



STEG PATHFINDING PAPER

CAN MASS ELECTRIFICATION (STILL) CAUSE STRUCTURAL CHANGE?

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Abstract

Despite its ubiquity in high income countries among households and in most industries, evidence is mixed for the socioeconomic impacts of electrification in low and middle income countries. Can mass electrification today still induce changes in productivity, labor allocation, and incomes which are associated with structural change, as it seems to have in the past? In this paper we discuss current evidence and directions for future research, with focus on (1) the role of electricity reliability, (2) identifying key investments that are complementary to electrification, and (3) selection, migration, and agglomeration effects when electrification is spatially uneven.

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1 Introduction

Electricity is used by households and by firms in virtually every major industry and is a core input into modern consumption, leisure, and production. Electricity is so fundamental an input that output growth can be tracked by nighttime lights produced by electric lightbulbs (Henderson, Storeygard, & Weil, 2012). It is intuitive, then, that structural transformation and the transition to modern economic growth would be tightly linked to increasing access and usage of electricity both across and within countries (e.g. Lee, Miguel, & Wolfram, 2020a; Lewis & Severnini, 2020). The link between electricity and economic development has also resonated strongly with policymakers, who are investing public resources into rapidly expanding electricity access. Examples include Kenya’s Last Mile Connectivity Project which aims to provide universal electricity access for Kenyans by 2030, and Ethiopia’s National Electrification Program which aims for universal electricity access by 2025.

Although associations between economic development, structural change, and electrification are not necessarily causal, they are supported by a large quasi-experimental literature aimed at estimating the causal impact of electrification on outcomes such as income and sector of employment. While results vary from country to country and between different quasi-experimental approaches, the findings of this literature are broadly consistent with electricity leading to higher incomes (Lipscomb, Mobarak, & Barham, 2013; Moretti, 2014), higher employment and human capital particularly for women (Dinkelman, 2011; Gaggl et al., 2019; Vidart, 2022), rural productivity (Kitchens & Fishback, 2015), and higher industrial output (Kassem, 2021; Rud, 2012), all of which are hallmarks of structural change.

More recent work conducting well-identified evaluations of electrification in policy-relevant settings, however, has found negligible effects on economic outcomes, with little indication that electricity changed key outcomes associated with structural change, including income, labor market behaviors, or education (Burlig & Preonas, 2021; Lee, Miguel, & Wolfram, 2020b). These results are reinforced by the fact that household demand and willingness-to-pay for electricity is measured to be very low, consistent with the idea that the benefits are small.

Taken together, these results present a puzzle. If access to electricity does not substantially change household behavior, how can mass electrification today be a driver of structural change?

Resolving this tension is crucial to expanding our understanding of how structural change and electrification interact. Better understanding sources of heterogeneity in the impacts of electrification is also critical for policy, with USD 3.6 billion spent annually on electrification from 2000 through 2014 justified in large part by its socioeconomic impacts (World Bank 2015). Our goal in this paper is to synthesize the existing literature and identify productive paths for future research aimed at improving our understanding.

In Section 2 below, we take stock of what is known about the relationship between electrification and structural change. We begin by summarizing some key cross-country facts about the relationship between electrification and GDP. As is well-known, there is a strong relationship between access to electricity and output. In addition to this, we document a strong cross-country relationship in electrical connection quality (as measured by frequency and duration of outages for firms) and output. The large variation in connection quality between rich and poor countries is at least suggestive that connection quality may be as important as access in driving structural change. We also compare the cross-country relationship between access to electricity and output to the historical relationship within the United States and United Kingdom and show that countries today by and large have much higher electrification rates than the US or UK when they were at similar income levels. We return to these facts later when we discuss productive research paths forward.

