The Economics of Electricity and Development: Planning for Growth and a Changing Climate*

Robyn C. Meeks† Anil Pokhrel‡

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Abstract

Many low and middle income countries have made tremendous gains in electrification over the past few decades. These improvements in electricity access have enabled a growing body of empirical evidence on its impacts. This paper complements prior review articles on the impacts of electrification by addressing several major remaining challenges faced by the electricity sector in developing countries – impediments to maximizing electricity services' economic effects, obstacles to recovering utility costs, difficulties in forecasting future electricity demand, and uncertainty regarding the future adoption of climate mitigating technologies – and the existing micro economic causal evidence addressing those challenges. We describe how randomized experiments have complemented the quasi-experimental evidence, and then highlight some remaining gaps in the existing literature. Specifically, we highlight climate adaption within the electricity sector in developing countries, which remains a crucial gap in both the discussion on and financing of electrification for development. We use case studies of Nepal and Pakistan, countries in South Asia – a region that both recently experienced great electrification gains and is among the most vulnerable to climate change – to illustrate the need for additional work on adaptation in the electricity sector. We conclude by linking to recent discussions on climate adaptation finance.

Keywords: electricity; development; utilities; climate mitigation and adaptation;
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†Sanford School of Public Policy, Duke University. Email: robyn.meeks@duke.edu
‡National Disaster Risk Reduction and Management Authority, Government of Nepal

1 Introduction

When world leaders gathered in 2000 and committed to achieving development targets by 2015 – the Millennium Development Goals – electricity access was not listed as one of the goals, even though only 20.2% of populations living in the world's least developed countries (per the United Nations classification) had access to electricity at the time (IEA et al., 2023). When the United Nations General Assembly created the Sustainable Development Goals in 2015, it highlighted the need for greater attention to energy in development strategies by including the goal to "ensure access to affordable, reliable, sustainable, and modern energy for all." Coinciding with this focus, the number of people without access to electricity dramatically decreased, from 1.1 billion (2010) to 675 million (2021) (IEA et al., 2023).

With electricity access increasing, so too has the empirical evidence on its impacts. Studies of firms and households find substantial impacts from electricity access in some settings (see, e.g., Dinkelman, 2011; Rud, 2012; Lipscomb et al., 2013; Barron and Torero, 2017; Meeks et al., 2021; Fetter and Usmani, 2020; Kassem, 2024), but not others (see, e.g., Peters et al., 2011; Burlig and Preonas, 2021; Lee et al., 2017). The review articles that have followed (see, e.g., Jiménez, 2017; Bayer et al., 2020; Moore et al., 2020; Lee et al., 2020; Chakravorty and Pelli, 2022), provide insights into those results as well as explanations for the heterogeneities in findings across studies (e.g., empirical methods employed, length of study period, location, electrification source).

In this paper, we first seek to complement the existing literature by drawing attention to additional challenges – beyond electricity access – that pervade the electricity sector in many developing countries and impede the realization of the full benefits from those electricity gains. Specifically we ask: what are some of the major constraints holding back the electricity sector in developing countries? What is the existing economic evidence addressing these challenges, using either quasi-experimental methods or randomized controlled trials (RCTs)?[1] What are some important remaining gaps in the evidence?

To do so, we highlight four areas of challenge – on which some empirical evidence does

[1] In our coverage of the literature, we aim to focus on the most recent empirical evidence, particularly randomized control trials (RCTs) that build upon the existing evidence from quasi-experimental studies.

exist – that impede electricity service provision and therefore development, more broadly.[2] First, in many low and middle income countries, consumers may not be maximizing the economic benefits from electricity connections due to impediments such as unreliable and poor quality service and low adoption of energy efficient technologies. Second, electricity service providers are often unable to recover the full cost of electricity services delivered due to subsidized electricity prices, high electricity losses (i.e., theft), and low bill payment (Burgess et al., 2020). This low cost recovery undermines any utility efforts to improve electricity service quality. Third, considerable uncertainty remains regarding the demand for and use of technologies promoted through climate mitigation efforts, particularly decentralized renewable energy sources. Fourth, there are difficulties in predicting future demand for electricity services. The extent to which newly electrified consumers will adopt and use electric appliances, beyond the most basic low wattage items, remains unclear. Additionally, the extent to which consumers in low and middle income countries will adjust to changing temperatures by consuming additional cooling (or heating) services is uncertain.

One additional and pertinent and challenge in developing countries – climate adaptation within the electricity sector – receives little attention in existing research.[3] Recent literature describes how climate change will impact the electricity grid via increased demand for cooling services and therefore electricity demand overall (Davis and Gertler, 2015).[4] However, most of the evidence on the relationship between temperature and demand for electricity services is from high income countries, not low income countries. Additionally, climate change is impacting the sector – and therefore requiring adaptation – in ways other than through temperature. For example, changes in water availability due either to changes in precipitation or glacial melt can affect electricity generation through hydropower plants (as well as

[2]This is not intended to be a exhaustive and complete review of the existing literature; rather we are attempting to address literature focusing on these specific challenges. Also, with our focus on electricity sector specifically, this paper is more narrowly focused than the literature reviews encompassing energy and development broadly (see, e.g., Jeuland et al., 2021). As such, we are not tackling cooking and cookstoves literature – beyond the literature that addresses electric cooking specifically – given much of that work addresses changes to more efficient stoves or switching fuels from burning biomass to gas, etc.

[3]Existing research does address other aspects of adaptation in low and lower middle income countries, more broadly. See Kala et al. (2023) for a recent review of the economics research related to adaptation and development. Specific to the electricity sector, there is substantially less evidence on adaptation.

[4]Higher temperatures also reduce thermal power plant output, transmission line carrying capacity, and solar pv output.

cooling for thermal power plants). Moreover, flooding and landslides can debilitate or even destroy electricity infrastructure. Such events, which are particularly a concern in South Asia (Johnston et al., 2012), occur with increased frequency and threaten to undo recent progress in electricity access.

The second half of the paper illustrates why and how these climate hazards are an important topic for future economics research. We do so through case studies of two South Asian countries, Nepal and Pakistan. South Asia, and these two countries in particular, are important cases for multiple reasons. First, they represent two of the eight countries in the Hindu Kush Himalayan (HKH) region, which is a mountainous region in Asia that also spans Afghanistan, Bangladesh, Bhutan, China, India, and Myanmar (International Centre for Integrated Mountain Development, 2023). Second, both surface temperatures and precipitation are important for natural systems and Asia has seen substantial changes in both in recent history (World Meteorological Organization, 2023). The mean temperature in 2022 over Asia was either the second or third highest on record and the warming trend for the last 30 years (1991-2022) was approximately double that of the prior 30 years (1961-1990) (World Meteorological Organization, 2023).

Additionally, the HKH mountains are covered by glaciers containing substantial ice mass that is sensitive to changes in climate. Glaciers, snow, and permafrost within mountain regions have shrunk dramatically in recent decades worldwide and those in the HKH region are no different (Intergovernmental Panel on Climate Change, 2022). Furthermore, the glaciers and snow covering the HKH region's mountains are an important source of water not only for people in those 8 countries, but also those inhabiting the 16 Asian countries relying on them (International Centre for Integrated Mountain Development, 2023). Given an estimated 240 million people inhabit the region's mountains and hills and another 1.9 billion reside in the 12 major river basins sourced by water from this mountain range (International Centre for Integrated Mountain Development, 2023), what happens in these mountains affects a substantial proportion of the world's population. Changes in water availability not only affect drinking water, and agricultural and industrial uses; a decrease in water resources can also affect the ability to generate electricity through built hydropower plants (Brown et al., 2013). Yet there is still relatively little systematic evidence on the impacts of changes in water sources on the “operation and productivity of hydropower facilities” anywhere in the world (Intergovernmental Panel on Climate Change, 2022).

Furthermore, evidence indicates that climate change has increased the occurrences of natural hazards in areas with glacial cover (Intergovernmental Panel on Climate Change, 2022) and these hazards can harm energy infrastructure. For example, evidence shows that changes in glacial lakes, and the resulting sudden emptying of water and sediment, have left hydropower infrastructure severely impaired and destroyed (Intergovernmental Panel on Climate Change, 2022). Between 1985 and 2014, the HKH region experienced an estimated 45 billion USD in economic losses from flood and mass movements, which was the highest absolute value of economic losses of any mountain regions worldwide (Intergovernmental Panel on Climate Change, 2022). If hydropower facilities are destroyed or even temporarily offline, that is costly not only in terms of the expenses incurred to repair the infrastructure, but also in terms of the economic benefits missed from the unrealized consumption of electricity services not provided. This necessitates mechanisms to finance future climate adaptation, as the IPCC reports with high confidence that “mountain flood and landslide hazards, exposure and vulnerability” will require substantial intervention to lower risks and improve adaptation (Intergovernmental Panel on Climate Change, 2022).

Lastly, glacial melt also contributes to sea level change (World Meteorological Organization, 2023), which is an important factor for South Asia. Not only is sea level rising but land is also subsiding, and the regions of the world in which subsidence of coast cities occurred most quickly between 2015 and 2020 are in Asia (i.e., South, Southeast, and East) (Wu et al., 2022). We will return to this specifically for the case of Pakistan.

The remainder of the paper proceeds as follows. Sections 2, 3, 4, and 5 present the existing evidence in four overarching areas in which electricity service providers continue to face substantial challenges in developing countries and then discuss areas in which additional research is needed. First, Section 2 introduces some of the impediments to maximizing the benefits from electricity: unreliable and poor quality electricity services and uncertainty in the adoption and use of energy efficient technologies. Section 3 provides details on issues plaguing electricity utilities’ cost recovery in developing countries. Next, Section 4 discusses factors that make predicting demand for electricity services more complicated and therefore more difficult, including the changing climate. Section 5 discusses climate mitigation through decentralized renewables and the associated challenges for those service providers. Section 6 provides studies of cases in South Asia to illustrate why additional work on adaptation in the electricity sector is needed. Section 7 concludes.

2 Maximizing the Effects of Electricity Access

Although electricity access has substantially improved in recent decades, certain factors impede consumers from maximizing the benefits from electricity connections. Here, we focus on two such factors. The first, poor electricity service quality and reliability, means that there are fewer hours per day when consumers can fully power their appliances and equipment. The second, low adoption and use of energy efficient technologies, means that customers could be consumer the same quantity of electricity services at a lower cost. We describe both of these in more detail below.

2.1 Reliability and Service Quality

Hundreds of millions of households that are connected to electricity grids only receive low-quality and unreliable electricity services (Ayaburi et al., 2020). Electricity reliability and service quality (i.e., voltage fluctuations) are substantially worse in low and lower-middle income countries than in high income countries. There are a number of typical causes of outages and voltage fluctuations in such settings, including load shedding (Burgess et al., 2020) and insufficient investments leading to low quality (McRae, 2015b) or overloaded infrastructure that exceeds the systems' technical capacities (Carranza and Meeks, 2021). The evidence as to how outages and poor service quality affect firms and households in developing countries is evolving, with important implications as to how electricity utilities and planners approach both planned (i.e., loadshedding) and unplanned outages.

