastructures. The transmission of electricity by local distribution networks requires load and capacity management that increases in complexity with the number of users. Moreover, a local electric network is limited in physical capacity, and its overuse leads to reduced reliability of electricity service. Using firm- and substation-level data from a sample of Nepalese firms, the results provide an empirical evidence of CPR problems across ownership boundaries and network configurations. The findings show that those with captive substations are less likely to report frequent unplanned outages than those with shared substations. Moreover, unplanned outages reported by captive-substation firms last for shorter periods. These findings are consistent with the results of Pless and Fell (2017) that consumer-level behavior on the demand side of the electricity market creates negative impacts on the overall quality of the service due to common-pool resource characteristics of electricity.

The findings of this chapter indicate that the CPR problem could be largely solved if private firms were allowed to own and operate substations. Currently, private ownership of substations is prohibited in Nepal unless they are unique to a single firm that owns and uses all the electricity from a substation. The cost-benefit analysis presented in this paper demonstrates that the annual gain to a representative firm from eliminating this restriction would be on the order of 0.32 USD million.

One concern about privatizing a part of the distribution segment would be the possibility of local monopoly pricing by parties owning the substations. This requires a contracting system to mitigate local monopoly pricing of electricity. Moreover, the need to consider the hold-up risk is critical during the transition period to competition (Valletti & Estache, 2001). Allowing both public and private substations to exist side-by-side can be a solution to facilitate the transition to competitive pricing.

Table 2.1: Retail electricity tariffs in Nepal (2016 prices)

Tariff category	Electricity charge by voltage (US cents per kWh)		Rate difference (US cents per kWh) Reference for high voltage: 7.14 US cents per kWh	
	Low	Medium	Between low & high	Between medium & high
Industrial	9.14	8.19	2.00	1.05
Commercial	10.67	10.57	3.53	3.43
Average	9.90	9.38	2.76	2.24

Table 2.2: Contribution value per kWh by industry (2016 prices)

Variable	Sector					
	Grain mill products	Sawmilling & planning of wood	Plastic products	Structural metal products	Cutting, shaping & finishing of stone	Manufacture of articles of concrete & cement
Value of output (USD mil.)						
Value of output	334	24	152	288	27	10.85
Direct costs of production (USD mil.)						
Raw material	276.05	16.45	107.84	215.59	8.85	5.94
Electricity	3.60	0.25	3.95	4.98	0.95	0.09
Other (fuel, water, repair and maintenance, etc.)	3.35	0.65	4.22	8.81	5.25	0.92
Total direct costs	283.00	17.35	116.01	229.38	14.19	6.95
Total contribution value (*USD mil.)*	51	6.65	35.99	58.62	12.81	3.90
MWh of electricity purchased	74,418	5,293	46,914	105,811	12,863	1,326
Contribution value (USD per kWh)	**0.69**	**1.26**	**0.77**	**0.55**	**1.00**	**2.94**

Source: author’s calculations based on the data from the 2011 National Census of Manufacturing Establishment

Table 2.3: Descriptive statistics

Variable	Voltage of Connection		
	Low n = 435	Medium n = 105	High n = 50
Current monthly utility electricity bill (USD)	1,565	4,296	7,267
	(5,437)	(5,173)	(9,660)
Electricity reliability measures			
Whether experienced unplanned outages on a daily basis (No = 0 , Yes =1)	0.36	0.36	0.04
Number of unplanned outages in a day	1.07	0.93	0.09
	(1.69)	(1.38)	(0.43)
Duration of most extended unplanned outage experienced (hours)	3.44	2.31	1.24
	(3.10)	(1.54)	(0.72)
Firm characteristics			
Number of full-time employees	50.89	129.00	125.28
	(128.00)	(302.15)	(223.18)
Firm size			
Small	0.53	0.32	0.16
Medium	0.37	0.36	0.42
Large	0.10	0.32	0.42
Sector of activity			
Industry/manufacturing	0.49	0.80	0.88
Services	0.51	0.20	0.12

Table 2.4: Substation configuration and electricity reliability

Variable	OLS Dep. Var.: Whether experienced unplanned outages daily (No = 0 , Yes =1)	OLS Dep. Var.: Frequency of unplanned outages in a day	OLS Dep. Var.: Duration of most extended unplanned outage experienced (hours)
Voltage of connection			
Medium	- 0.02	- 0.06	- 0.99***
	(0.06)	(0.19)	(0.38)
High	- 0.30****	- 0.78***	- 1.49***
	(0.08)	(0.27)	(0.52)
Regional distribution center FE	YES	YES	YES
No. of observations	451	451	409

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Figures in parentheses are standard errors.

