Queen's Economics Department Working Paper No. 1468

The Economic Benefits of Mitigating the Risk of Unplanned Power Outages

Majid Hashemi

Glenn Jenkins
Queen's University

Department of Economics
Queen's University
94 University Avenue
Kingston, Ontario, Canada
K7L 3N6

10-2021

The Economic Benefits of Mitigating the Risk of Unplanned Power Outages

Majid Hashemi[a,*], Glenn Jenkins[b,c]

[a] Department of Economics, Queen's University, Kingston, ON K7L 3N6, Canada
[b] Department of Economics, Queen's University, Kingston, ON K7L 3N6, Canada
[c] Center for Applied Research in Business, Economics and Technology, Cyprus International University, North Cyprus

Abstract

This paper takes on a novel perspective to the overloading of distribution substations by considering the common-pool characteristics of electric infrastructure capacity. Using firm- and substation-level data from a sample of Nepalese firms, the results provide evidence of common-pool resource (CPR) problems across substations' ownership boundaries: firms with captive substations experience fewer and shorter unplanned outages than firms connected to shared substations. Based on these findings, private investments in captive substations emerge as a coping mechanism against unreliable electricity supply. Lastly, an appraisal framework for such investments is developed and used to quantify the economic benefits to Nepal's economy.

Keywords: Opportunity cost of power outages; electricity reliability; common-pool resource; electricity.

* Corresponding author. E-mail address: majid.hashemi.86@gmail.com

1. Introduction

In many developing countries, insufficient investments in transmission capacity or seasonal shortages in electricity generation 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. Previous studies show that there is often a significant willingness to pay among consumers to eliminate planned outages (Abrate et al., 2016; Ozbafli & Jenkins, 2016; Carlsson et al., 2020; Niroomand & Jenkins, 2020; Hashemi, 2021; Carlsson et al., 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 (Carranza & Meeks, 2018; Meeks et al., 2020)[†]. Electric utilities upgrade substation capacities to keep up with growing demand over time and to prevent or reduce overloading. The cost of such investments is recovered from adjustments to retail electricity prices (EIA, 2017).

There is often political pressure against raising electricity prices in many developing countries. The situation gets worse where access to electricity is viewed as a right. Unaccounted electricity usage (electricity theft) through illegal connections and unpaid electricity bills often becomes a socially accepted part of the system (Burgess et al., 2020). Consequently, electric

[†] 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.

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. In other words, electricity reliability at the substation level creates a network externality with actions of one user affecting electricity reliability for all other users (Kimmich and Sagebiel, 2016).

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 CPR issues. 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 substations enables firms to mitigate those problems.

The data analyzed in this paper indicate that firms with captive substations are less likely to experience unplanned outages[‡]. In particular, firms with private substations are less likely

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

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. The benefits from deregulation of substation ownership would generate substantial economic gains to Nepal's economy, up to 1.62 USD billion as of 2020.

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 capacities of upstream generation and transmission can effectively eliminate *planned* outages, the situation for 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. In other words, as Lal (2006) suggests, the key will lie in getting the local consumers to "own" the problem (rather than forcing a solution on them) and facilitating their own solutions, such as forming clusters of firms to control local distribution.

2. 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. Unfortunately, the reliability of service is reduced for everyone connected to that substation (Kimmich & Sagebiel, 2016; Gertler et al., 2017; Pless and Fell, 2017).

Similarly, Kimmich and Sagebiel (2016) develop a game-theoretic model to analyze electricity distribution for irrigation in Andhra Pradesh, India. In their model, substation personnel either provide formal authorization, including the provision of sufficient capacity, or accept informal payments, neglecting the capacity overuse. The electric utility either faces part of the costs for providing capacity or repair costs due to overloading damages. Given that these costs do not accrue to the substation personnel, they have clear incentives to take informal payments. Consequently, both farmers and the distribution company face costs that result from the actions of all connected farmers. 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 a significant proportion of developing countries. 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 cannot be (i.e., load balancing, voltage control, and reactive power). 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).

3. Cost-benefit analysis of distribution substations' ownership

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 serve 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[§]. In either case, the framework below can be used to quantify the costs and benefits of investments in substations.

[§] 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.

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 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 1). 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.