Some prior research has focused on the potential for firms to adapt to frequent outages through investments in self-generation (Steinbuks and Foster, 2010). Self-generation may be one reason as to why some prior research on the effects of outages ad electricity shortages found relatively small or statistically insignificant effects of outages (see, e.g., Fisher-Vanden et al., 2015; Allcott et al., 2016; Abeberese, 2017).

More recently, macro evidence indicates that, in the long-run general-equilibrium, outages substantially limit economic output of firms (Fried and Lagakos, 2023). These findings are from steady state model in which the consistent provision of electricity allows productive capital to avoid idling (due to the absence of outages) and firms demand more productive capital with that expectation. These findings – that firms, with the certainty that they will have no outages, will demand dramatically more electricity services (Fried and Lagakos, 2023) – has implications for utilities that employ loadshedding policies, which are a complete stoppage in electricity distribution to parts of grid when the electricity supply is less than the quantity of electricity demanded. These results are also informative to regulators as they consider eliminating or changing loadshedding policies in the future.

Until relatively recently – and in contrast with other sub-categories of research within the overarching literature on electricity and development – much of the evidence on the effects of reliability changes (or shortages in electricity supply) has centered on firms rather than households. Yet, service quality matters for households as well (see, e.g., Chakravorty et al., 2014) and even a relatively small additional amount of outages in a month lead to a non-inconsequential reduction in electricity consumption (Khanna and Rowe, 2024). Indeed, evidence on household willingness-to-pay indicates substantial demand for reductions in electricity outages and more hours of electricity services per day (Alberini et al., 2020; Deutschmann et al., 2021; Meles et al., 2021; Hashemi, 2021; Khanna and Rowe, 2024).

Although outages have been the focus of much of the existing economics research, poor electricity quality, in the form of voltage spikes and surges, are prevalent in many low and middle income countries (Jacome et al., 2019). Poor electricity quality can be costly, as it can damage appliances or prevent consumers from adopting or using some appliances. New evidence by Berkouwer et al. (2024) indicates that some infrastructure improvements, such as adding new transformers within distributions lines to reduce the distance between consumers and their nearest transformer (as well as reduce the burden on the existing transformers), may only lead to small improvement in voltage quality. The authors found no economic effects of the infrastructure improvement on consumer outcomes in Accra, Ghana; however, they acknowledge this might be due to insufficient improvements in the service quality.

Meeks et al. (2023) complement the above mentioned evidence on electricity service quality with a randomized experiment in the Kyrgyz Republic. The intervention randomly introduced smart meters, which led to significantly fewer voltage fluctuations per day. The authors argue that the improvement occurred because the smart meters allowed the consumer to hold the utility accountable to meeting the voltage quality standards required by the regulator. The experimental design permits the estimation of the household response to the service quality improvements. Treated households increased their billed electricity consumption during the winters, with evidence that this occurred through an increase in electric heating. These results are consistent with the willingness-to-pay results discussed above. However, further heterogeneity analyses suggest that the increase in consumption of electricity services among renters – who are less likely to pay the full cost of additional consumption of electricity services than homeowners – was four times that of the increase among homeowners. These results suggest that residential consumers may be sensitive to the additional cost of electricity services consumed that may come with more reliable service provision.

There is a relatively little causal empirical evidence on potential ways to reduce demand and improve service quality. Ahmad et al. (2023a) show that the installation of theft-resistant cables in Karachi, Pakistan reduced loadshedding hours, after losses decreased; this effect was a function of the utility's policy on assigning loadshedding based on losses. Carranza and Meeks (2021) and Khanna et al. (2024) complement those quasi-experimental results with randomized experiments testing approaches to reduce load. Carranza and Meeks (2021) found that reducing the load at transformers through high saturation of energy efficient technologies within the Kyrgyz Republic led to fewer unplanned outages. More recently, Khanna et al. (2024) randomly tested smart switches – a demand-side management tool – that controls "switch-off" events for appliances such as air conditioners within households. Their results provide insights into hour automation and financial incentives can be employed to avoid outages by reducing demand when needed.

With recent efforts around the world to "electrify everything" – from cooking and water heating to vehicle charging – the attention to reliable electricity service is important not only for adoption of basic appliances, but for climate mitigation and the reduction of fossil fuels use as well. More research is needed to understand the extent to which poor service quality is currently impeding the adoption of such technologies. Given how expensive improving service quality may be, it will be important to understand whether there are tipping points in longer-run service quality that determine adoption of these technologies.

2.2 Energy Efficiency

Energy efficiency is often promoted as a way to deliver sustainable development: permitting increased consumption of electricity services while limiting emissions of harmful pollutants. The International Energy Agency (IEA) declared that energy efficiency could play a major role in climate change mitigation, providing approximately one third of the necessary reductions in greenhouse gas emissions (IEA, 2018).

Indeed, energy efficient technologies were expected to reduce the quantity of electricity (in kWh) consumed – relative to an inefficient version of the technology – as an energy efficient appliance or upgrade can permit end-users (whether they are residential or industrial) to consume the same services with less electricity. In other words, the implicit price per hour of that service (whether it be lighting services, heating services, or some other electricity service) is lower for an efficient version of an electric appliance than it is for the inefficient version (Fowlie and Meeks, 2021).

Household electricity consumption is determined by appliance use on both the extensive and intensive margins. The extensive margin is the adoption of additional appliances (e.g., televisions, refrigerators, washing machines, irons) or light bulbs. The intensive margin is the extent to which the adopted appliances and lighting are used (e.g., how many hours per day is the television or washing machine used). The extent to which energy efficient technologies affect consumption of electricity services depends on both the extensive (adoption of the energy efficient technologies) and the intensives margins (use of the energy efficient technologies). We discuss the evidence on both margins below.

2.2.1 Adoption of Energy Efficient Technologies

The few existing experimental studies on demand for energy efficient technologies are focused on lighting technologies. Consistent with the increased services enabled through energy efficiency in developing countries, and findings for energy efficient lighting in the Kyrgyz Republic specifically (Carranza and Meeks, 2021), Fowlie and Meeks (2021) provide evidence that households were willing to pay a positive price for energy efficient bulbs in that same setting. Using randomly varied prices, they found that potential customers were very sensitive to prices; take-up dropped substantially for the randomly drawn prices that were higher than the prices for which households could purchase incandescent lightbulbs in the local markets at the time. However, it is worth noting that those data were collected in 2013, when energy efficient light bulbs were still new (and the electricity savings potential less known) among the study population.

Indeed, experiments have shown that information on the effects of and benefits from energy efficient lightbulbs is important for adoption. Toledo (2016) found that – among residents of favelas in Rio de Janeiro, Brazil – environmental messages in addition to subsidies significantly increased take-up of energy efficient lightbulbs. Further, an experiment implemented in China found that potential consumers were imperfectly informed on the benefits from energy efficient lightbulbs. Potential consumers randomly provided with information on the energy cost savings from the efficient technology had significantly higher demand for the lightbulbs (Beattie et al., 2022).

Together these results indicate that decreasing prices and learning about the technology are important aspects of energy efficient lightbulb adoption. Yet, we still know relatively little about the drivers of demand for larger energy efficient appliances, such as air conditioners and electric stoves, which require substantially larger financial investments. We will return to this topic in the section on responses to changing temperatures and climate.

2.2.2 Use of Energy Efficient Technologies

Evidence from low and lower-middle income countries has shown that the effect of energy efficient technologies on electricity consumption is complex. For a number of reasons, the adoption of these technologies might not lead to the electricity savings expected.[5] Davis et al. (2014) provided early evidence of this phenomenon through a quasi-experimental analysis of an appliance replacement program in Mexico. They found that the reductions in electricity consumption due to refrigerator replacements were only one-quarter of the decrease expected based on prior engineering estimates, whereas air conditioner replacements actually increased electricity consumption. The ex ante engineering calculations assumed that the old refrigerators being retired would be older and less efficient than the appliances that actually were traded in.[6] In the case of space cooling, Davis et al. (2014) provide evidence of a more classic rebound effect – the energy efficient air conditioners were used for more hours per day than the air conditioners that they replaces, because they providing cooling services at a lower cost.

Evidence from randomized experiments in India (Ryan, 2018) and the Kyrgyz Republic (Carranza and Meeks, 2021) provide two additional explanations as to why the effects of energy efficient technologies on electricity consumption might be lower than engineering predictions. Following energy consultations that were randomly provided to Indian manufacturing plants, Ryan (2018) found that treated plants actually increased (rather than decreased) energy use in their production processes. With additional analyses and a model of complementary inputs into the production process, the author provides evidence that the energy serves as a complement to skill and capital. Thus the consulting information from the treatment increased energy use, but allowed the plants to become more productive.

Carranza and Meeks (2021) used a two-staged randomized saturation design, which allows them to estimate both the aggregate effects from energy efficient lighting within the electricity distribution system as well as at individual homes. The authors find that transformers (the unit within the electricity distribution system that serves a neighborhood) in which a higher intensity of households are treated experience less congestion in the distribution system. This leads to fewer electricity outages in households served by those transformers, and therefore additional hours during which households can consume lighting services.

[5] There is a substantial literature on the economics of energy efficient technologies, which we do not cover here. For a brief summary of that literature, see Fowlie and Meeks (2021).

[6] Somewhat similarly, Davis et al. (2020) found that the effects from energy efficient building weatherization improvements in Mexico did not meet those expected based on ex ante engineering calculations.

As a result, the energy efficient light bulbs only have the expected impact in the transformer with the lower treatment intensity, where there were no aggregate effects on outages.

Taken together, these empirical findings indicate several channels through which energy efficient technologies do not lead to the expected reductions in electricity consumption. However, some of these channels indicate that the energy efficient technologies aid development, in that the end users can consume additional electricity services at a lower cost.

Differences in the effects of energy efficiency over time, space, and across technologies are important for utility planners to understand. Promoting energy efficient technologies might more optimal in some situations than others. If energy efficiency can lead to increased electricity consumption in some situations, the they would not help a utility that needs to reduce peak demand. Yet promoting energy efficient technologies might be useful at times when policy or technological changes (e.g., when tariff structure changes or rates increase or smart meters are installed) may lead to higher electricity bills for consumers. In such cases, energy efficiency could mitigate bill increases (holding consumption constant) and reduce the likelihood of public opposition or protest to such policy or technological change. Alternatively, energy efficient technologies introduced to consumers served by decentralized renewable energy sources might allow more households to be connected to and served by a single mini-grid. How consumers respond in these scenarios remains open for future study.