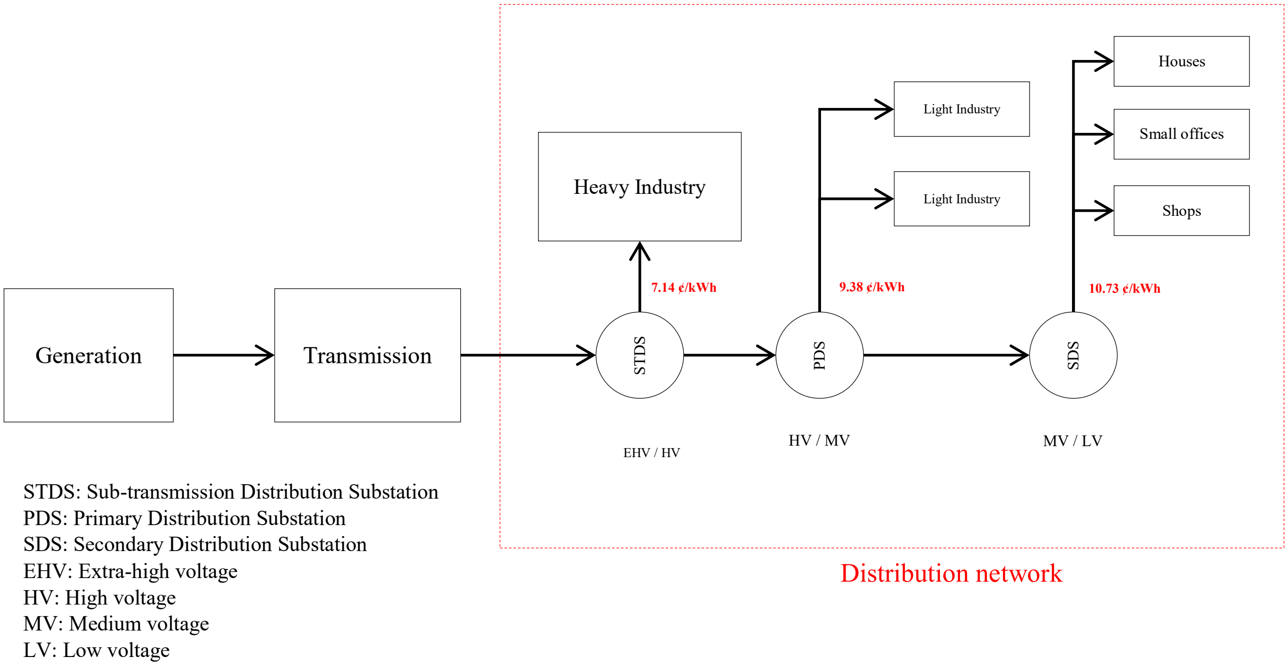

Figure 2.1: General Layout of Electricity Distribution Network

Note: The figure depicts a schematic of the electric network in Nepal. Distances in the layout are not to scale, and they have been shrunk or exaggerated to elaborate the concept. At the distribution level, three voltages are offered to consumers: high, medium, and low. Each step of voltage reduction adds to the cost of supply. Therefore, the energy charge per kWh of electricity delivered to a high voltage consumer is less than medium voltage, and medium voltage is less than low voltage.

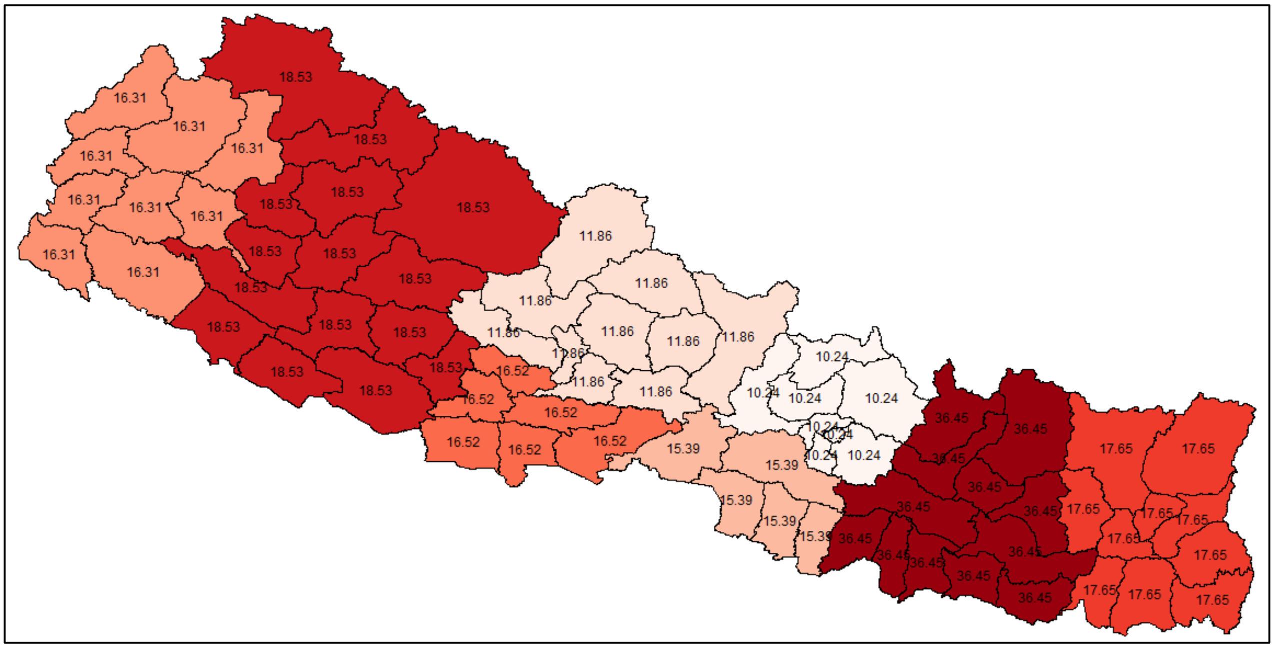

Figure 2.2: Percentage loss in distribution networks across Nepal by regional distribution centers

Source: author’s calculations based on NEA’s reports.

CHAPTER 3

THE EFFECT OF IMPROVEMENTS IN GRID-ELECTRICITY ACCESS ON HOUSEHOLD ELECTRICITY CONSUMPTION ACROSS INCOME STRATA: A MULTI-DIMENSIONAL APPROACH

3.1 Introduction

As low-income countries strive to meet United Nations Sustainable Development Goal 7 (SDG 7, universal access to electricity), residential electricity consumption remains low despite substantial investments in grid expansion programs (Blimpo & Cosgrove-Davies, 2019; Blimpo et al., 2020)[30]. Supply-side constraints have been blamed for low electricity consumption (Bhatia & Angelou, 2015; Aidoo & Briggs, 2019; Pelz & Urpelainen, 2020), since insufficient upstream capacity in the generation and transmission segments and overloaded downstream infrastructure in the distribution segment cause varying availability and reliability levels for consumers connected to the same national grid[31].

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[30] "Universal access to modern energy by 2030" is one of the three key pillars of the Sustainable Energy for All (SE4All) program, an initiative co-chaired by the United Nations (UN) Secretary General and the World Bank President.

[31] Availability of grid-electricity takes into account the timing and duration of supply and reliability considers the frequency of interruptions to supply. Although availability and reliability may be seen as the same issue, addressing them requires different interventions.

This study investigates the impact of improvements in grid-electricity access on the electricity consumption of households at different income levels[32]. Using a nationally representative sample of Nepalese residential consumers consisting of 4,660 households, I investigate the extent to which improved reliability of the electricity grid is likely to affect electricity consumption of both the poor and the non-poor.

I segment households into similar groups based on the supply constraints they face using an unsupervised machine learning technique. To categorize the different levels of reliability available to households, I group households along three dimensions: available hours of electricity per day (maximum of 24 hours), available hours of electricity during the evening peak-time (6-10 PM, a maximum of 4 hours), and frequency of outages experienced by households in a typical week. I estimate the optimal number of clusters via the K-means clustering technique[33]. The largest cluster comprises 55% of the sample, with the rest of the households are distributed across four clusters, representing 5%, 11%, 10%, and 19% of the sample. The clusters reveal three distinct patterns of grid-electricity constraints: (1) low availability with frequent outages (clusters 1 and 2); (2) high availability with frequent outages (clusters 3 and 4); and (3) high availability without frequent outages (cluster 5).