Next, we discuss the empirical microeconomic literature on the impacts of electrification. We conduct a brief literature review and show that there is substantial variation in the estimated effects of electrification on economic outcomes across the literature. A closer examination of the literature reveals that the large variance of estimated effects seems explainable, at least in part, based on the characteristics of the episode of electrification being studied. Papers that examine older historic episodes of electrification, such as those in the United States, Brazil, and certain India states, tend to find larger effects while those studying more recent episodes find smaller effects. Similarly, studies of large-scale electrification initiatives with large units of analysis such as states or regions tend to find larger effects than those that examine initiatives targeted at the household or village level. Of course, these patterns are only suggestive, driven by a small set of recent studies finding null results and complicated by methodological differences. Further studies of electrification at various scales in various time periods would be highly valuable in confirming these trends. Notably, there are very few studies (that we are aware of) of electrification in the East and Southeast Asia regions.

Such studies would be particularly valuable as these countries cover a wide range of income levels and many have achieved universal electrification in recent decades during times of rapid economic change.

Having documented some cross-country facts and established some stylized facts in the quasi-experimental literature, we spend Section 3 discussing promising avenues for future research examining the impact of electrification on structural change. We focus in particular on potential mechanisms that can rationalize the large role of electricity as a historical driver of structural change with the small impacts measured in more recent studies of last-mile electrification. We identify three types of mechanisms, each of which represents a productive path for future research, and we discuss briefly the existing work related to each mechanism.

First, electricity reliability and quality may be as important as electricity access in driving structural change. If electricity drives structural change by enabling the use of electrified industrial machines, poor quality connections that provide little power and are frequently unusable may be insufficient to induce industrialization. Future research can better examine the importance of improved electricity quality (e.g. for firms in different sectors and for households) and economic and political barriers to achieving improved quality. Second, investment in electrical infrastructure may be strongly complementary to other types of investments. For example, improved public infrastructure, such as roads and ports, may enhance the impacts of electrification by improving market access and the benefit to firms from adopting electrical equipment. Strong complementarities of this sort could justify electrification as part of "big push" style programs. Relatedly, electricity as an input to production may be strongly complementary to investments in physical capital (e.g. electrical appliances and machinery) and human capital (e.g. additional schooling). It's possible that electricity may have low returns in low income regions that have little capital and low levels of education at baseline. Future research can productively document key areas of complementarity and frictions that may cause underinvestment in complements to electricity. Third, electrification at scale may have important features such as agglomeration, migration, and selection of locales into electrification that can help explain why improvements in electricity infrastructure in an already partially electrified region could have limited impacts.

In the final section of the paper, we conclude with a brief summary of what we have discussed and highlight the importance of a multitude of research approaches — including experimental and quasi-

experimental approaches and general equilibrium macroeconomic modeling — to address these key questions and further our understanding of the relationship between electrification and structural change.

2 What Do We Know About Electrification?

In this section, we consider what is known about the relationship between electrification and structural change. We first present some simple cross-country facts about electrification and income. Next, we discuss experimental and quasi-experimental studies on the effects of electrification. Rather than a comprehensive literature review, we aim to provide a representative summary capturing the broad findings of the literature.

2.1 Key Cross-Country Facts

We begin by summarizing some cross-country and historic facts on the relationship electrification and development. These are descriptive and not causal in nature, but we view these as the key facts that any macroeconomic theory of structural change and electrification must be able to replicate. They also provide a lens through which we can interpret the discussion of experimental and quasi-experimental studies in subsection 2.2 and motivation for our suggested paths forward for future research.

Unsurprisingly, cross-country data document a strong negative relationship between GDP per capita and access to electricity. Figure 1 plots the proportion of the population with access to electricity (taken from World Bank’s World Development Indicators) against GDP per capita for the year 2018 (in black). Although there is little variation in the top half of the income distribution, where all countries have essentially universal access to electricity, the bottom half of the distribution exhibits a strong, albeit noisy, positive relationship.