3 Recovering Utility Costs

A challenge that commonly confounds the electricity sector in developing countries – and electricity service providers, in particular – is difficulty recovering the full costs of electricity services. Burgess et al. (2020) detail how low bill payment and high electricity theft contribute to this cost recovery problem and, with low recovery, utilities are challenged to provide reliable, high quality electricity services. In this section, we discuss recent causal evidence – from both quasi-experiments and randomized experiments – on ways to address bill payment and theft.[7]

[7] Burgess et al. (2020) note a third factor contributing to low cost recovery in developing countries: subsidized electricity prices. We do not address that here; however, we note that there is a body of research that studies the consumer response to pricing reforms in developing countries (see, e.g., McRae, 2015a;

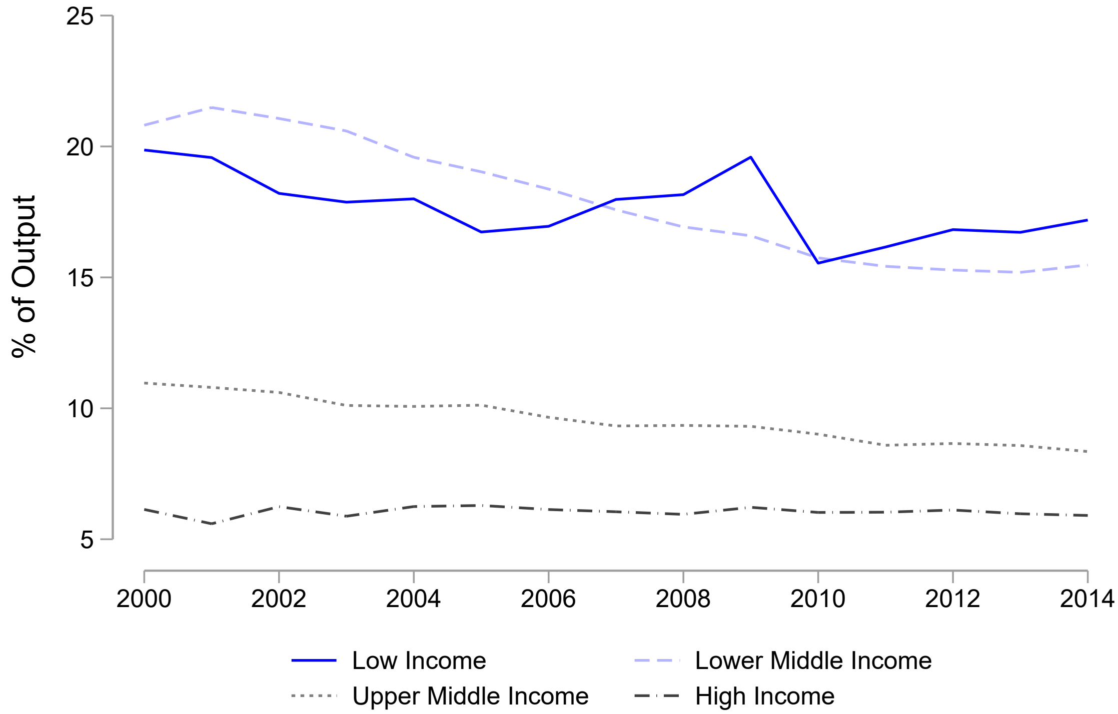
Non-payment of bills – when end-users consume electricity services and are billed for that consumption, but the bill is not paid – is a substantial problem for electricity utilities serving end-users that are poor. This issue is particularly acute therefore in low and lower-middle income countries. Historically, utilities could manually disconnect end-users if they have not paid their bills by a particular date, but manual disconnection is costly to the utility (e.g., requiring a crew of employees and a vehicle dispatched to the end-users' premises) and requires a similarly costly re-connection once the bill is paid. If non-payers are not disconnected, there is little enforcement of requirements (and therefore little incentive) to pay one's bill.

Relatively recently, some utilities have turned to a technological change – replacing the post-paid, analog meters with prepaid meters. Prepaid meters require that end-users pay for units that will be consumed in advance of the electricity being provided. By virtue of not providing electricity services until payment is received, prepaid meters nullify the need for manual disconnections. With the increase of prepaid meters, so too has the evidence increased, both through quasi-experiments (Beyene et al., 2022b) and randomized experiments (Jack and Smith, 2020), on their effects. Yet, the finding that prepaid meters led to a reduction in the quantity of electricity services consumed (Jack and Smith, 2020) may be of concern in some settings, such as settings in which utilities have invested in increased generation and are therefore trying to grow consumption. Moreover, it is not obvious that prepaid meters would help in settings with high electricity theft, because end-users circumvent the meters, connecting illegally and directly to the low-voltage transmission lines. As a result, more research is needed on ways to increase bill payment in areas with high theft.

Electricity theft occurs when end-users are able to consume electricity services without their consumption being billed. By passing electricity meters is not the only route to steal electricity; meter tampering and irregular billing (often with meter readers receiving some sort of bribe or side payment) are also sources of theft (see, e.g., Alam et al., 2004; Abdollahi et al., 2020; Savian et al., 2021). These are not uncommon occurrences in many low and lower-middle income countries, and the main reason that transmission and distribution losses are several times higher there than in high income countries (IEA Statistics, 2018). Figure 1

McRae and Meeks, 2016; Alberini et al., 2022; Beyene et al., 2022a).

Figure 1: Electric power transmission and distribution losses (OECD/IEA, 2018)



Notes: Calculations made using OECD/IEA data (OECD/IEA, 2018). Includes losses in transmission between sources of supply and points of distribution and in the distribution to consumers, including pilferage.

illustrates both the differences in losses by country income groups as well as the persistence of those differences over time.

Utilities face difficulties in cracking down on theft, however, as locating manipulated meters and illegal connections typically requires manual inspections (and therefore teams of employees to go physically to premises). Politically influential individuals may also impede theft prevention efforts. Some utilities have used reward and reprimand policies to allocate loadshedding when electricity supplied is insufficient to meet demand (Ali et al., 2023).

There is recent evidence that a purely technological intervention – replacing bare distribution wires with aerial bundled cables (ABCs), which are theft-resistant – can reduce theft and losses. Through a study of ABCs installed over time in Karachi, Pakistan, Ahmad et al. (2023b) show that these theft-resistant cables reduced theft by increasing the number of formal customers and increasing the billed consumption by the formal end-users. However, customers in areas in which these theft-resistant cables were installed were more likely to believe that the utility makes billing errors, which suggests that this technology may not be a panacea for utility cost recovery.

4 Predicting Future Demand for Electricity Services

The push to increase electrification rates in many developing countries has required massive investments in electricity generation. In many countries, additional investments are still needed to increase generation capacity (as well as to the extend the transmission and distribution systems). In other countries, surpluses in electricity supplies exist following recent new construction of generation. Not infrequently, debt is incurred to finance such construction. How and when the debt is repaid depends on the income of the utility, which is also affected by the issues of electricity losses and revenue recovery described earlier, as well as the demand for electricity services. A common struggle for utilities is that predicting future electricity demand in low and middle income countries can be challenging, and for several reasons, even more uncertain than in high income countries.

As we mentioned earlier in the discussion of energy efficiency, electricity consumption is determined by appliances at both the extensive (i.e., appliance and equipment adoption) – and intensive margins (i.e., use of those appliances and equipment). Electricity service providers may be uncertain regarding the extent to which newly-electrified consumers (i.e., those consumers who change from no electric grid connection to having such a connection) will adopt (extensive margin) and use (intensive margin) lighting and appliances. If infrastructure brings electricity to the poorest households, how will they respond? The most basic questions surround whether newly electrified households will buy appliances beyond the most basic items such as light bulbs and cell phone chargers, how many appliances will these households buy, and how much will they use them. Lee et al. (2017) find that providing electricity connections to households that were "under the grid" – households that were not themselves currently connected to the grid, but were close to existing to transformers in areas that were already served by the electric grid – did not lead to large increases in the appliances owned or use of appliances (as indicated by their low electricity bills).[8] These

[8] Through an experiment randomizing residential connections to the electric grid in rural Kenya, Lee et

are some of the core questions addressed in the recent experimental literature estimating the effects of household electrification (see Lee et al., 2017, 2020) and already covered in existing review articles, so we will not go into further detail here.

We note, however, that there is a relatively nascent literature that informs efforts to electrify the residential (e.g., electric cooking and water heaters) sector (see e.g., Pattanayak et al., 2019; McRae and Wolak, 2021; Gould et al., 2023). This is a distinctly different than the literature focusing on first time adoption of appliances, as this work addresses shifting consumers to electric cooking from methods employing fuels that require the burning of fossil fuels (e.g., fuel wood, charcoal, and LPG). There is still a great need for research to understand the factors affecting adoption and use of electric cooking, as well as the effects it has on both households (e.g., health impacts) and the electricity distribution system (e.g., electric load).

In the subsections that follow, we focus on two additional sources of uncertainty for the utilities regarding the demand for electricity. First, as countries develop and shift from low income to middle income, changes in consumers' income may affect the appliances owned (extensive margin) and how they are used (intensive margin). Second, it is not obvious the extent to which consumers may or may not adopt and use appliances for cooling and heating services as temperatures fluctuate and climate changes. In the rest of this section, we review evidence on these sources of uncertainty in predicting future electricity demand.

4.1 Changes in Income or Wealth

It is generally accepted that as households' incomes increase, they are likely to purchase additional new durable assets, including new electricity-using appliances (Wolfram et al., 2012). Yet, evidence shows that this relationship is nuanced, both non-linear in nature and sensitive to credit constraints (Gertler et al., 2016). The shape of this relationship suggests

al. (2017) are able to test the extent to which electrifying households that are "under the grid" leads to economics effects. At baseline (pre-treatment), the unconnected households already had some basic lower-wattage appliances (mobile phone chargers, radios), which could be powered with rooftop home solar systems (not the higher-wattage appliances like TVs or electric irons). Yet, at the post-intervention follow-up 18 months later these households had just a small increase in appliances. There was no explosive increase in the adoption of appliances, either lower- or higher wattage. And the impact of treatment led to only a small electricity bill, indicating that consumers used their appliances sparingly.

that household energy use grows faster for those exiting poverty – as they purchase basic appliances, such as refrigerators, for the first time – than for those higher in the income distribution (Wolfram et al., 2012).

Air conditioners are typically not among the very first appliances that households purchase as their incomes increase, so investments in cooling for climate adaptation require a separate investigation. Randazzo et al. (2023) provide quasi-experimental evidence on the affects of changes in income, in the form of remittances, on the adoption of air conditioners in Mexico. The authors find that additional remittance income increased the probability of air conditioner adoption, but only in the coastal areas, which have hotter temperatures. Furthermore, this effect is driven by adoption among low and middle income households (not high income households), which the authors interpret as suggestive evidence that higher income households do not need remittances to purchase air conditioners (and the authors note that they are also less likely to receive remittances).