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[32] Improved access to the grid-electricity supply can be defined in terms of enhanced attributes of electricity that make it more usable for the desired applications. In this paper, I focus on the impact of enhancing the availability and reliability attributes on electricity consumption.

[33] The objective of the K-means clustering technique is to achieve the highest intra-cluster similarity and lowest inter-cluster similarity. Observations are grouped into k homogenous clusters. The first step of the analysis is to determine the optimal number of clusters. Following the previous literature, I use the elbow method (Ramachandran et al., 2018), which determines the number of clusters by examining the within-cluster variance as a function of the number of clusters.

After identifying household clusters, I investigate the extent to which unreliable access constrains households' electricity demand at different income levels by focusing on the impact of system reliability on electric appliance ownership. The residential demand for electricity is derived from the household's demand for electric appliance services. Unreliable electricity affects a household's choice of appliances because it reduces the benefit for the household from ownership of such appliances. Therefore, if reliability improvements impact households' purchase decisions and the portfolio of appliances owned, they will also impact electricity consumption (McRae, 2010; Meeks et al., 2020). This approach avoids the potential endogeneity bias due to unobserved factors determining both the appliance choice and electricity consumption when electric appliance ownership is an independent variable in electricity demand estimation (McRae, 2010).

I find that improved access to grid electricity is positively correlated with the probability of electric appliance ownership. The interaction of income and supply-constraint indicators in a piecewise regression model suggests that the insufficient capacity of power supply constrains households equally at all income levels. In contrast, the frequency of unplanned service interruptions does not appear to matter at any income level. These findings imply that if electricity from the grid were available 24-hour a day, the average duration of the remaining outages would probably be so short that it would not affect electric appliance ownership decisions.

In addition, I find that the effect of income on appliance ownership is approximately the same across all income quintiles. The importance of this finding is highlighted when I investigate how households' coping behavior changes when they experience different levels of reliability. The results from an ordered probit model with three backup decision alternatives indicate no association between backup decisions and income in the first two income quintiles. On the other hand, higher-income quintiles are associated with significant changes in coping behavior when electricity is available from the grid all day long, and unplanned outages are not frequent. Thus, the increased availability of supply hours from the grid matters more for poor households, for whom the combined cost of both appliances and backup equipment may be prohibitive[34].

With more progress being made toward achieving SDG7, the findings in this study highlight how unreliable access to electricity constrains the acquisition of household electric appliances. Thus, reliability improvements are expected to increase benefits from electric appliance usage through greater household appliance ownership and, consequently, increased electricity consumption.

Recent studies have highlighted the importance of employing a multi-dimensional measurement framework rather than simply counting grid connections when measuring energy access and the associated economic impacts (Bhatia & Angelou, 2015; Mendoza et al., 2019; Pelz & Urpelainen 2020). A focus on counting connections - politically motivated in most cases - without considering household electrical energy service utilization has deteriorated electric utilities' cash flows in low-income countries (Blimpo & Cosgrove-Davies, 2019). The findings presented in this paper show that a multi-

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[34] Poorer households either do not invest in coping equipment or use low-quality coping equipment (such as kerosene and candles) that provide low-quality lighting services.

dimensional measure framework is extremely useful in studying the impact of improvements in grid-electricity constraints on electricity consumption.

3.2 Methodology and data

3.2.1 Methodology

The availability and reliability of grid-electricity supply is a multi-dimensional issue that should be measured using a variety of indicators representing multiple attributes. For instance, outages may be frequent but last for only a few minutes or for several hours. In addition, the time of day when grid electricity is available is an essential factor because the demand for lighting services - the main category of electricity consumption in low-income countries - is highest during the evening hours. Therefore, if grid power is available for extended hours during the day but constrained during the evening, households will still be significantly constrained in their electricity use.

Various supply-side and demand-side factors can cause power outages. Supply-side causes include insufficient upstream capacity in the generation and transmission segments and overloaded downstream infrastructure in the distribution segment. Outages can also occur when the peak demand for electricity exceeds the total amount that the system can supply. Thus, the availability and reliability of electricity supply from the same national grid may vary from one locality to another.

In this paper, differences in system reliability are explored using K-means clustering, an unsupervised data-mining technique with applications in various fields such as market segmentation analysis and social network studies. In the energy economics literature, K-means clustering has been used to analyze smart-meter data to understand residential electricity load profiles and consumption patterns (Trotta, 2020). Estimates of these patterns have been used in load forecasting, tariff design, and demand-response programs (Rhodes et al., 2014; Trotta, 2020). Identifying consumer segments with similar electricity load profiles allows for a broader range of policy analyses in electricity markets, including studies of the advisability of grid expansion and the efficient level of service reliability (Hayn et al., 2014).

After identifying the relevant household clusters in terms of service reliability, I exploit the variation in reliability across household clusters to estimate the effect of improvements on high-load electric appliance ownership. The residential demand for electricity is derived from the households' demand for electric appliances. Unreliable electricity affects a household's choice of appliances because it reduces the benefit for the household from ownership of such appliances. Therefore, if reliability improvements impact households' purchase decisions and the portfolio of appliances owned, they will also shift the demand curve for residential electricity. The alternative of estimating the electricity demand, using either electricity bills or hours of consumption as the dependent variables, is likely to yield inconsistent estimates because of the clear endogeneity of appliance ownership as a regressor.

3.2.2 Data Description

I use a nationally representative survey of Nepalese households, collected as part of the World Bank's Multi-Tier Framework (MTF) for Assessing Energy Access Program (World Bank, 2019). The survey was conducted in 2017, one year after the total elimination of load shedding in Nepal through electric power imports from India. The sample design was based on a two-stage stratification to ensure the national representativeness of the sample. In the first stage, the enumeration areas were selected randomly within stratifications, representing urban and rural areas and Nepal's three distinct ecological regions (mountains, hills, and terai). In the second stage, households were randomly selected for interviews from wards chosen in the first stage. The raw dataset consists of 6,000 households, of which 4,660 were grid-connected. I focus only on those grid-connected households in this study. Table 3.1 presents summary statistics for the 3,847 grid-connected households for which there are no missing data.