More interestingly, Figure 1 also plots (in red) the historic relationship between GDP per capita (as estimated by the Maddison project) and electricity access in the United States (taken from the Census’s *Historical Statistics of the United States, Colonial Times to 1957*) starting in 1907 when only 8 percent of the population had access to electricity and continuing until 1957 when the US achieved near-universal electricity access of 99 percent. The pattern is striking as the slope of this

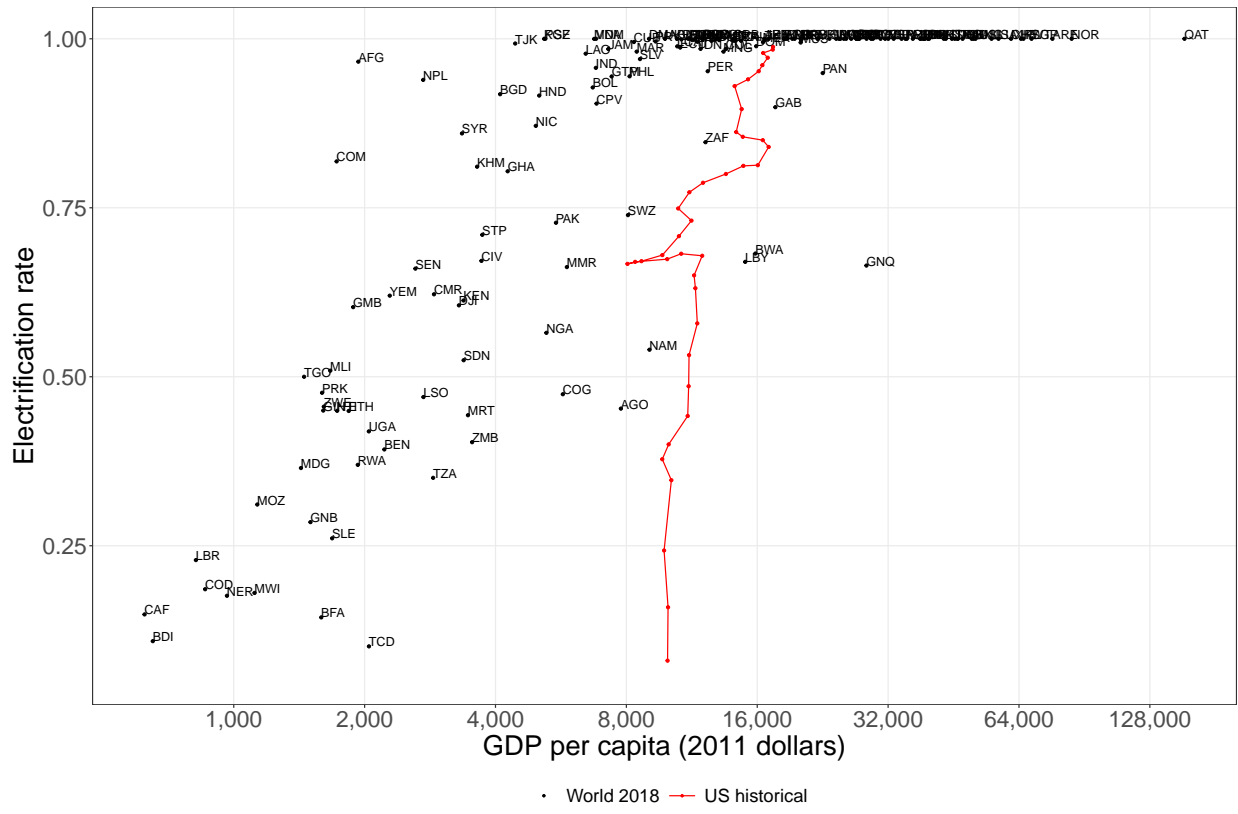


Figure 1: Relationship between GDP and Electricity Access

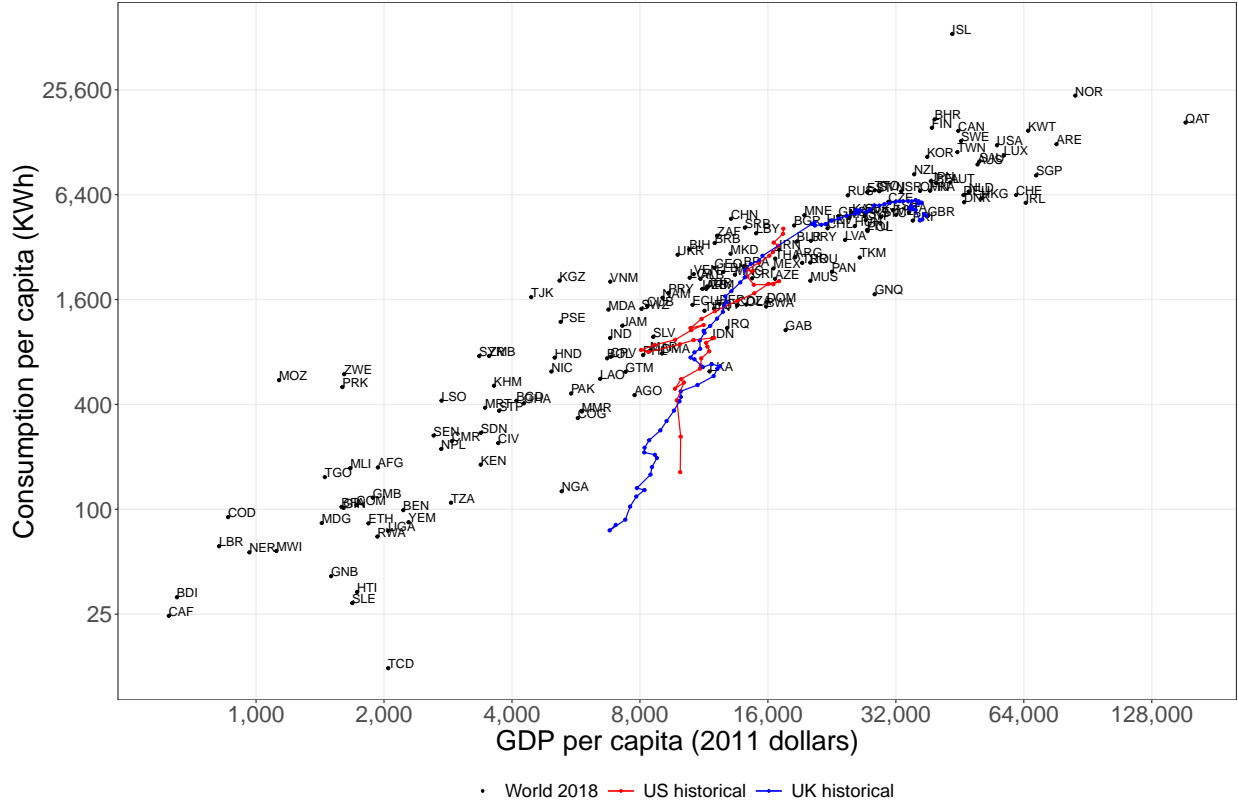


Figure 2: Relationship between GDP and Electricity Consumption

line is substantially steeper than that of the cross-country relationship. The interpretation of the steep red line is straightforward; although only 8 percent of the US had access to electricity in 1907, the vast majority of countries today with GDP per capita comparable to the 1907 US exhibit universal or near-universal access.

We can perform a similar analysis by looking at electricity usage, rather than electricity access. Figure 2 does this by plotting electricity consumption per capita (from the US Energy Information Administration) against GDP per capita for various countries. As in Figure 1, the relationship is positive and strong. Historical energy consumption in the US from 1907-1957 is plotted by the red line (this choice of years makes the red lines in Figures 1 and 2 directly comparable). The blue line plots the same for the United Kingdom over a longer time horizon from 1920 to 2017 (data taken from the *Digest of United Kingdom Energy Statistics*). The overall story is similar to the previous figure; modern countries with GDP per capita comparable to the historic US or UK consume substantially more electricity (note that electricity consumption follows a log scale) than