These findings underscore an intertwined relationship between income and temperature that is driving air conditioning on both the intensive and extensive margins, as we discuss below.

4.2 Changing Temperature

A big source of uncertainty for electricity utilities – in the face of climate change – is how the population and electricity consumers will adapt as temperatures increase. Indeed, as household incomes and temperatures increase, so too has adoption of air conditioners worldwide (Biardeau et al., 2019). Households can adapt to increasing temperatures by consuming cooling services, such as fans and air conditioning. These adaptations can require either intensive (i.e., using an air conditioner or fan already owned more than the household previously had) or extensive margin (i.e., buying a new air conditioner or fan) changes. Indeed, Barreca et al. (2016) showed that the historical adoption of air conditioners in the United States reduced the mortality due to high temperatures within the country.

Higher temperatures are known to reduce worker productivity in developing countries. Firms (and/or their employees) may adapt to climate shocks, particularly changes in temperature. For example, Adhvaryu et al. (2020) show that lowering the ambient temperature in Indian garment factories – which is a co-benefit from the installation of energy efficient light bulbs – increased worker productivity. Yet, it would be a mistake to assume firms in hot locations will all invest in air conditioning, as it has been shown that firms may choose not to employ methods of climate control if the value of increased productivity per worker from cooling does not outweigh the costs (Somanathan et al., 2021).

In fact, billions of people live in low and middle income countries in tropical climates without air conditioners currently (Biardeau et al., 2019). Davis et al. (2021) use household-level microdata from 16 countries with a sample that it representative of more than 50% of the world's population to highlight the interactions between climate and income in the adoption of air conditioners. They find that although both income and climate are important for explaining future predicted increases in air conditioner ownership, their models imply that increased in income are more important than increasing temperatures. High income households, both those in high income countries and the high income households in low income countries, are most likely to own air conditioners. Given the increases in temperatures expected in many low income countries, these results indicate that large populations will be unlikely to adapt to increasing temperatures through air conditioning.

A relatively small number of papers have investigated this extensive margin in middle income countries. Auffhammer (2014) focuses on adoption of air conditioners in China. The paper is motivated by the rapid increase in air conditioner ownership that occurred as China developed and focuses on this extensive margin of air conditioners. Analyses using province level data on both temperature, income and air conditioner adoption indicate that adoption is linked to both income and weather.

McRae (2023) studies the relationship between temperature and air conditioning on both margins (adoption and electricity consumption) in Colombia. He finds some evidence that the lower income households to some extent – all be it not fully – narrow the gap between them and higher income households in air conditioning ownership over time. He finds that electricity consumption increases with higher temperatures, but the largest increased are among the high income households in the hottest regions of the country.

On the intensive margin, Li et al. (2019) use data on daily household electricity consumption in the Chinese city of Shanghai to estimate how consumption alters in response to changes in temperature. They do not have the data to look at extensive margin (ownership), and therefore focus on the intensive margin looking at the relationship between temperature and electricity consumption, given a fixed appliance stock. They find a U-shaped relationship between electricity consumption and daily temperature, which is steeper for hot days than cold. The existence of the relationship between cold temperatures and electricity consumption is indicative of electric heating, which is noteworthy.

Although electric heating is not uncommon to meet heating needs in locations unserved by gas infrastructure – which includes developing countries – relatively little evidence exists on electric heating on either the extensive or intensive margins. Beyond Li et al. (2019), there is evidence of a relationship between colder temperatures and hourly electricity consumption in South Africa Berkouwer (2020). And electric heating is the reason that electricity bills are approximately two to three times higher in the winter than in the summer in the Kyrgyz Republic (Carranza and Meeks, 2021).

Importantly, we know relatively little about how poor households – particularly in low and lower middle income countries – will adapt to temperatures increasing with climate change, particularly if they are not adopting air conditioners. This is an important gap in the literature, given seven of the ten top ranked countries for total cooling degree day exposure are lower middle income countries (Biardeau et al., 2019).[9] Further, recent surveys show that poor households in some lower and lower-middle income countries – that also face extreme heat – still rarely have air conditioners. Further understanding adaptation to increasing temperatures in such areas, and the technologies that can be used to increase resilience, will certainly be a crucial area for future research.

Beyond adapting to increasing temperatures, there is relatively little existing evidence on other forms of adaption in the electricity sector. We will discuss additional gaps in understanding adaptation in the electricity sector in greater detail in Section 6.

[9] Biardeau et al. (2019) calculate total cooling degree day exposure of cities and countries as the product of population and annual CDDs.

5 Adopting Climate Mitigating Technologies

Uncertainty around household and firm demand for and use of such climate mitigating technologies provides another challenge for the electricity sector in developing countries, as these technologies may or may not also affect the demand for other services, such as those provided by the electricity grid.

Developing countries – particularly those we are focusing on in our case studies, Nepal and Pakistan – are responsible for an extremely small fraction of the historical CO_2 emissions worldwide. At current levels of development, there is not much space for discussion on climate mitigation in many developing countries. Arguably, a main exception is in the context of climate financing in general. For example, the Clean Development Mechanism (CDM) was created to both assist in the development of low and lower-middle income countries, while providing high income countries with opportunities to meet the commitments that they made under the Kyoto Protocol. Through the CDM, high income countries invest in particular projects for which they earn certified credits. Many of these projects have focused around deploying climate mitigating technologies in developing countries, such as energy efficient technologies (discussed earlier in this paper) and decentralized renewables.

Decentralized renewable energy technologies such as microhydro or solar mini-grids have been lauded as ways to reach remote, hard to reach populations at a lower cost than than expanding the central grid (Meeks et al., 2021).[10] The extent to which populations will adopt these technologies remains an important question for planners and a source of uncertainty for electricity utilities considering making plans to expand either electricity generation or transmission and distribution networks.

What do we know about the demand for decentralized renewables in developing countries? Through a randomized experiment in India, Burgess et al. (2023) show that the demand for solar microgrids is highly elastic: when the grid is available and subsidized, it is highly favored by households. This grid preference is consistent with their findings that the grid increases household surplus more than off-grid solar does.

[10]Such mini-grids are typically powered by a renewable source that is small in scale and located in close proximity to the load center. A mini-grid typically serves a small fraction of consumers that a centrally-managed national or regional grid could serve.

Factors impacting the demand for smaller scale renewable energy technologies (e.g. solar lanterns, kits, and household solar panels) have been experimentally measured in several studies (see, e.g., Grimm et al., 2020; Wong et al., 2022; Alem and Dugoua, 2022; Mahadevan et al., 2023). These technologies are perhaps less likely to be a substitute for the electricity grid than a solar microgrid, for example. However, these smaller-scale technologies can serve as a stop-gap either during short-term outages or in the longer run before the grid or a microgrid provides electricity on a larger scale.

Demand for these technologies is, by and large, sensitive to price. For example, through an experiment in Bihar, India, Wong et al. (2022) found that neither household wealth nor perceptions regarding lighting substantially affected demand for solar lanterns; vouchers reducing the price of the lanterns had the largest effect on adoption. Once some households adopt a solar lantern, others may learn and also be induced to adopt. Research by Alem and Dugoua (2022) provides evidence that peer effects significantly affect WTP in Uttar Pradesh, India.

Yet other factors also can play a substantial role in increasing willingness to pay and overall adoption. Grimm et al. (2020) found that relaxing liquidity constraints increased WTP for low wattage solar kits by up to 13% in Rwanda. When such constraints are already addressed, such as through pay-as-you-go models, information constraints may still limit adoption. Mahadevan et al. (2023) found that a mobile phone application designed to standardize information disseminated in the sales process and alleviate information asymmetries between solar panel sales agents and potential customers increased the latter's intent-to-adopt (a stated preference measure).

Much of this existing evidence on decentralized renewables is from India where, as Burgess et al. (2023) note, the government has made a big push in extending the national grid in recent years. There is room for additional evidence both from different countries, particularly those in which extending the central grid is less feasible than in India, as well as more research on larger-scale decentralized renewable technologies such as microgrids. Additional microgrid-related questions that require further study – and are of importance for the electricity sector – include: (i) does demand vary by different types of ownership models (e.g., community owned versus privately owned)? (ii) when the grid does expand, can these systems be successfully integrated into the grid and, if so, what is required?

6 Adapting to Climate Change: Cases in South Asia

As we discussed in Section 1, the Hindu Kush Himalaya region, which spans 8 Asian countries, is both important ecologically and markedly vulnerable to the effects of climate change. Although many countries in this region experienced increases in electricity access and services in recent years, their vulnerability to climate change puts both those gains – as well as the associated development – at risk.

In the subsections that follow, we discuss the cases of Nepal and Pakistan to illustrate how this vulnerability to climate change puts the electricity sector specifically at risk in these countries. We draw on similarities between and note differences across the two countries.

6.1 Case of Nepal

The country's recent development progress is summarized by Nepal's recent shift in its economic status from low income to lower-middle income status in 2020. However, there is concern that climate change will undo or reverse these recent development gains (World Bank, 2022b).

Below, we present background information on the country's electricity sector, an overview of the climate hazards to which the country's electricity sector is particularly vulnerable, and then review cases of prior climate damage within the sector.

6.1.1 Background on Electricity in Nepal

Electricity access in Nepal has increased impressively in recent decades. As of 2021, 89.9% of Nepal's population had access to electricity, up from 68.6% in 2010 and 29.9% in 2000.[11] With recent rural electrification gains, electrification rates in rural areas is now close to that of urban populations (IEA et al., 2023).

[11] As of 2019, the population of Nepal was 28 million people, 80% of which is located in rural locations (World Bank and ADB, 2021a).

The Nepal Electricity Authority (NEA) is responsible for the country's main electricity grid. The vast majority of the generation for the national grid is hydropower. Electrifying remote and mountainous parts of the country is challenging and expensive to reach with the central grid. To achieve rural electrification goals, the country has relied heavily on off-grid sources, particularly microhydro mini-grids (Meeks et al., 2021).

After many years of unreliable service and frequent loadshedding, NEA has relatively recently improved electricity reliability. For many years, the country extensively employed loadshedding in order to address insufficient electricity generation that fell far short of meeting electricity demand. These years of loadshedding took an economic toll on the country. Timilsina and Steinbuks (2021) estimated that absent loadshedding, the country's annual GDP would have grown by approximately 7 percent more than it did between 2007 to 2017. NEA was able to drastically decrease loadshedding beginning in 2017, in large part due to investments in additional hydropower generation (Timilsina and Steinbuks, 2021). The new generation was largely due to private sector investments that enabled installed capacity to grow to 1,397 WM in 2021 (from less than half that in 2010) (World Bank, 2022b).