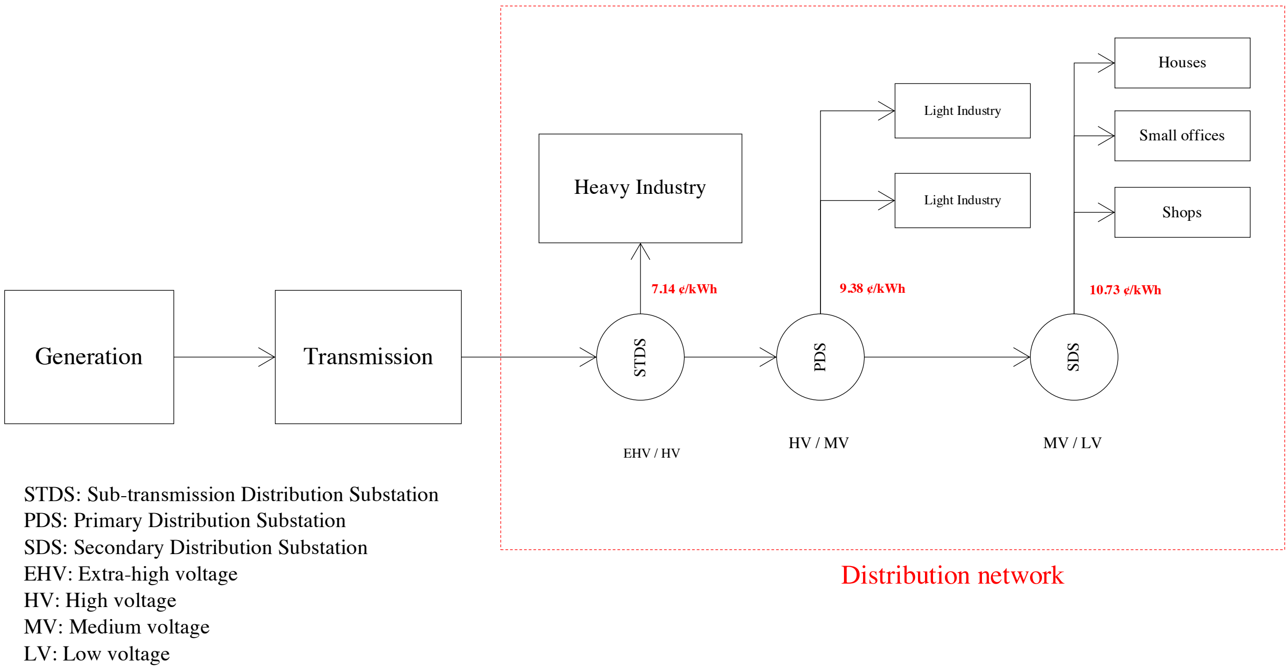

Figure 1: General Layout of Electricity Distribution Network

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.

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 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.

Table 1: Retail electricity tariffs in Nepal

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

Source: NEA's annual reports

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 (Oseni & Pollitt, 2015; Allcott et al., 2016; Abdisa, 2018).

The savings from the differential kWh tariff rates between voltages 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 the 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

$$CM_i = R_i - c_i^m - c_i^e - c_i^{other} \quad (1)$$

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 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,

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

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. Sales revenues are not directly reported in the census data, but the value of output can be used as an approximation for sale revenues.

Table 2: Contribution value per kWh by industry

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: authors' calculations based on the data from the 2011 National Census of Manufacturing Establishment

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 substation owner could charge a higher price for lower voltage power if it was supplied with a greater degree of reliability. 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.

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 zero if "No." The central assumption here is that frequent unplanned outages reported by a firm, relative to other firms in the same distribution center, implies 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.

3.4 Investment appraisal of a captive substation

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

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

where C_i is the substation investment cost, 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*, h is averted hours of power outages for firm i due to having a captive substation, and $OPEX_{i,t}$ is the operating expenditures of a captive substation. 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 distribution lines takes one year to be completed.

4. Data and methodology

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, the percentage of losses across distribution centers ranged from as low as 10.24 percent to as high as 36.45 percent in 2016. This variation suggests that the sample firms drew electricity from distribution networks with different electricity reliability levels.