The household segmentation variables listed in Table 3.1 represent three dimensions of system reliability. Households report in the survey that electricity from the grid is available on average for almost 22 hours per day, with a minimum of 7 and maximum of 24 hours of availability. Moreover, the frequency of outages per week varies greatly across households, with a mean of 7 and a standard deviation of 9.37. The third dimension of reliability is peak-time availability, measured as the hours of grid electricity availability from 6 PM to 10 PM. The sample average is 3.56 hours with a standard deviation of 0.68 hours. The three panels in Figure 3.1 illustrate the district-level average hours of grid electricity availability, frequency of outages, and peak-time availability.

Households reported a wide variety of electric appliance ownership, ranging from light bulbs and mobile phone chargers, which require only a few watts, to space heaters and air conditioners, which require several kilowatts. Based on the amount of electricity needed to operate, their electric appliances can be categorized as low-power or high-power (see Table 3.2)[35]. The more high-load appliances a household owns, the higher is its demand for grid electricity for a given level of income. In addition, wealthier households tend to have more high-load appliances because of their higher incomes. The distribution of the total number of high-load appliance ownership represents skewness in consumption, with a mean and median of 1.46 and 1, respectively.

In electricity markets with frequent power outages, household coping behavior is a strong predictor of current and future electricity demand (Hashemi, 2021)[36]. The households in the sample reported ownership of a wide range of coping equipment for lighting purposes during blackouts, including disposable batteries (used with flashlights), kerosene lamps, solar lanterns, and solar lighting. Some households also use high-quality coping equipment such as rechargeable batteries, voltage stabilizers, and generators to power their appliances during service outages. The survey asked two questions about each household's coping behavior: whether it uses any backups for (1) lighting only and (2) lighting plus appliances. Based on the responses to these two questions, I define three binary variables for a household's backup status: no backup, backup for lighting only, and backup for both lighting and appliances. While 9 percent of households do not engage in

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[35] According to the World Bank's MTF framework, appliances with load levels less than 200 watts are low-power appliances, and those with load levels greater than 200 watts are high-power appliances.

[36] Coping behavior refers to decisions made by electricity consumers about how to deal with power outages. During blackouts, consumers may use their off-grid coping equipment (such as rechargeable batteries and generators) or delay all electricity-intensive activities until power returns.

any coping behavior, 60 percent of them back up for lighting only and 31 percent back up for both lighting and appliances.

The survey also collected information about households' characteristics. I use those characteristics documented in the literature as predictors of electricity demand (Lee et al., 2016; Blimpo & Cosgrove-Davies, 2019; Tesfamichael et al., 2020): income, time spent at home, educational attainment, and urban/rural locality. I use the recurring combined monthly expenses reported by households on food, rent, and other services as a proxy for income[37]. I divide households into quintiles of total monthly expenditures. Thirty three percent of the households in the sample live in rural areas, with the other 67 percent spread across urban areas. Thirteen percent of household heads in the sample report as retired and 12 percent report as housewives/househusbands. This is relevant because if the household head is a housewife/husband or retiree, electricity demand is likely to be affected because that person spends more time at home.

3.3 Results

I use the elbow method developed by Makles (2012) to find the optimal number of clusters. Figure 3.2 illustrates the within-cluster variance plotted against the number of clusters. The criterion for choosing the optimal number of clusters is to find a point where the marginal decline in within-cluster variance falls to the "elbow" point. For these data,

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[37] Other goods and services include medical and pharmacy expenses; cleaning supplies, cosmetics, toiletries, water expenses; mobile phone top-up; internet, land phone, cable, and other household communication; and transportation costs.

the number of clusters beyond which marginal reductions in within-cluster variance are not significant is five.

Table 3.3 lists the unscaled mean and standard deviation of segmentation variables across the five clusters and the number of observations in each cluster. Cluster 5 is the largest group comprising 55% of the sample. The rest of the sample households are distributed across clusters 1 to 4, representing 5%, 11%, 10%, and 19% of the sample. As shown in Figure 3.3, overall and peak-time availability hours are significantly less than the sample average for the first group (clusters 1 and 2). While the frequency of outages is above the sample average for the second group (clusters 3 and 4), grid electricity is available for longer hours for the households in this group. Cluster 5 exhibits the lowest variability in the duration of grid-electricity availability (standard deviation of 0.77 hours). Households in this cluster also report an uninterrupted service during the evening peak hours. Based on the segmentation variables, the clusters reveal three distinct system reliability levels: (1) low availability with frequent outages (clusters 1 and 2); (2) high availability with frequent outages (clusters 3 and 4); and (3) high availability without frequent outages (cluster 5).

Table 3.4 reports the estimated coefficients for a linear probability model with an indicator for high-load appliance ownership as the dependent variable without applying the K-means clustering method. These estimates imply, counterintuitively, a negative relation between peak-time availability and appliance ownership. Additionally, the frequency of outages is estimated to have only a very small effect on the likelihood of high-load appliance ownership. It seems likely that the K-means clustering method offers a better way to characterize grid reliability, essentially because of the way it deals with multicollinearity among system reliability measures. The K-means clustering method achieves that by grouping households into unique clusters of supply constraints instead of using each measure of supply constraint as a separate regressor.

Table 3.5 shows the results of a linear piecewise regression model with indicators for reliability clusters and defined breakpoints at income quintiles to allow the marginal effect of income to vary by quintile. I find that extended hours of availability matter equally for all income levels, whereas the frequency of unplanned service interruptions does not matter at any income level. As shown in column 1, although improvements in each supply constraint are associated with a higher probability of high-load electric appliance ownership, the magnitude of these impacts is the same in all income quintiles. In particular, when availability hours are extended, those with and without frequent outages are equally more likely (17 percent) to own high-load appliances. Thus, it appears that once availability is increased, the frequency of unplanned outages does not affect households' appliance ownership decisions.

Moreover, there are no differences in the marginal effects of income across clusters when they are interacted with cluster indicators (column 2). With the most severe constraints as the reference group (low availability with frequent outages), the results indicate that none of the income groups is more constrained than others by service availability. I also estimate separately the impact of each availability measure (daily and peak-time) on appliance ownership. As shown in Tables 3.6 and 3.7, I find no statistically significant difference in the impact of reliability on appliance ownership across income levels.