These recent investments in new hydropower generation are important for the country's future economic plans. In fact, Nepal has moved from struggling to meet its own demand to planning future electricity exports. By 2022, the country was expected be in a surplus (World Bank, 2022b), with reports that the Government of Nepal plans to export 10,000 MW of electricity in the near future. Yet, erratic precipitation – and the potential for low rainfall to reduce hydropower generation – has some concerned regarding the country's future export potential (Poudel, 2023). We discuss that climate concern, as well as other potential issues for the electricity sector, in the the following section.

6.1.2 Current and Expected Future Climate Issues

Much of Nepal is considered disaster prone (World Bank, 2022b). Of all climate-related disasters, floods and landslides are currently the most common hazards in the country and affect the largest number of people. In recent years, flooding frequency has doubled, while erosion and landslides have also increased. Climate change is affecting the country's hydrology and is expected to increase the country's disaster risk in the future (World Bank and ADB, 2021a). Although Nepal's Ministry of Forests and Environment has noted that loss and damages are difficult to estimate due to challenges in attributing specific events to climate change and a lack of a global approach to measuring such loss and damages, the ministry argues that the loss and damages due to climate change have increased in recent years (and increases are expected to continue) (Goverment of Nepal, 2021).

Temperature and Water Flows

Future climate change is expected to impact both temperature and water flow – including glacial melt and precipitation – in Nepal.

First, temperature is expected to increase in Nepal and these increases are expected to be greater than the global average (World Bank and ADB, 2021a). Yet, it is not obvious how temperature increases will affect electricity consumption in the country, as some common adaptation measures, such as air conditioning, may be out of reach for much of Nepal's population (World Bank and ADB, 2021a).

Temperature changes are also expected to affect the country's water flow. Temperature increases are expected to be largest in the winter months and therefore substantially affect the melting of glaciers (World Bank and ADB, 2021a). Both glacial melting and the increased frequency rainfall extremes mean that flooding is expected to increase. Two types of flooding that are of particular concern in Nepal: river flooding, which is when the water levels rises above the river banks such as during periods of extreme rainfall, and glacial lake outburst flooding (World Bank and ADB, 2021a), which we explain further below.

Changes in precipitation are also expected to affect the country. Rainfall events will increase both in frequency and intensity (Merzdorf, 2020). Furthermore, NASA research on the relationship between precipitation and landslides in the region (China, Tibet, and Nepal) indicates that landslide risk will increase as a result (Merzdorf, 2020). Landslides can lead to other (cascading) disasters, such as floods and can wipe out infrastructure or even entire communities as we will discuss in the section on electricity infrastructure.

Glacier Lake Outburst Floods (GLOF)

Glacier lake outburst floods (GLOF) are major climate hazards in Nepal, and the HKH region more broadly. GLOFs are floods that occur when an immense quantity of water – that was previously dammed and held in place by a glacier – breaks free. GLOFs have been recorded for hundreds of years and are not a new concern for Nepal. As of 2011, the country had been affected by at least 24 GLOF events, more than half of which were believed to have occurred within the country itself (International Centre for Integrated Mountain Development , ICIMOD). Approximately 70% of documented GLOFs were triggered by a release from ice dammed lakes (Carrivick and Tweed, 2016).

GLOF occurrences, however, are believed to be increasing in frequency and this increase associated with greater glacial melt due to climate change. As temperatures increase globally, glaciers are melting; the number and size of glacial lakes is increasing and this water eventually must go somewhere (Carrivick and Tweed, 2016).

Carrivick and Tweed (2016) have estimated the "societal damages" from GLOFs around the world. There is spatial variation in the damages caused by GLOFs due to differences in where they occur and their proximity to human populations and important infrastructure. Yet, overall GLOFs have caused deaths, injuries, evacuations and displaced people, destroyed crop land, killed livestock, and damaged buildings and infrastructure. Through their analyses, the authors determined that "central Asia" – a region that they designate to include Bhutan, India, Kazakhstan, Kyrgyzstan, Nepal, Pakistan, Tajikistan, and Tibet, and spanning much of the HKH region – is the region that is most vulnerable to extreme impact from GLOFs. Further, country-level estimates indicate that Nepal has 22% of the total global GLOF damage, which is the highest of any country (Carrivick and Tweed, 2016).

6.1.3 Electricity Infrastructure Vulnerability to Climate Hazards

According to the Government of Nepal, floods and landslides regularly inflict large and costly damage on electricity infrastructure in the country (Goverment of Nepal, 2021). Such damages and their effects on electricity service provision and reliability are cause for concerning given both the negative effects that prior load shedding had on the country's economic development (Timilsina and Steinbuks, 2021) and the extensive costs required to repair damaged infrastructure (Shrestha, 2022).

Below, we discuss some of the recent evidence of such damages to three types of electricity infrastructure: small to large hydropower plants that serve the main electricity grid, microhydro power plants that serve remote communities through mini-grids, and transmission and distribution systems.

Small to Large Hydropower Plants

The majority of Nepal's hydropower is run-of-river. This form of hydropower generation does not include dams and water storage, which makes the relationship between water and electricity all the more complex. Run-of-river hydropower is typically considered better for the environment due to lower GHG emissions and less direct ecological impacts. However, these hydropower systems are largely unable to provide co-benefits that would increase climate adaptation and resilience, such as flood mitigation (World Bank, 2022b). The run-of-river design also means that if the water flow into the plants is insufficient, then hydropower systems cannot generate electricity (Goverment of Nepal, 2021). Unpredictable precipitation (both under- and over-) and water flows could jeopardize Nepal's plan to export electricity in the future. Even hydropower with storage is susceptible to this concern, if precipitation and water flows are insufficient for a long enough time period.

These hydropower plants, regardless of whether they are run-of-river or dammed, are susceptible to damage due to where they are built in the HKH region, the current hazards in the region, and expected climate change. As discussed earlier, excessive precipitation is expected to increase and this rainfall can both damage dams and other hydropower system components (i.e., hydro turbines) (Goverment of Nepal, 2021). Excessive rainfall can also cause landslides, which can then cause damage the infrastructure (Shrestha, 2022).

There is a history of damage to hydropower infrastructure from flooding and GLOFs in Nepal. In 1981, a GLOF caused major damage at the Sun Koshi Hydropower Plant (Goverment of Nepal, 2021). A GLOF also damaged the Namche Small Hydroelectric Project in 1985, which was still under construction at the time. Hydropower projects can be damaged by GLOFs originating a substantial distance away and from other countries (i.e., one GLOF in Tibet damaged the Bhote Koshi Project in Nepal) (Goverment of Nepal, 2021). Furthermore, not only can flood waters damage the hydro infrastructure, the sediment, debris, and landslides generated from a GLOF can cause blockage behind the dams, leading to damage.

In 2014, the Sun Koshi River destroyed both the Bhotekshi and the Sunkoshi hydropower plants in this manner and killed hundreds of people as a result (Goverment of Nepal, 2021).

Climate-related hazards made 2021 a particularly destructive year. After the early arrival of the monsoon and abnormal monsoon rains eroded glacial ice and induced tremendous snow melt, a moraine lake dam released water flooding downstream. The waters and debris passed through the area of a prior landslide and induced a new landslide, severely flooding the community of Melamchi. These floods had devastating impacts for the communities, with people injured, killed, and displaced. Furthermore, the floods destroyed settlements, as well as infrastructure that included both hydropower plants and distribution system electric poles (Bikash Maharjan et al., 2021).[12]

Damage to hydropower infrastructure, unfortunately, has not been infrequent in Nepal. The Independent Power Producers Association of Nepal (IPPAN), the organization representing private power producers in the country, reported that more than 20 projects sustained damage due to floods and landslides in 2021 alone (Shrestha, 2022). Furthermore, IPPAN reported that at least 30 hydropower projects – just within the eastern part of the country alone – were damaged by floods and landslides in the 2023 monsoon, as of July (midway through the expected season). The organization estimated the direct damages to those projects – which account for 463 MW of rated capacity – to be approximately 8.5 billion NPR (63 million USD). The hydro projects are then offline during repairs, which additionally hurts the project's finances (in addition to the repair costs) (Poudel, 2023).

Microhydro Power Plants

As previously mentioned, decentralized renewable energy sources have provided a key way to electrify rural populations in Nepal at a cost lower than that required to extend the central electric grid. Microhydro power plants, as well as the populations served by them, are sensitive to climate change for multiple reasons. First and foremost, they are built within the high hills and low mountain areas, which are particularly vulnerable to floods and landslides. As a result, many microhydro plants have been reportedly damaged by such climate related

[12] Given this paper is focused on electricity systems, we address electricity sector damages here, but by no means are we intending to indicate that these are the most important aspects of the disaster.

hazards, with their powerhouses particularly at risk (Goverment of Nepal, 2021).

To our knowledge, there is not a systematic reporting of such damage. As such, the records we found on climate-related microhydro damage were limited. However, the illustrative reports that we found indicate that damage to microhydro is similarly common as damage to larger hydropower systems. For example, in two remote districts in western Nepal, almost half (14 out of a total of 34) of the microhydro plants were damaged by flooding and landslide events between 2018 and 2023 (UNDP, 2023). This is a problem for the communities served by these systems, as microhydro is their only source of electricity generation. Repairs are expensive, requiring time, money, and human capital to conduct the necessary work (UNDP, 2023). A formal channel is needed through which the rural communities served by these systems can access expertise for assistance or equipment and replacement parts to facilitate repairs.

Transmission and Distribution Systems

Large and unexpected rainfall, both in time (e.g., earlier or later than the typical monsoon) and space (e.g., higher altitude rainfall), can lead to floods and landslides, bring down transmission and distribution lines, interrupt related infrastructure, and disrupt electricity service provision. We do not have comprehensive records on these occurrences, but such events are reported in local news. For example, the Kathmandu Post documented disruption through transmission towers in multiple locations in the country, as the monsoon rains continued much later than typical in 2022 (Shrestha, 2022). Additionally, in the country's flat Terai region, floods are documented to damage transmission lines as well (Goverment of Nepal, 2021).

6.1.4 Some Steps Forward

Given the hazards described above, attention to the resilience of the country's physical infrastructure in the country must be increased (World Bank, 2022b). For example, GLOFs can discharge a quantity of water that exceeds the flood values planned for many hydropower plants that are between 50 and 100 km downstream. Given the recent construction of additional generation within the country, there is a need to increase awareness among investors, create appropriate regulations, and install early warning systems (Goverment of Nepal, 2021). With GLOFs expected to continue into the future, the country has started efforts to monitor glacial lakes and implement early warning systems (International Centre for Integrated Mountain Development, 2023).