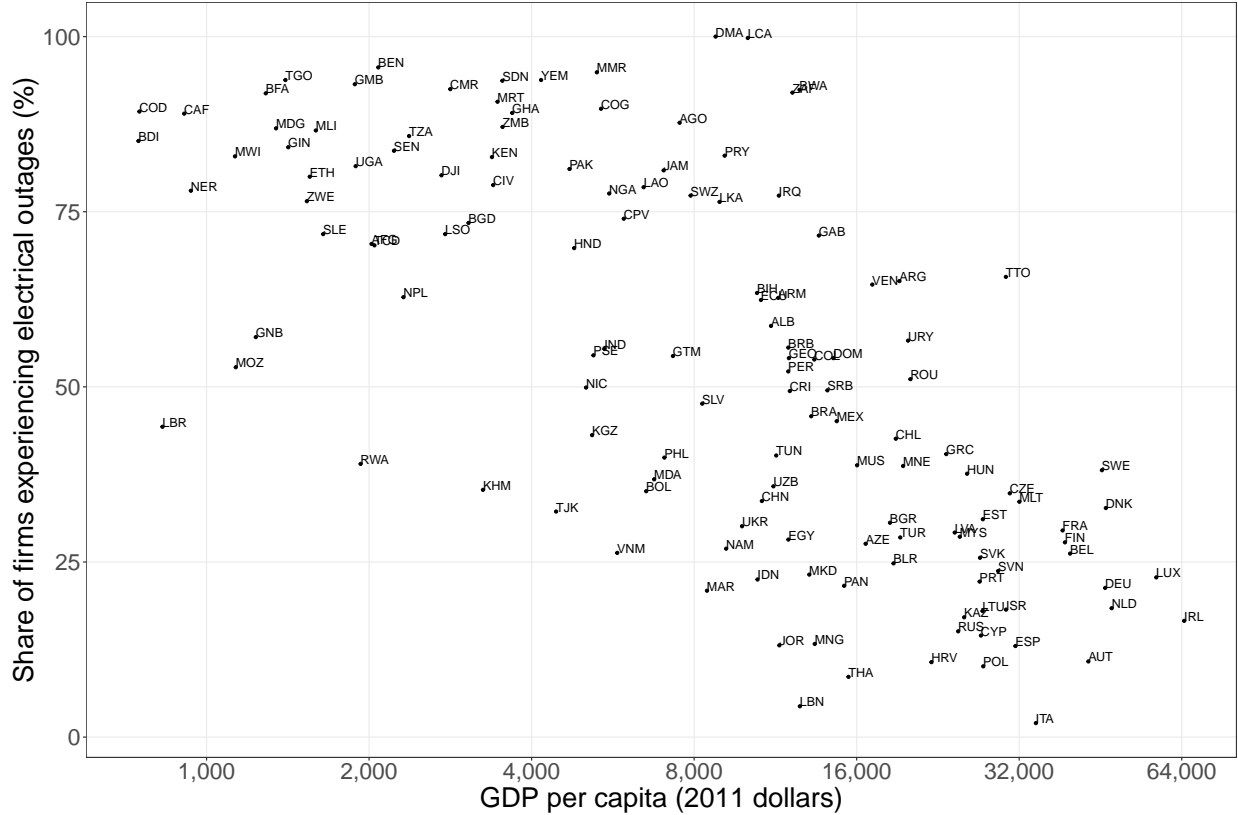


Figure 3: Relationship between GDP and Electricity Consumption

either country did at that level of GDP.

One notable difference between Figure 2 and the previous figure is that the difference between the US time series and the cross-country relationship vanishes much quicker when looking at consumption. In particular, although the 1907 US starts at substantially lower electricity consumption than a modern country with the same GDP per capita, by the 1930s the difference in consumption between the United States and modern countries with comparable levels of GDP is minimal. The story is somewhat different for the UK which lags behind the US on energy consumption per capita and does not reach the consumption level of a modern country with the same GDP per capita until the 1950s, although this difference is hard to interpret without reliable data on electricity access in the UK for the same time period.