In all specifications the marginal effect of income on appliance ownership is statistically significant at the first income quintile, holding constant the reliability level. The importance of this finding is highlighted more when I investigate how a household's coping behavior changes with access improvements. The estunates for an ordered probit model with the three alternative backup decisions as the ranked categories (Table 3.8) suggest that when the availability and reliability of service are relatively improved, consumers change their coping behavior. In particular, with a reasonably reliable service, when power outages occur households reschedule their use of electric appliances and use backup for lighting only. However, for poorer households, the marginal effect of income is not significant. In other words, income constraints limit both appliance ownership and coping decisions. Thus, it is expected that the impact of increased availability of supply hours from the grid may be more substantial for poorer households.

3.4 Conclusion

This paper estimates the extent to which electricity consumers of different income levels would increase their use of high-load appliances in response to improvements in grid reliability. The results indicate that although grid-connected households are counted in the electrification statistics, unreliable electricity service significantly constrains their electric appliance ownership and, consequently, electricity consumption. Putting this paper’s findings into SDG 7’s perspective, a connection to the grid by itself does not necessarily translate to realized benefits from electricity consumption. The availability and reliability of the service play a critical role for households at all income levels.

Table 3.1: Summary statistics

Variable	Mean	St. Dev.	Min	Max
Segmentation variables				
Daily availability of grid electricity	21.93	2.89	7	24
Frequency of outages	6.97	9.37	0	88
Availability during the evening peak time (6 – 10 PM)	3.56	0.68	0	4
Household characteristics				
Electricity bill in a typical month (USD)	4.94	7.43	0.04	77.31
Total number of high-load appliances	1.43	1.94	0	10
Quintiles of total monthly expenditures				
1st	73.44	19.66	14.28	100.66
2nd	122.09	12.46	100.76	144.19
3rd	166.90	13.81	144.28	192.57
4th	228.20	23.27	192.66	274.00
5th	492.05	415.52	274.17	3,666.48
Backup status				
No backup	0.09			
Only for lighting	0.61			
Both for lighting and appliances	0.30			
Education status of the household head				
No formal education	0.35			
Primary	0.22			
Secondary	0.38			
College education	0.05			
Household head gender				
Female	0.20			
Time spent at home				
Retired / too old to work	0.12			
Housewife/husband	0.11			
Locality				
Urban	0.66			
Number of observations	3,847			

Table 3.2: Appliances owned by households in the sample

Appliance type by the power load	
Low-load	High-load
Incandescent Light Bulb	Refrigerator
Fluorescent Tube	Hairdryer
Compact Fluorescent Light (CFL) Bulb	Electric food processor/blende
LED Light Bulb	Electric rice cooker
Radio/CD Players/sound system	Microwave oven
VCD/DVD	Electric Iron
Fan	Washing machine
Computer/ Laptop	Electric sewing machine
Smartphone (internet phone) charger	Air cooler
Regular mobile phone charger	Air conditioner
Black & White TV	Space Heater
Regular Color TV	Electric water heater
Flat color TV	Electric hot water pot/kettle
	Electric Water Pump

Source: Nepal’s Multi-Tier Framework Survey (World Bank, 2019)

Table 3.3: Variation in segmentation variables across clusters

Segmentation variable	Cluster				
	1	2	3	4	5
Daily availability hours (max. of 24 hours)	13.70	18.48	21.40	21.63	23.55
	(3.26)	(2.36)	(1.98)	(1.25)	(0.77)
Frequency of outages	37.09	9.73	12.81	8.44	2.14
	(10.83)	(6.11)	(7.49)	(5.90)	(2.20)
Availability during the peak time (max. of 4 hours)	2.86	2.26	3.99	2.99	4.00
	(0.81)	(0.57)	(0.05)	(0.09)	(0.00)
Number of observations	193	417	392	716	2,129
Percentage of the sample	5%	11%	10%	19%	55%

Figures in parentheses are standard deviations.

Table 3.4: Estimates of system reliability impacts without K-means clustering

Variable	OLS Dep. var.: high-load electric appliance ownership
Grid-electricity supply constraints	
Daily availability hours	0.0264*** (0.0035)
Frequency of outages	- 0.0034*** (0.0010)
Availability during the peak time	- 0.0419*** (0.0127)
Controls	YES
Number of observations	3,847

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Figures in parentheses are robust standard errors. Controls include indicators household's income, housewife/husband, too old to work or retired, female, educational attainment, and rural-urban status.

Table 3.5: System reliability and appliance ownership

Variables	Dep. Var.: High-load electric appliance ownership	
	(1)	(2)
Clusters of grid-electricity supply constraint		
High availability with frequent outages	0.1678*** (0.0222)	0.1963 (0.1447)
High availability without frequent outages	0.1728*** (0.0205)	0.1936 (0.1682)
Total monthly expenditures (USD)		
Quintile 1 expenditures	0.0031*** (0.0006)	0.0040*** (0.001)
Quintile 2 expenditures	- 0.0010 (0.0012)	- 0.0025 (0.003)
Quintile 3 expenditures	0.0003 (0.0013)	0.0018 (0.003)
Quintile 4 expenditures	- 0.0013 (0.0009)	- 0.0047** (0.0023)
Quintile 5 expenditures	- 0.0001*** (0.0003)	0.0013 (0.0009)
Interaction between high availability with frequent outages and expenditures		
Quintile 1 expenditures × High availability with frequent outages		- 0.0004 (0.0018)
Quintile 2 expenditures × High availability with frequent outages		0.0004 (0.0038)
Quintile 3 expenditures × High availability with frequent outages		- 0.0027 (0.0041)
Quintile 4 expenditures × High availability with frequent outages		0.0056* (0.0029)
Quintile 5 expenditures × High availability with frequent outages		- 0.0030** (0.0012)
Interaction between high availability without frequent outages and expenditures		
Quintile 1 expenditures × High availability without frequent outages		- 0.0011 (0.0016)
Quintile 2 expenditures × High availability without frequent outages		0.0020 (0.0035)
Quintile 3 expenditures × High availability without frequent outages		- 0.0071 (0.0037)
Quintile 4 expenditures × High availability without frequent outages		0.0028 (0.0026)
Quintile 5 expenditures × High availability without frequent outages		- 0.0030*** (0.0010)
Controls	YES	YES
Observations	3,847	3,847

Notes: * p < 0.1, ** p < 0.05, *** p < 0.01. Figures in parentheses are robust standard errors. Controls include indicators for housewife/husband, too old to work or retired, female, educational attainment, and rural-urban status.