Since the Melamchi disaster, there are efforts to learn and prevent such events in the future (Bikash Maharjan et al., 2021; Takamatsu et al., 2022). Projects are being piloted with the intention of preventing future damage at that scale. For example, the governments of Bhutan, Nepal, and India are piloting projects with the Global Facility for Disaster Reduction and Recovery, to monitor via satellite for potential signs of impending landslides (World Bank, 2022a).

Lastly, Nepal's National Adaptation Plan aims to build climate resilience before 2050 in multiple sectors, including water resources and energy. However, there is still great future need, such as modernizing the country's observation network and forecast system to produce accurate flood warnings (World Bank, 2022a).

6.2 Case of Pakistan

As of 2019, the population of Pakistan was 216.5 million people; the majority of which live near the Indus River, (World Bank and ADB, 2021b). Pakistan has seen development progress in recent decades, including a reduction in the number of people living in extreme poverty (World Bank, 2022c). However, like Nepal, it is among the 10 countries most negatively impacted by climate change and natural disasters (World Bank, 2022c). As result, and with the devastating floods of 2022 in mind, climate change is a major concern for the country's future.

There are both additional similarities and many differences between Nepal and Pakistan. For example, like Nepal, the country has mountains with glaciers that are melting making it prone to GLOFs and related disasters. Unlike Nepal, Pakistan has two additional major sources of flooding: the Indus River and a coastline that includes Karachi, the country's economic center. In the subsections that follow, we provide background on the electricity sector in Pakistan, information on climate risks within the country, and then discuss vulnerabilities to climate change specific to the electricity sector.

6.2.1 Background on Electricity in Pakistan

As of 2021, 94.9% of Pakistan's population had access to electricity (IEA et al., 2023). While there have been gains in electricity access over the past few decades, electricity access rates were not as low in 2000 in Pakistan (72.8%) as they were in Nepal (29.9%) (IEA et al., 2023). The electrification rate has historically been and remains slightly lower in rural areas (91.9% in 2021) than the country overall (IEA et al., 2023).

The National Electric Power Regulatory Authority (NEPRA) regulates the country's power sector. There are nearly a dozen different utilities, each of which is responsible for electricity distribution within a metropolitan area. Almost all of the distribution companies are owned and operated by the government. Karachi Electric (KE) is the country's only privately-owned company and it is responsible for generation, transmission and distribution within the city of Karachi. This means that KE serves the country's major coastal area, which come with a few specific climate-related concerns that we will address later.

Even without considering climate-related disasters, the electricity sector in Pakistan faces challenges. The majority of the country's electricity generation is from the burning of fossil fuels, with 63% of the country's electricity generated from burning oil, gas, and coal sources (U.S. Energy Information Administration, 2018). In addition, the country's electric power transmission and distribution losses are quite high at 17% of total output in 2014 (U.S. Energy Information Administration, 2018), which is primarily driven by informal connections to the electricity grid and pilfering.

6.2.2 Current and Expected Future Climate Issues

Here, we address the climate-relevant factors in Pakistan: temperature and flooding due to GLOFs and precipitation extremes. We will both discuss recent events and expectations for the future.

Temperature Changes

Already, temperatures observed in Pakistan are among the highest recorded in Asia, with average temperatures in many parts of the country exceeding 30 degrees Celsius for multiple consecutive months (World Bank and ADB, 2021b). In 2022, the country experienced a heat wave so extreme that the mean temperatures in March and April of that year were hotter than any recorded since 1961 (World Meteorological Organization, 2023). In the future, the country is expected to experience temperature increases that are higher than the global average (World Bank and ADB, 2021b).

These extreme temperatures put large proportions of the population at risk for heat stress and it is not obvious how populations will adapt to increasing temperatures. For example, research on poor households in the city of Karachi, Pakistan indicates that as of 2021 only 3% of more than 3,000 households surveyed – all whom had electric grid connections – reported owning air conditioners (Ahmad et al., 2023b). Statistics such as this are particularly concerning in a city like Karachi, which is the 4th highest ranked city worldwide for total cooling degree day exposure (Biardeau et al., 2019).

Flooding Risks

Pakistan has one of the world's highest exposures to flooding (8th in the world), with multiple sources of flood risk (World Bank and ADB, 2021b). One source is from Pakistan's mountain regions, which have approximately 7,000 glaciers and 3,000 glacial lakes. The region now commonly experiences GLOF events, snow melt floods, and flash flooding (World Meteorological Organization, 2023). Similar to Nepal, higher temperatures have led to additional glacial melt. These changes in water flow have contributed to increased frequency and severity of flooding and landslides within the country (World Bank, 2022c). Further increasing the risks from glacial melt, GLOF events in Pakistan have the ability to cause damage and destroy infrastructure and communities located hundreds of kilometers away from the glacial lake's location (Carrivick and Tweed, 2016).

The flooding in Pakistan was particularly catastrophic in 2022. The Indian summer monsoon both started earlier and ended later than typical that year, leading to precipitation anomalies in the southern part of Pakistan (World Meteorological Organization, 2023). These heavy rains and the resulting river and urban flooding impacted 84 of the country's districts and displaced nearly 8 million people (OCHA, 2022). By the end of September 2022, the flooding had killed more than 1,600 people and hurt more than 12,800 people (OCHA, 2022).

Houses and basic infrastructure were destroyed, as well as sources of livelihood (World Bank, 2022c). The economic losses induced by these 2022 floods in Pakistan were estimated to be more than 15 billion USD (World Meteorological Organization, 2023).

The 2022 floods were not the first catastrophic floods to impact the country. Just a little over a decade earlier, in 2010, the monsoon brought abnormally large amounts of precipitation to the country. The resulting flood covered approximately one fifth of the country, killing more than 2,000 people (World Bank and ADB, 2021b).

With increased temperatures, greater glacial melt, more frequent GLOF events, and extreme precipitation during monsoons, the frequency and magnitude of flooding are expected to increase (World Bank and ADB, 2021b).

6.2.3 Urban Flooding and Vulnerability of Electricity Infrastructure

Having a coastline – and not being landlocked – introduces an additional climate factor beyond those faced by Nepal: the sea. Sea level is indeed rising, which is something to which glacial melt is contributing. In some locations, however, land is also subsiding, including in major cities and economic centers in developing countries. Karachi, the economic center of Pakistan, is one of a number of major developing country cities experiences particularly fast subsidence (Wu et al., 2022). This subsidence contributes to the city's propensity to flood. The rate of subsidence identified for Karachi means that the city will be inundated by flooding much sooner than predicted by climate models that incorporate only sea level rise (Wu et al., 2022).

Beyond sea level rise and land subsidence, other factors that contribute to Karachi's regular flooding are river flooding, extreme precipitation, and insufficient storm water drainage. Indeed, monsoon season flooding in Karachi has been a frequent occurrence for quite some time, challenging city inhabitants and Karachi Electric. During and following heavy precipitation events and urban flooding, city streets can be under deep water. At these times, electricity outages are not uncommon, often due to components of the distribution system (e.g., substations and transformers) being submerged in water. Following heavy rains, efforts to restore power require clearing storm water drains and removing blockages. Additionally, electricity distribution infrastructure must dewater after being submerged under water before it can resume electricity distribution, which means that outages can last for many days at a time.

In an effort to make the distribution infrastructure more resilient to the recurring flooding, Karachi Electric embarked on "rain mitigation" efforts recently. These investments in the distribution system are an effort to avoid lengthy electricity outages during the monsoon. Over several years, the utility has made investments to raise the foundations of distribution infrastructure and to waterproof substations (Karachi Electric, 2021; Siddiqi, 2021). The utility hopes that these infrastructure investments will build resilience to precipitation anomalies and heavy monsoon rains. These investments are expensive, however, and the costs of upgrades increasing resilience to climate change are eventually borne by the rate payers.

7 Conclusion

In this paper, we build upon and complement the growing body of evidence on the economic impacts of electricity access. We do so in two parts. First, we focus on and draw attention to challenges – beyond that of increasing electricity access – that pervade the electricity sector in developing countries and are represented in recent causal econometric studies. These challenges include: impediments to maximizing the economic benefits from electricity connections due to unreliable and poor quality electricity services, difficulties recovering the full cost of electricity provision due to high losses and low bill payment, challenges in predicting future demand for electricity services, and uncertainty regarding the demand for decentralized renewable energy sources. We argue that these challenges impede the realization of the full benefits from the recent electricity gains in development countries and we highlight some areas in need of additional research.

Second, we seek to highlight an additional challenge to the electricity sector in developing countries to which relatively little attention is currently paid in the empirical economics literature: adaptation and resilience to climate change. We underscore this issue by discussing recent events in two South Asian countries – Nepal and Pakistan – both of which are extremely vulnerable to the changing climate. We believe that these cases illustrate how climate change could undo much of the recent progress that has been made in electricity access and services within the region.

Finally, we conclude noting that this is a critical time to ensure financing for climate adaptation and resilience in the electricity sector within countries vulnerable to climate change. Adaptation and building resilience to the effects of climate change will be costly (Ahmed and Suphachalasai, 2014) and require sufficient and predictable finance to address climate risk to the power sector (Johnston et al., 2012). The COP28 meetings in December 2023 resulted in a historical agreement to create a loss and damage fund to assist countries vulnerable to climate change with much needed financing to recover from disasters induced by climate change. Yet, following the launch of this fund, many decisions such as funding commitments and who will host the fund remain undecided (Gibson, 2023). As a result, this is a particularly critical time to understand and address vulnerabilities to climate change within the electricity sector in developing countries.

References

Abdollahi, Rohollah, Majid Moradi, Hossein Alizadeh, and Abolfazl Rafiei, "Impact of replacing overhead lines with aerial bundled cable, and installation of new transformers to reduce losses and improve distribution network voltage profiles, technical and economic analysis," *Engineering Reports*, November 2020, *2* (11).

Abeberese, Ama Baafra, "Electricity Cost and Firm Performance: Evidence from India," *The Review of Economics and Statistics*, December 2017, *99* (5), 839–852.

Adhvaryu, Achyuta, Namrata Kala, and Anant Nyshadham, "The Light and the Heat: Productivity Co-Benefits of Energy-Saving Technology," *The Review of Economics and Statistics*, October 2020, *102* (4), 779–792.

Ahmad, Husnain F, Ayesha Ali, Robyn C Meeks, Zhenxuan Wang, and Javed Younas, "The Economic and Environmental Effects of Making Electricity Infrastructure Excludable," *Working Paper*, 2023.

_ , _ , _ , _ , and _ , "The Economic and Environmental Effects of Making Electricity Infrastructure Excludable," *SSRN Working Paper*, 2023. http://dx.doi.org/10.2139/ssrn.4391170.