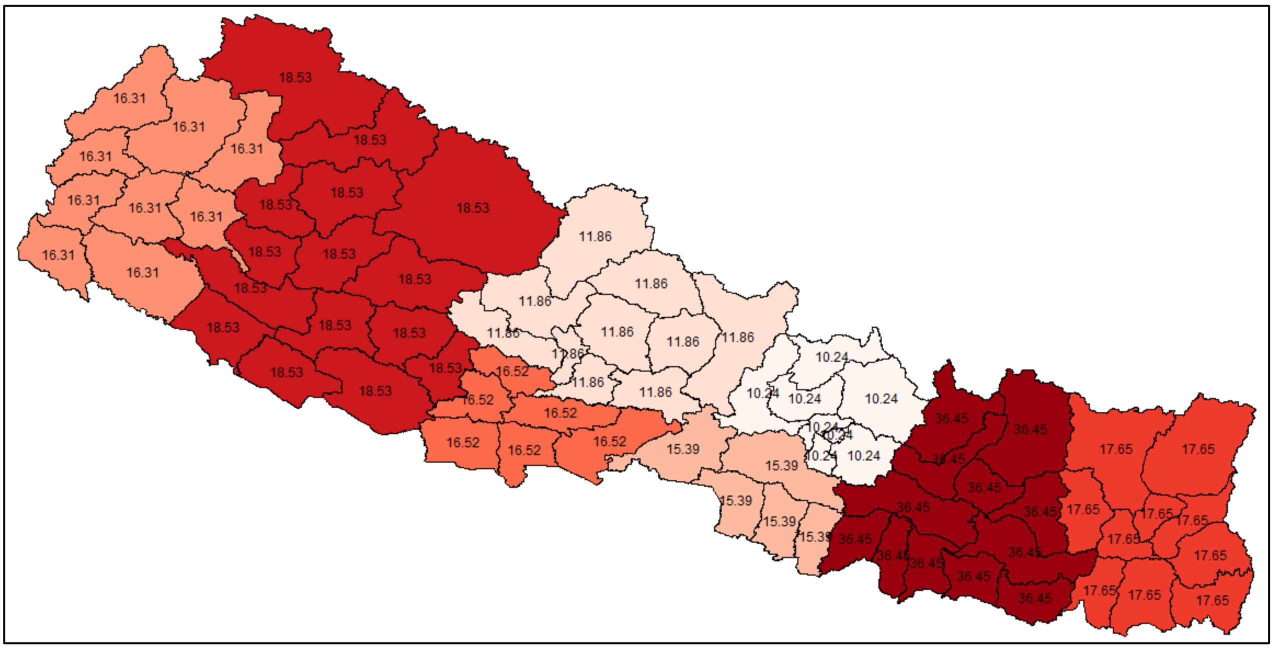

Figure 2: Percentage loss in distribution networks across Nepal by regional distribution centers

Source: authors' calculations based on NEA's reports.

4.2 Firm-level data

The firm-level data is obtained from a sample of 590 Nepalese firms surveyed in 2016[**]. The survey collected information about the voltage at which each firm purchased electricity from the national electric utility. This rich information facilitates the identification of each

[**] 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/index.php/catalog/194/study-description.

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.

5. Results

Table 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 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 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

[*] See Appendix A for more detail about national-representativeness.

Table 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).

Table 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.

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 3 is carried out in this section.

The cost-benefit analysis (CBA) is conducted for per megavolt ampere (MVA) of distribution substation investment[††]. The CBA starts with estimating the financial NPV from saving in tariff rates as the only benefit considered (i.e., the difference between $t_{i,t}^{high}$ and $t_{i,t}^{low}$ in Eq. 4). The investment cost of constructing a distribution substation in Nepal (C_i) is around 0.38 USD million per MVA, with annual operating and maintenance costs of 0.01 USD million ($OPEX_{i,t}$), at 2020 prices[‡‡]. Using a tariff difference of 2.76 US cents per kWh (the average value of rate difference presented in Table 1), the NPV of savings in tariff rates to the substation owner amounts to 0.86 million USD over 10 years (see column 1 of Table 5).