Table 3.6: Daily availability and appliance ownership

Variables	Dep. Var.: High-load electric appliance ownership	
	(1)	(2)
Grid-electricity supply constraint (ref. group: < 24-hour availability)		
24-hour availability	0.0594***	- 0.0157
	(0.0148)	(0.1143)
Total monthly expenditures (USD)		
Quintile 1 expenditures	0.0032***	0.0029***
	(0.0006)	(0.0008)
Quintile 2 expenditures	- 0.0013	- 0.0006
	0.0012	(0.0015)
Quintile 3 expenditures	0.0006	- 0.0001
	(0.0013)	(0.0017)
Quintile 4 expenditures	- 0.0012	- 0.0016
	(0.0009)	(0.0012)
Quintile 5 expenditures	- 0.0012***	- 0.0006
	(0.0003)	(0.0004)
Interaction between availability and expenditures		
Quintile 1 expenditures × 24-hour availability		0.0006
		(0.00127)
Quintile 2 expenditures × 24-hour availability		- 0.0018
		(0.0025)
Quintile 3 expenditures × 24-hour availability		0.0020
		(0.0027)
Quintile 4 expenditures × 24-hour availability		0.0005
		(0.0018)
Quintile 5 expenditures × 24-hour availability		- 0.0015**
		(0.0007)
Controls	YES	YES
Observations	3,847	3,847

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Figures in parentheses are robust standard errors. Controls include indicators for housewife/husband, too old to work or retired, female, educational attainment, and rural-urban status.

Table 3.7: Peak-time availability and appliance ownership

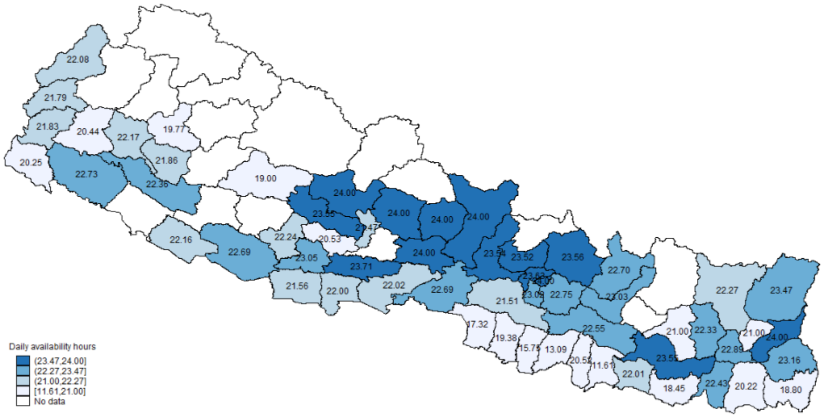
Variables	Dep. Var.: High-load electric appliance ownership	
	(1)	(2)
Grid-electricity supply constraint (ref. group: < 4 hours of availability between 6-10 PM)		
Peak-time availability (4 hours of availability between 6-10 PM)	0.0309**	0.0220
	(0.016)	(0.1041)
Total monthly expenditures (USD)		
Quintile 1 expenditures	0.0031***	0.0033
	(0.0006)	(0.0010)
Quintile 2 expenditures	- 0.0013	- 0.0012
	(0.0012)	(0.0021)
Quintile 3 expenditures	0.0005	- 0.0013
	(0.0013)	(0.0022)
Quintile 4 expenditures	- 0.0013	0.0005
	(0.0009)	(0.0016)
Quintile 5 expenditures	- 0.0012***	- 0.0014
	(0.0003)	(0.0006)
Interaction between availability and expenditures		
Quintile 1 expenditures × Peak-time availability		- 0.0002
		(0.0013)
Quintile 2 expenditures × Peak-time availability		- 0.0003
		(0.0026)
Quintile 3 expenditures × Peak-time availability		0.0034
		(0.0027)
Quintile 4 expenditures × Peak-time availability		- 0.0031
		(0.0020)
Quintile 5 expenditures × Peak-time availability		0.0003
		(0.0008)
Controls	YES	YES
Observations	3,847	3,847

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Figures in parentheses are robust standard errors. Controls include indicators for housewife/husband, too old to work or retired, female, educational attainment, and rural-urban status.

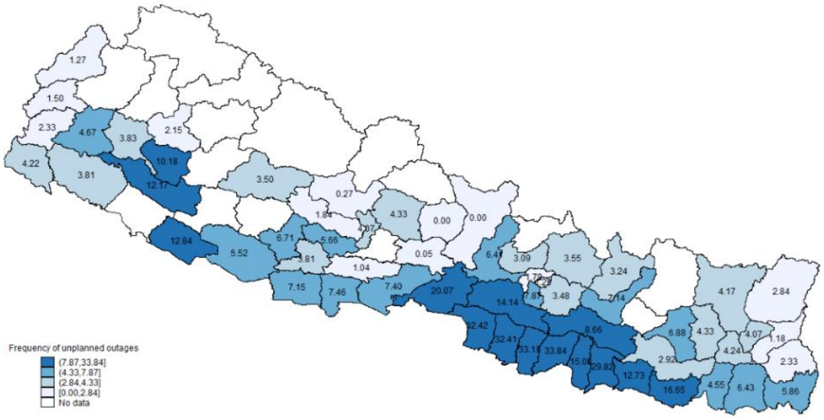
Table 3.8: Supply constraints and coping behavior

Variables	Backup status		
	No backup	Lighting only	Lighting and appliances
Clusters of grid-electricity supply constraint			
High availability with frequent outages	- 0.0156*	- 0.0184*	0.0341*
	(0.0081)	(0.0096)	(0.0176)
High availability without frequent outages	0.0332***	0.0393***	- 0.0726***
	(0.0081)	(0.0091)	(0.0170)
Total monthly expenditures (USD)			
Quintile 1 expenditures	- 0.0002	- 0.0003	0.0005
	(0.0002)	(0.0002)	(0.0005)
Quintile 2 expenditures	- 0.0007	- 0.0009	0.0016
	(0.0004)	(0.0005)	(0.0010)
Quintile 3 expenditures	0.0013**	0.0016**	- 0.0029**
	(0.0005)	(0.0006)	(0.0011)
Quintile 4 expenditures	- 0.0008*	- 0.0009**	0.0017**
	(0.0004)	(0.0004)	(0.0008)
Quintile 5 expenditures	0.0004***	0.0005***	- 0.0009***
	(0.0001)	(0.0001)	(0.0003)
Controls	YES	YES	YES
Observations	3,847	3,847	3,847