Ahmed, Mahfuz and Suphachol Suphachalasai, *Assessing the Costs of Climate Change and Adaptation in South Asia*, Mandaluyong City, Philippines: Asian Development Bank, June 2014. https://www.adb.org/sites/default/files/publication/42811/assessing-costs-climate-change-and-adaptation-south-asia.pdf.

Alam, M, E Kabir, M Rahman, and M Chowdhury, "Power sector reform in Bangladesh: Electricity distribution system," *Energy*, September 2004, *29* (11), 1773–1783.

Alberini, Anna, Jevgenijs Steinbuks, and Govinda Timilsina, "How Valuable is the Reliability of Residential Electricity Supply in Low-Income Countries? Evidence from Nepal," *World Bank Policy Research Working Paper*, June 2020, *9311.* http://hdl.handle.net/10986/34026.

_ , Levan Bezhanishvili, and Milan Ščasný, ""Wild" tariff schemes: Evidence from the Republic of Georgia," *Energy Economics*, June 2022, *110*, 106030.

Alem, Yonas and Eugenie Dugoua, "Learning from Unincentivized and Incentivized Communication: A Randomized Controlled Trial in India," *Economic Development and Cultural Change*, October 2022, *71* (1).

Ali, Ayesha, Khusrav Gaibulloev, and Javed Younas, "Do Reward and Reprimand Policies Work in Reducing Electricity Distribution Losses?," *SSRN Electronic Journal*, 2023. https://www.ssrn.com/abstract=4651990.

Allcott, Hunt, Allan Collard-Wexler, and Stephen D. O'Connell, "How Do Electricity Shortages Affect Industry? Evidence from India," *American Economic Review*, 2016, *106* (3), 587–624.

Auffhammer, Maximilian, "Cooling China: The Weather Dependence of Air Conditioner Adoption," *Frontiers in China*, 2014, *9.*

Ayaburi, John, Morgan Bazilian, Jacob Kincer, and Todd Moss, "Measuring "Reasonably Reliable" access to electricity services," *The Electricity Journal*, August 2020, *33* (7), 106828.

Barreca, Alan, Karen Clay, Olivier Deschenes, Michael Greenstone, and Joseph S. Shapiro, "Adapting to Climate Change: The Remarkable Decline in the US Temperature-Mortality Relationship over the Twentieth Century," *Journal of Political Economy*, February 2016, *124* (1), 105–159.

Barron, Manuel and Maximo Torero, "Household electrification and indoor air pollution," *Journal of Environmental Economics and Management*, November 2017, *86*, 81–92.

Bayer, Patrick, Ryan Kennedy, Joonseok Yang, and Johannes Urpelainen, "The need for impact evaluation in electricity access research," *Energy Policy*, February 2020, *137*, 111099.

Beattie, Graham, Iza Ding, and Andrea La Nauze, "Is There an Energy Efficiency Gap in China? Evidence from an Information Experiment," *Journal of Environmental Economics and Management*, 2022, *115.*

Berkouwer, Susanna B., "Electric Heating and the Effects of Temperature on Household Electricity Consumption in South Africa," *The Energy Journal*, July 2020, *41* (4), 209–230.

Berkouwer, Susanna B, Pierre E Biscaye, Maya Mikdash, Steven L Puller, and Catherine D Wolfram, "Voltage quality and economic activity," *Working Paper*, 2024. https://papers.pierrebiscaye.com/BBMPW$_V$*oltage*$_G$*hana.pdf*.

Beyene, Abebe D, Marc Jeuland, Alemu Mekonnen, Samuel Sebsibie, Sied Hassen, Tensay H Meles, and Thomas Klug, "Electricity pricing reform and firms' electricity consumption in Ethiopia," *Energy and Economic Growth Working Paper*, 2022.

_ , _ , Samuel Sebsibie, Sied Hassen, Alemu Mekonnen, Tensay H Meles, Subhrendu K Pattanayak, and Thomas Klug, "Pre-paid meters and household electricity use behaviors: Evidence from Addis Ababa, Ethiopia," *Energy Policy*, 2022, *170*, 113251.

Biardeau, Léopold T., Lucas W. Davis, Paul Gertler, and Catherine Wolfram, "Heat exposure and global air conditioning," *Nature Sustainability*, December 2019, *3* (1), 25–28.

Brown, Casey, Robyn Meeks, Yonas Ghile, and Kenneth Hunu, "Is water security necessary? An empirical analysis of the effects of climate hazards on national-level economic growth," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, November 2013, *371* (2002), 20120416.

Burgess, Robin, Michael Greenstone, Nicholas Ryan, and Anant Sudarshan, "The Consequences of Treating Electricity as a Right," *Journal of Economic Perspectives*, February 2020, *34* (1), 145–169.

_ , _ , _ , and _ , "Demand for Electricity on the Global Electrification Frontier," *Warwick Economics Research Papers*, 2023, *1445.* https://www.anantsudarshan.com/uploads/1/0/2/6/10267789/twerp$_1$445$_{-s}$*udarshan.pdf*.

Burlig, Fiona and Louis Preonas, "Out of the darkness and into the light? Development effects of rural electrification," *Energy Institute Working Paper*, 2021, *268R.* https://haas.berkeley.edu/wp-content/uploads/WP268.pdf.

Carranza, Eliana and Robyn Meeks, "Energy Efficiency and Electricity Reliability," *The Review of Economics and Statistics*, July 2021, *103* (3), 461–475.

Carrivick, Jonathan L. and Fiona S. Tweed, "A global assessment of the societal impacts of glacier outburst floods," *Global and Planetary Change*, September 2016, *144*, 1–16.

Chakravorty, Ujjayant and Martino Pelli, "Electrification and development: Empirical evidence on the effect of electricity provision on household welfare," Technical Report, CIRANO 2022.

_ , _ , and Beyza Ural Marchand, "Does the quality of electricity matter? Evidence from rural India," *Journal of Economic Behavior & Organization*, November 2014, *107*, 228–247.

Davis, Lucas, Paul Gertler, Stephen Jarvis, and Catherine Wolfram, "Air conditioning and global inequality," *Global Environmental Change*, July 2021, *69*, 102299.

Davis, Lucas W., Alan Fuchs, and Paul Gertler, "Cash for Coolers: Evaluating a Large-Scale Appliance Replacement Program in Mexico," *American Economic Journal: Economic Policy*, November 2014, *6* (4), 207–238.

_ and Paul J. Gertler, "Contribution of air conditioning adoption to future energy use under global warming," *Proceedings of the National Academy of Sciences*, May 2015, *112* (19), 5962–5967.

_ , Sebastian Martinez, and Bibiana Taboada, "How effective is energy-efficient housing? Evidence from a field trial in Mexico," *Journal of Development Economics*, March 2020, *143*, 102390.

de Souza Savian, Fernando, Julio Cezar Mairesse Siluk, Taís Bisognin Garlet, Felipe Moraes do Nascimento, José Renes Pinheiro, and Zita Vale, "Non-technical losses: A systematic contemporary article review," *Renewable and Sustainable Energy Reviews*, September 2021, *147*, 111205.

Deutschmann, Joshua W., Agnieszka Postepska, and Leopold Sarr, "Measuring Willingness to Pay for Reliable Electricity: Evidence from Senegal," *World Development*, February 2021, *138*, 105209.

Dinkelman, Taryn, "The Effects of Rural Electrification on Employment: New Evidence from South Africa," *The American Economic Review*, 2011, *101* (7), 3078–3108.

Fetter, Robert T. and Faraz Usmani, "Fracking, Farmers, and Rural Electrification in India," *Ruhr Economic Papers*, 2020, *864.* https://www.econstor.eu/bitstream/10419/224779/1/1733938761.pdf.

Fisher-Vanden, Karen, Erin T. Mansur, and Qiong Juliana Wang, "Electricity Shortages and Firm Productivity: Evidence from China's Industrial Firms," *Journal of Development Economics*, 2015, *114*, 172–188.

Fowlie, Meredith and Robyn Meeks, "The Economics of Energy Efficiency in Developing Countries," *Review of Environmental Economics and Policy*, June 2021, *15* (2), 238–260.

Fried, Stephie and David Lagakos, "Electricity and Firm Productivity: A General-Equilibrium Approach," *American Economic Journal: Macroeconomics*, October 2023, *15* (4), 67–103.

Gertler, Paul J., Orie Shelef, Catherine D. Wolfram, and Alan Fuchs, "The Demand for Energy-Using Assets among the World's Rising Middle Classes," *American Economic Review*, June 2016, *106* (6), 1366–1401.

Gibson, Shannon, "Don't applaud the COP28 climate summit's loss and damage fund deal just yet – here's what's missing," December 2023.

Gould, Carlos, M. Lorena Bejarano, Brandon de la Cuesta, Darby Jack, Samuel Schlesinger, Alfredo Valarezo, and Marshall Burke, "Climate and health benefits of a transition from gas to electric cooking," preprint, Environmental Public Health January 2023.

Goverment of Nepal, *Vulnerability and Risk Assessment and Identifying Adaptation Options: Summary for Policy Makers*, Kathmandu, Nepal.: Ministry of Forests and Environment, Government of Nepal., 2021.

Grimm, Michael, Luciane Lenz, Jörg Peters, and Maximiliane Sievert, "Demand for Off-Grid Solar Electricity: Experimental Evidence from Rwanda," *Journal of the Association of Environmental and Resource Economists*, 2020, *7* (3).

Hashemi, Majid, "The economic value of unsupplied electricity: Evidence from Nepal," *Energy Economics*, March 2021, *95*, 105124.

IEA, IRENA, UNSD, World Bank, and WHO, "Tracking SDG7: The Energy Progress Report 2023," Technical Report 2023.

IEA Statistics, "Electric power transmission and distribution losses (% of output) dataset," 2018.

Intergovernmental Panel on Climate Change, "High Mountain Areas," in "The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change," 1 ed., Cambridge University Press, 2022.

International Centre for Integrated Mountain Development, *Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook*, International Centre for Integrated Mountain Development (ICIMOD), 2023. https://lib.icimod.org/record/36322.

International Centre for Integrated Mountain Development (ICIMOD) , *Glacial lakes and glacial lake outburst floods in Nepal*, Kathmandu: International Centre for Integrated Mountain Development, 2011.

Jack, Kelsey and Grant Smith, "Charging Ahead: Prepaid Metering, Electricity Use, and Utility Revenue," *American Economic Journal: Applied Economics*, April 2020, *12* (2), 134–168.

Jacome, Veronica, Noah Klugman, Catherine Wolfram, Belinda Grunfeld, Duncan Callaway, and Isha Ray, "Power Quality and Modern Energy for All," *Proceedings of the National Academy of Sciences*, 2019, *116* (33), 16308–16313.