Following the discussion in Section 3.2, apart from the savings in electricity expenses a captive substation also provides substantial benefits by reducing losses during power outages for electricity consumers. Therefore, 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

[††] One MVA is approximately equal to one kilowatt (kW). So, a one-MVA substation distributes about 8,760 megawatt-hour (MWh) per year.

[‡‡] 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.

electricity lost[§§]. Estimates of contribution values presented in Table 2 are used in this paper as the levelized cost of the electricity lost during power outages. Moreover, 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).

Table 5: CBA results per MVA of substation investment (12% discount rate, million USD)

Beneficiary	NPV of savings in tariff rates	NPV of savings in lost production due to power outages
	(1)	(2)
Substation owner	0.86	
Industrial electricity consumer		
Structural metal products		1.93
Grain mill products		2.20
Plastic products		2.36
Cutting, shaping & finishing of stone		2.80
Sawmilling & planning of wood		3.31
Manufacture of articles of concrete & cement		6.58

Source: Authors' calculations

Following the regression results presented in Table 4, it is assumed that the captive substation mitigates approximately 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 supplied. This assumption is reasonable given that the low-voltage firms with shared 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 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.

Column 2 of Table 5 reports the value of savings in lost production for a representative firm in each sector. Unsurprisingly, these values differ by sector of activity, ranging from 1.93 million USD for structural metal producers to 6.58 million USD for manufacturers of articles of concrete and cement. It is worthwhile noting that although concrete and cement manufacturers consume the lowest amount of electricity among the sectors analyzed in this study, their benefits from savings in forgone production value turn out to be the highest. This can be explained by the fact that when a firm uses less electricity in its production operation, then an interruption in the supply of that small quantity of electricity prevents the utilization of the other inputs and can result in significant losses. Consistent with Hashemi et al. (2018), if a tiny amount of electricity is used to turn on a switch to keep the production going and if that electricity is not supplied, clearly the opportunity cost of that quantity of power would be very substantial.

Because the sample is nationally representative, the economic gains to the whole economy can also be estimated[***]. As of 2020, Nepal's electricity distribution network consists of 202 high-voltage and 35,561 low-voltage distribution substations with a total distribution capacity of 3,200 MVA (see Table 6). Also, NEA's report points out that an average of 37 percent of the distributed electricity by regional distribution centers is purchased by industrial consumers. Assuming that 75 percent of this amount is distributed through low-voltage substations, the total capacity of low-voltage substations is approximately 888 MVA. With 1.83 USD million net economic gains from a representative one-MVA substation, the net present value of economic gains to Nepal of mitigating the risk of unplanned outages for industrial consumers would total 1.62 USD billion (see Table 7).

[***] See Appendix A for more detail about the sample's national-representativeness.

Table 6: Electricity distribution network's structure and capacity

Regional distribution centers	Number of distribution substations		Consumers per low-voltage substation	Total distribution capacity (MVA)	% sold to industrial consumers	Distribution capacity supplied to industrial consumers (MVA)
	High voltage	Low voltage				
1	38	6,217	128	526	48%	252
2	33	6,546	134	634	42%	266
3	29	6,666	115	719	14%	101
4	10	1,989	132	172	50%	86
5	25	4,325	88	292	18%	53
6	21	3,601	127	351	63%	219
7	16	2,573	126	277	47%	130
8	30	3,644	110	228	16%	39
Total	202	35,561		3,199		1,147

Source: NEA's reports

Table 7: CBA results – Nepal's economy (12% discount rate, million USD)

Item	Value
1. NPV of annual savings in tariffs per MVA of substation capacity	0.86
2. NPV of annual savings in losses during power outages*	0.54
3. NPV of substation cost per MVA (investment + annual operating costs)	0.43
4. NPV of gains per MVA of substation capacity**	1.83
5. Total capacity of distribution substations in Nepal (MVA)	3,200
6. Percentage of total electricity distributed to industrial consumers	37%
7. Percentage of total electricity distributed to low-voltage industrial consumers (% of row 6)	75%
8. NPV of economic gains to Nepal of mitigating the risk of unplanned outages for industrial consumers***	1,625

Notes: * A conservative contribution value of 0.50 USD cents per kWh is assumed for all industrial consumers in Nepal.
** (row 1+ row 2) – (row 3)
*** row 4 × row 5 × row 6 × row 7

6. Conclusion

This paper 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 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 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. Similarly, Kimmich and Sagebiel (2016) point out that coordination problems exist in electricity provision to farmers at the distribution substation level in Andhra Pradesh, India. They argue that a coordinated improvement of power quality would be feasible if the farmers were to become aware of the necessity and potential outcomes of collective action at the substation level.