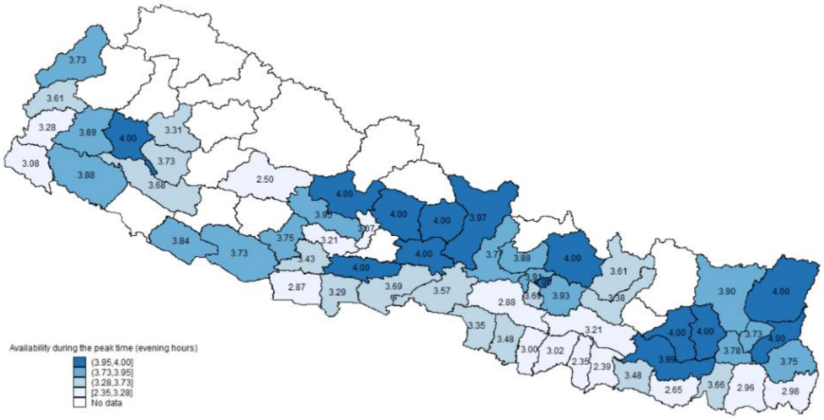
Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Figures in parentheses are robust standard errors. Controls include indicators for housewife/husband, too old to work or retired, female, educational attainment, and rural-urban status.



Panel A. Daily availability of grid electricity



Panel B. Frequency of outages



Panel C. Availability of grid-electricity during the evening peak time (6-10 PM)