Jeuland, Marc, T. Robert Fetter, Yating Li, Subhrendu K. Pattanayak, Faraz Usmani, Randall A. Bluffstone, Carlos Chávez, Hannah Girardeau, Sied Hassen, Pamela Jagger, Mónica M. Jaime, Mary Karumba, Gunnar Köhlin, Luciane Lenz, Erin L. Litzow, Lauren Masatsugu, Maria Angelica Naranjo, Jörg Peters, Ping Qin, Remidius D. Ruhinduka, Montserrat Serrano-Medrano, Maximiliane Sievert, Erin O. Sills, and Michael Toman, "Is energy the golden thread? A systematic review of the impacts of modern and traditional energy use in low- and middle-income countries," *Renewable and Sustainable Energy Reviews*, January 2021, *135*, 110406.

Jiménez, Raúl, "Development Effects of Rural Electrification," Technical Report, Inter-American Development Bank January 2017.

Johnston, Peter Campbell, Jose Frazier Gomez, and Benoit Laplante, *Climate Risk and Adaptation in the Electric Power Sector*, Mandaluyong City, Metro Manila, Philippines: Asian Development Bank, 2012.

Kala, Namrata, Claire Balboni, and Shweta Bhogale, "Climate Adaptation," *VoxDevLit*, June 2023, *7* (1).

Karachi Electric, "K-Electric inaugurates the first substation under PKR 9.5 billion rain-mitigation investment - K-Electric," March 2021. https://www.ke.com.pk/k-electric-inaugurates-the-first-substation-under-pkr-9-5-billion-rain-mitigation-investment/.

Kassem, Dana, "Does electrification cause industrial development? Grid expansion and firm turnover in Indonesia," *Journal of Development Economics*, March 2024, *167*, 103234.

Khanna, Shefali and Kevin Rowe, "The long-run value of electricity reliability in India," *Resource and Energy Economics*, January 2024, p. 101425.

_ **, Ralf Martin, and Mirabelle Muuls**, "ShiftingHousehold Power Demand Across Time: Incentives and Automation," *Working Paper*, 2024.

Lee, Kenneth, Edward Miguel, and Catherine Wolfram, "Experimental Evidence on the Economics of Rural Electrification," *Journal of Political Economy*, April 2017, *128* (4), 1523–1565.

_ **,** _ **, and** _ , "Does Household Electrification Supercharge Economic Development?," *Journal of Economic Perspectives*, February 2020, *34* (1), 122–144.

Li, Yating, William A. Pizer, and Libo Wu, "Climate change and residential electricity consumption in the Yangtze River Delta, China," *Proceedings of the National Academy of Sciences*, January 2019, *116* (2), 472–477.

Lipscomb, Molly, A. Mushfiq Mobarak, and Tania Barham, "Development Effects of Electrification: Evidence from the Topographic Placement of Hydropower Plants in Brazil," *American Economic Journal: Applied Economics*, January 2013, *5* (2), 200–231.

Mahadevan, Meera, Robyn Meeks, and Takashi Yamano, "Reducing information barriers to solar adoption: Experimental evidence from India," *Energy Economics*, April 2023, *120*, 106600.

Maharjan, Sudan Bikash, Jakob Friedrich Steiner, Arun Bhakta Shrestha, Amina Maharjan, and Santosh Nepal, "The Melamchi flood disaster: Cascading hazard and the need for multihazard risk management," Technical Report, International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal 2021. Edition: 0.

McRae, Shaun, "Efficiency and Equity Effects of Electricity Metering: Evidence from Colombia," *Working paper*, 2015a.

_ , "Infrastructure Quality and the Subsidy Trap," *American Economic Review*, 2015b, *105* (1), 35–66.

_ , "Residential Electricity Consumption and Adaptation to Climate Change by Colombian Households," *Economics of Disasters and Climate Change*, July 2023, *7* (2), 253–279.

_ **and Robyn Meeks**, "Price perception and electricity demand with nonlinear tariffs," *Working Paper*, 2016.

McRae, Shaun D. and Frank A. Wolak, "Retail pricing in Colombia to support the efficient deployment of distributed generation and electric stoves," *Journal of Environmental Economics and Management*, October 2021, *110*, 102541.

Meeks, Robyn C., Arstan Omuraliev, Ruslan Isaev, and Zhenxuan Wang, "Impacts of electricity quality improvements: Experimental evidence on infrastructure investments," *Journal of Environmental Economics and Management*, 2023, *120*, 102838.

Meeks, Robyn, Hope F. Thompson, and Zhenxuan Wang, "Electrification to Grow Manufacturing? Evidence from Nepal," *SSRN Electronic Journal*, 2021.

Meles, Tensay Hadush, Alemu Mekonnen, Abebe D. Beyene, Sied Hassen, Subhrendu K. Pattanayak, Samuel Sebsibie, Thomas Klug, and Marc Jeuland, "Households' valuation of power outages in major cities of Ethiopia: An application of stated preference methods," *Energy Economics*, 2021, *102*, 105527.

Merzdorf, Jessica, "Climate Change Could Trigger More Landslides in High Mountain Asia - NASA," February 2020. https://www.nasa.gov/centers-and-facilities/goddard/climate-change-could-trigger-more-landslides-in-high-mountain-asia/.

Moore, Nichols, Douglas Glandon, Janice Tripney, Tomasz Kozakiewicz, Shannon Shisler, John Eyres, Rami Zalfou, Maria Daniela Anda Leon, Varant Kurkjian, Birte Snilstveit, and Ari Perdana, "Effects of Access to Electricity Interventions on Socioeconomic Outcomes in Low- and Middle- Income Countries," *3ie Systematic Review*, August 2020. https://www.3ieimpact.org/sites/default/files/2020-11/SR45-ADB-electricity-interventions.pdf.

OCHA, U.N., "Pakistan 2022 Floods Response Plan," Technical Report, United Nations Office for the Coordination of Humanitarian Affairs (OCHA) October 2022.

Pattanayak, S. K., M. Jeuland, J. J. Lewis, F. Usmani, N. Brooks, V. Bhojvaid, A. Kar, L. Lipinski, L. Morrison, O. Patange, N. Ramanathan, I. H. Rehman, R. Thadani, M. Vora, and V. Ramanathan, "Experimental evidence on promotion of electric and improved biomass cookstoves," *Proceedings of the National Academy of Sciences*, July 2019, *116* (27), 13282–13287.

Peters, Jörg, Colin Vance, and Marek Harsdorff, "Grid Extension in Rural Benin: Micro-Manufacturers and the Electrification Trap," *World Development*, May 2011, *39* (5), 773–783.

Poudel, Arjun, "Climate change adds risk to investments in hydropower," *Kathmandu Post*, July 2023.

Randazzo, Teresa, Filippo Pavanello, and Enrica De Cian, "Adaptation to climate change: Air-conditioning and the role of remittances," *Journal of Environmental Economics and Management*, July 2023, *120*, 102818.

Rud, Juan Pablo, "Electricity Provision and Industrial Development: Evidence from India," *Journal of Development Economics*, March 2012, *97* (2), 352–367.

Ryan, Nicholas, "Energy Productivity and Energy Demand: Experimental Evidence from Indian Manufacturing Plants," Technical Report w24619, National Bureau of Economic Research, Cambridge, MA May 2018.

Shrestha, Prithvi Man, "Climate Shocks Add Risks to Nepal's Power Projects," *Kathmandu Post*, November 2022.

Siddiqi, "K-Electric & DHA inaugurate two substations elevations as part of pre-monsoon preparations," *Trade Chronicle*, June 2021.

Somanathan, E., Rohini Somanathan, Anant Sudarshan, and Meenu Tewari, "The Impact of Temperature on Productivity and Labor Supply: Evidence from Indian Manufacturing," *Journal of Political Economy*, June 2021, *129* (6), 1797–1827.

Steinbuks, J. and V. Foster, "When do firms generate? Evidence on in-house electricity supply in Africa," *Energy Economics*, 2010, *32* (3), 505–514.

Takamatsu, Masatsugu, Hemang D. Karelia, Thomas Oommen, and Ranjan Kumar Dahal, "MELAMCHI FLOOD DISASTER IN NEPAL: Damage and Risk Quantification with Drone Survey, Satellite-Based Land Displacement Analysis, and 2D Flood Modeling," World Bank 172836, World Bank Group, Washington, D.C. : June 2022.

Timilsina, Govinda and Jevgenijs Steinbuks, "Economic costs of electricity load shedding in Nepal," *Renewable and Sustainable Energy Reviews*, August 2021, *146*, 111112.

Toledo, Chantal, "Do Environmental Messages Work on the Poor? Experimental Evidence from Brazilian Favelas," *Journal of the Association of Environmental and Resource Economists*, March 2016, *3* (1).

UNDP, "How energy is transforming communities in Bajura," August 2023.

U.S. Energy Information Administration, "Annual Energy Outlook 2018 with Projections to 2050," Technical Report, U.S. Department of Energy, U.S. Energy Information Administration Office of Energy Analysis, Washington, D.C. 2018.

Wolfram, Catherine, Orie Shelef, and Paul Gertler, "How Will Energy Demand Develop in the Developing World?," *Journal of Economic Perspectives*, February 2012, *26* (1), 119–138.

Wong, Jason Chun Yu, Brian Blankenship, S.P. Harish, and Johannes Urpelainen, "Increasing microsolar technology adoption: Efficacy of vouchers, cash transfers, and microfinance schemes," *Energy Economics*, June 2022, *110*, 105952.

World Bank, "In Nepal, 2 Major Climate Disasters in a Single Year Highlight the Need to Build Resilience," *World Bank Climate Stories*, March 2022, *Feature Story.* ttps://www.worldbank.org/en/news/feature/2022/03/28/in-nepal-2-major-climate-disasters-in-a-single-year-highlight-the-need-to-build-resilience.

_ , "Nepal Country Climate and Development Report," Technical Report 2022. https://openknowledge.worldbank.org/server/api/core/bitstreams/30a1cb25-232c-41ab-bd96-7046d446c2fc/content.

_ , "Pakistan Country Climate and Development Report," Technical Report 2022. https://openknowledge.worldbank.org/server/api/core/bitstreams/2d1af64a-8d35-5946-a047-17dc143797ad/content.

_ **and ADB**, *Climate Risk Country Profile: Nepal*, World Bank, September 2021. http://elibrary.worldbank.org/doi/book/10.1596/36374.

_ **and** _ , *Climate Risk Country Profile: Pakistan*, World Bank, September 2021. http://elibrary.worldbank.org/doi/book/10.1596/36372.

World Meteorological Organization, *State of the Climate in Asia 2022*, Geneva, Switzerland: World Meteorological Organization, 2023. https://library.wmo.int/records/item/66314-state-of-the-climate-in-asia-2022.

Wu, Pei-Chin, Meng (Matt) Wei, and Steven D'Hondt, "Subsidence in Coastal Cities Throughout the World Observed by InSAR," *Geophysical Research Letters*, April 2022, *49* (7).