The findings of this study indicate that the CPR problem could be largely solved if private firms were allowed to own and operate substations. Coordination at the substation level becomes more effective with investments directly translating into economic benefits for electricity consumers. 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. 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.

Acknowledgment

Authors would like to thank Roop Jyoti, William Dougan, Robert Fleck, Andrew Hanssen, Arnold Harberger, Reed Watson, Molly Espey, and other Public Economics Workshop participants at John E. Walker Department of Economics, Clemson University for their detailed review of this paper.

References

Abdisa, L. T. (2018). Power outages, economic cost, and firm performance: evidence from Ethiopia. Utilities Policy, 53, 111-120.

Abrate, G., Bruno, C., Erbetta, F., Fraquelli, G., & Lorite-Espejo, A. (2016). A choice experiment on the willingness of households to accept power outages. Utilities Policy, 43, 151-164.

ADB (Asian Development Bank), 2007. Energy Policy 2000 Review: Energy Efficiency for a Better Future. Available online: https://www.adb.org/sites/default/files /evaluation-document/35439 /files/ses-reg-2007-05.pdf.

ADB (Asian Development Bank), 2009. Bangladesh: Ninth Power Project. Available online: https://www.adb.org/sites/default/files/evaluation-document/35085/files/21182-ban-pper.pdf.

ADB (Asian Development Bank), 2011. Learning lessons – electricity sector. Available online: https://www.adb.org/sites/default/files/evaluation-document/35874/files/lessons-electricity.pdf.

ADB (Asian Development Bank), 2020a. High Voltage Distribution Systems Experience and Technical Study. Available at: https://www.adb.org/sites/default/files/linked-documents/50193-003-sd-10.pdf.

ADB (Asian Development Bank), 2020b. Power Transmission and Distribution Efficiency Enhancement Project. Available at: https://www.adb.org/sites/default/file s/project-documents/50059/50059-002-emr-en.pdf.

Alberini, A., Steinbuks, J., & Timilsina, G. (2020). How Valuable is the Reliability of Residential Electricity Supply in Low-Income Countries? Evidence from Nepal.

Allcott, H., Collard-Wexler, A., & O'Connell, S. D. (2016). How do electricity shortages affect industry? Evidence from India. American Economic Review, 106(3), 587-624.

Burgess, R., Greenstone, M., Ryan, N., & Sudarshan, A. (2020). The Consequences of Treating Electricity as a Right. Journal of Economic Perspectives, 34(1), 145-69.

Carlsson, F., Demeke, E., Martinsson, P., & Tesemma, T. (2020). Cost of power outages for manufacturing firms in Ethiopia: A stated preference study. Energy Economics, 104753.

Carlsson, F., Kataria, M., Lampi, E., & Martinsson, P. (2021). Past and present outage costs– A follow-up study of households' willingness to pay to avoid power outages. Resource and Energy Economics, 64, 101216.

Carranza, E., & Meeks, R. (2018). Energy efficiency and electricity reliability. Review of Economics and Statistics, 1-78.

EIA (Energy Information Administration), 2017. Electricity prices reflect rising delivery costs, declining power production costs. Available at: https://www.eia.gov/todayinenergy /detail.php?id=32812.

EIA (Energy Information Administration), 2019. How much electricity is lost in electricity transmission and distribution in the United States? Available at: https://www.eia.gov/tools/faqs/faq.php?id=105&t=3.

Galo, A. (2017). Contribution Margin: What It Is, How to Calculate It, and Why You Need It. Harvard Business Review. Available at: https://hbr.org/2017/10/contribution-margin-what-it-is-how-to-calculate-it-and-why-you-need-it.

Gertler, P. J., Lee, K., & Mobarak, A. M. (2017). Electricity reliability and economic development in cities: A microeconomic perspective. Oxford Policy Management, the Center for Effective Global Action and the Energy Institute at the University of California, Berkeley.