Figure 3.1: Grid electricity supply constraints – district-level averages

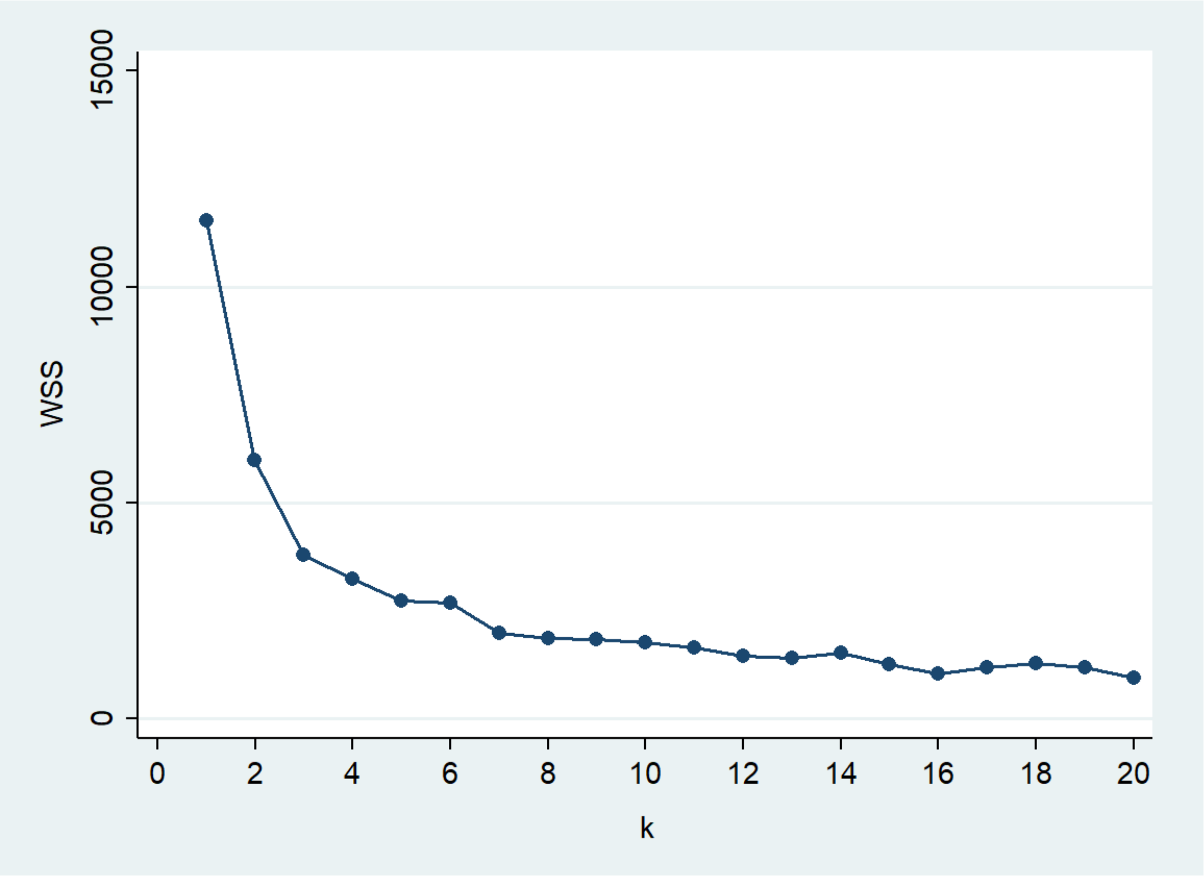


Figure 3.2: Elbow method outcome - the optimal number of clusters

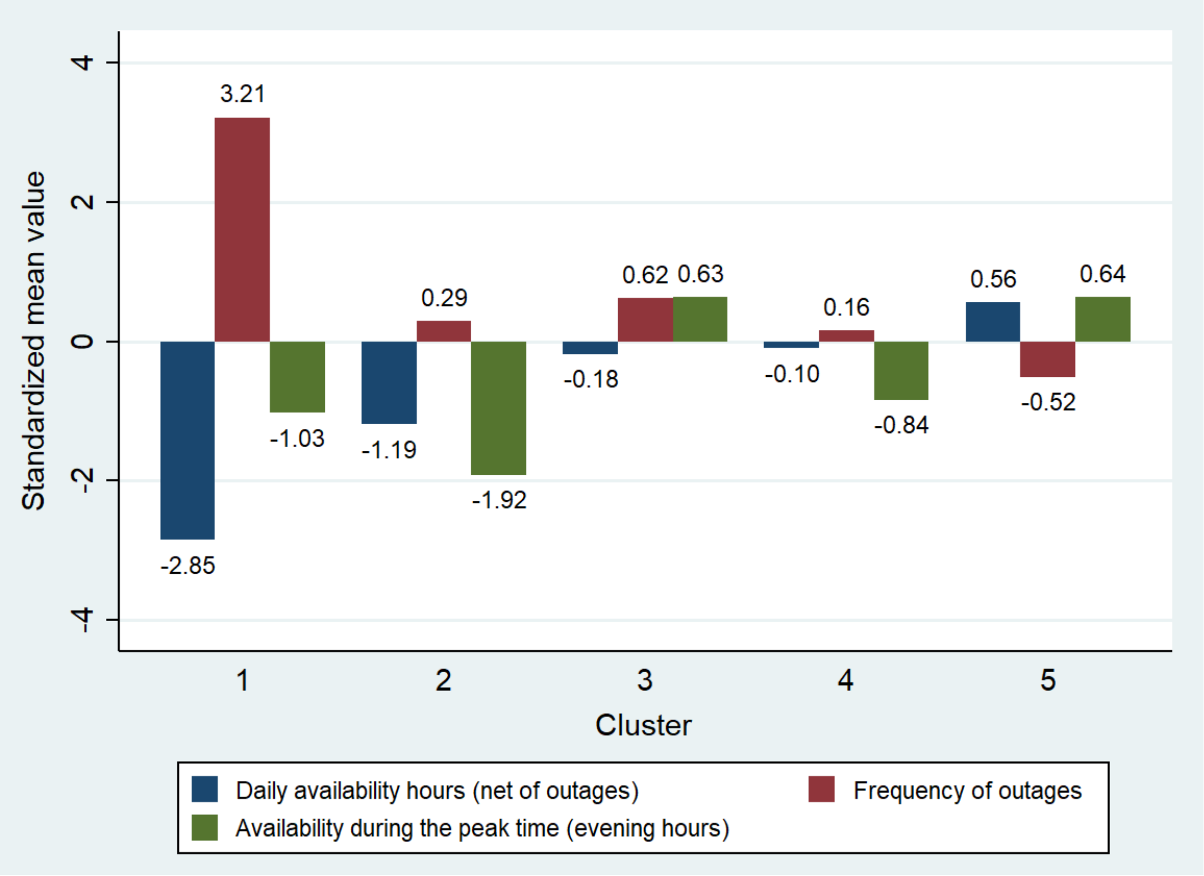


Figure 3.3: Standardized mean values of segmentation variables by cluster

Note: Variables are standardized to have a mean of 0 and a standard deviation of 1.

APPENDICES

I Appendix of Chapter 1: Sample Representativeness

How representative are the samples used in this study? For the household sample, there are two other samples available with a few comparable attributes. The first one is the sample collected by the World Bank's Multi-Tier Framework for Measuring Energy Access 2017. The second source is from Nepal's National Census of 2011 (the latest available at the time of this study). Along with most of the demographic and socioeconomic attributes, sample statistics appear to be reasonably representative of the population at large (see Table A1).

For the firm sample, the only available sample at the time of this study is the World Bank's Enterprise Survey 2013. As shown in Table A2, this study's sample statistics are similar to the World Bank's collected sample.

Table A1: How representative is the household sample?

Variables	The sample used in this study (2016)	World Bank (2017)	Nepal’s National Census (2011)
Sample size	1,800	4,042	2,067,609
Population distribution			
By urban/rural status			
Urban	0.56	0.82	0.73
Rural	0.44	0.18	0.17
By ecological region			
Mountain	0.02	0.10	0.05
Hill	0.58	0.50	0.47
Terai	0.40	0.40	0.48
By development Region			
Eastern	0.20	0.27	0.21
Central	0.43	0.44	0.41
Western	0.19	0.15	0.23
Mid-western	0.10	0.07	0.08
Far-western	0.08	0.07	0.06
Household characteristics			
No formal education	0.20	0.34	-
Household size	5.14	-	4.88
Coping technologies*			
Inverters	0.19	0.29	-
Solar panel	0.16	0.19	-
Solar lantern	0.01	0.03	-
Voltage stabilizer	0.11	0.15	-
Candle	0.20	0.08	-
Kerosene	0.13	0.14	-

Notes

* Torch and emergency lights are asked under different coping technologies, so inconsistent between surveys.

Table A2: How representative is the firm sample?

Variables	The sample used in this study (2016)	World Bank Enterprise Survey (2013)
Sample size	590	482
Firm location		
Urban	0.81	0.79
Rural	0.19	0.21
Region of establishment		
East	0.21	0.11
Central	0.43	0.70
West	0.36	0.19
Coping technology*		
Diesel generator	0.68	0.54
Firm size**		
Small	0.46	0.60
Medium	0.38	0.27
Large	0.16	0.13

Notes
* The World Bank survey only asks about diesel generators' ownership, whereas the sample used in this study asks about a list of different coping technologies.

** The World Bank survey measures a firm's size by the number of its employees, but the sample used in this study measure a firm's size by its annual turnover, the same approach used by Nepal's Internal Revenue Department. Given that there is a high correlation between a firm's number of employees and its annual turnover, these two firm size measures are used here for comparison purposes.

II Appendix of Chapter 1: Cheap Talk Script

Table B1. Cheap Talk script used for the contingent valuation

We would like to know how much you value better quality electricity service. No one will change your electricity tariff as a result of what you say. However, if you value electricity enough, the government may decide to invest more in electricity and your tariff may have to increase to pay for the investment.

Some people over-estimate the amount they are willing to pay because they are frustrated by the current situation and want the investment to happen. If many respondents provide higher estimates, then the government could set a higher tariff for electricity which is beyond your ability to pay.

Likewise, some people underestimate the amount that they are willing to pay because they are concerned that they already pay too much, or they lie thinking that the government will charge them less. But, if enough people respond this way, the government will think that electricity is not important to you and may not make additional investments in electricity improvement projects.

Please also be aware of your expenses on alternative energy sources, such as candles and kerosene, and how your family’s budget will be affected if you no longer have to purchase so many alternatives to electricity.

Your VDC or Municipality will be at a disadvantage whether you over-estimate or under-estimate your willingness to pay. So, please try to be honest and tell us only what you are truly able and willing to pay based on your income.

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