Hashemi, M. (2021). The economic value of unsupplied electricity: Evidence from Nepal. Energy Economics, 95, 105124.

Hashemi, M., Jenkins, G. P., Jyoti, R., & Ozbafli, A. (2018). Evaluating the cost to industry of electricity outages. Energy Sources, Part B: Economics, Planning, and Policy, 13(7), 340-349.

Interstates, 2020. Facility Assets: What Is The Value Of Owning Your Transformer? Available at: https://www.interstates.com/facility-assets-what-is-the-value-of-owning-your-transformer/

Jamil, F. (2013). On the electricity shortage, price and electricity theft nexus. Energy policy, 54, 267-272.

Kimmich, C., & Sagebiel, J. (2016). Empowering irrigation: A game-theoretic approach to electricity utilization in Indian agriculture. Utilities Policy, 43, 174-185.

Künneke, R., & Finger, M. (2009). The governance of infrastructures as common pool resources. Available at: http://dlc.dlib.indiana.edu/dlc/handle/10535/1676.

LaCommare, K. H., & Eto, J. H. (2006). Cost of power interruptions to electricity consumers in the United States (US). Energy, 31(12), 1845-1855.

Lal, S. (2006). Can good economics ever be good politics? Case study of India's power sector. The World Bank.

Meeks, R. C., Omuraliev, A., Isaev, R., & Wang, Z. (2020). Enforcement in Service Delivery: Smart Meters and the Returns to Electricity Quality Improvements. Available at: http://www.robynmeeks.com/wp-content/uploads/2020/08/Smart_ meters__20200826.pdf.

Melville, E., Christie, I., Burningham, K., Way, C., & Hampshire, P. (2017). The electric commons: A qualitative study of community accountability. Energy Policy, 106, 12-21.

Munasinghe, M., & Gellerson, M. (1979). Economic criteria for optimizing power system reliability levels. The Bell Journal of Economics, 353-365.

Niroomand, N., & Jenkins, G. P. (2020). Estimation of households' and businesses' willingness to pay for improved reliability of electricity supply in Nepal. Energy for Sustainable Development, 55, 201-209.

Oseni, M. O., & Pollitt, M. G. (2015). A firm-level analysis of outage loss differentials and self-generation: Evidence from African business enterprises. Energy Economics, 52, 277-286.

Ozbafli, A., & Jenkins, G. P. (2016). Estimating the willingness to pay for reliable electricity supply: A choice experiment study. Energy Economics, 56, 443-452.

Pless, J., & Fell, H. (2017). Bribes, bureaucracies, and blackouts: Towards understanding how corruption at the firm level impacts electricity reliability. Resource and Energy Economics, 47, 36-55.

PWC (2016). Best practices and strategies for distribution loss reduction. Available online: http://www.forumofregulators.gov.in/Data/study/11.pdf

Sanghvi, A. P. (1982). Economic costs of electricity supply interruptions: US and foreign experience. Energy Economics, 4(3), 180-198.

Tang, J. (2014). Project Information Document (Concept Stage) - Nepal: Grid Solar and Energy Efficiency - P146344 (English). Washington, DC: World Bank Group. Available from: http://documents.worldbank.org/curated/en/781901468288639841/Project-Information-Document-Concept-Stage-Nepal-Grid-Solar-and-Energy-Efficiency-P146344

Zhang, Fan. 2018. In the Dark: How Much Do Power Sector Distortions Cost in South Asia? World Bank, Washington, DC.

Valletti, T. M., & Estache, A. (2001). The theory of access pricing: an overview for infrastructure regulators.

Warren, C., Reeve, J. M., & Duchac, J. (2013). Financial & managerial accounting. Cengage Learning.

Wijayatunga, P., & Siyambalapitiya, T. (2016). Improving Energy Efficiency in South Asia. Availble at: https://www.adb.org/sites/default/files/publication/200651/sawp-047.pdf.

Appendix A

How representative is the sample used in this study? The only available sample at the time of this study with a few comparable attributes is the World Bank's Enterprise Survey 2013. As shown in Table A1, this study's sample statistics are similar to the World Bank's collected sample.

Table A.1: National representativeness of the 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.