In addition to access and usage, there is also substantial cross-country variation in the reliability and availability of electricity. Figure 3 displays how the percentage of firms who self-report ever experiencing electricity outages varies with GDP per capita. These data are taken from the World

Bank Enterprise Surveys (WBES) which span a variety of years, differing from country to country. For all countries possible, we use GDP per capita data from the year in which the enterprise survey took place, ranging from 2006 to 2018. Figure 3 displays a clear pattern; electricity is available much less reliably in poor countries. The variation is substantial. In many of the poorest countries, unreliable electricity is nearly universal with around 90 percent of firms reporting that they experience electrical outages. This number falls below 25 percent for the richest countries.

Although purely observational, these facts provide motivation for further research on the role of electricity in driving structural transformation. They also provide some basic stylized facts against which to test macroeconomic models of structural change incorporating electrification. One broad takeaway from Figures 1 and 2 is that the modern experience of electrification and structural change may be substantially different from the historical experience, at least for the US and UK. These historical episodes of rapid electrification seemed to have occurred when these countries were fairly rich relative to not-fully-electrified countries today. This difference may be key in explaining the contrast in results between evaluations of electrification using historical episodes and data and those examining modern interventions in developing countries.

2.2 Quasi-Experimental and Experimental Evidence

While the previous subsection focused on summarizing motivating cross-country facts without regard for causality, there is a moderate and growing literature using experimental and quasi-experimental techniques to evaluate the causal effect of electrification. Our discussion is not exhaustive and instead aims to provide a concise and accurate summary of the broad findings of the literature.

The earliest papers to investigate the causal effect of electrification on development outcomes largely exploited mass roll-outs of electrical infrastructure and electricity to households by government infrastructure projects. Broadly speaking, many of these papers address endogeneity concerns using a "least cost" instrumental variables strategy. Geographic features such as hills, mountains, and rivers all influence how much it costs to bring electricity to a particular area but are plausibly exogenous to demand-side concerns. As such, the predicted cost of electrification for an area constructed only from the surrounding geography serves as a plausible instrument for whether the area is connected to the electrical grid.

Two prominent early papers among these are Dinkelman (2011) and Lipscomb, Mobarak, and

Barham (2013) which employ a least-cost IV identification strategy in South Africa and Brazil respectively. Both papers find results consistent with electrification inducing structural change. Dinkelman (2011) finds increases in earnings, hours worked, and female employment while Lipscomb, Mobarak, and Barham (2013) find increases in income, education, and formal employment. The most direct evidence for the link between electricity and structural change comes from Rud (2012) who uses data from India and finds that electricity increases manufacturing output.

Other papers employing a similar approach find similar results. Chakravorty, Emerick, and Ravago (2016) find that electrification lead to large increase in income in the Philippines (although unlike the previous studies they find no impact on employment, with gains driven by agricultural income). In a similar vein as Rud (2012), Kassem (2021) finds that electricity access increases the number of manufacturing firms, workers, and manufacturing output in Indonesia. Grogan (2016), Grogan and Sadanand (2013), and Salmon and Tanguy (2016) all find that electrification increases female employment.

While the unit of observation varies from study to study, ranging from individuals to entire counties, it's important to note that a least-cost instrumental variable design based on geography generally exploits high-level variation in electrification. If geography makes it costly to bring electricity to one individual, it is also costly to bring electricity to their neighbor. Thus we generally view these studies as measuring the effect of electrification "at scale", which may differ from the effect of providing electricity to only a few households or villages in an area. We will return to potential implications of this in Section 3.

A similar strand of literature uses geographic or temporal variation in the roll out of electricity to measure the impacts of electrification in a differences-in-difference or natural experiment framework. Like the least-cost IV studies, these papers generally estimate the causal effect of electrification at a large scale. Unlike the IV literature, these papers establish causality either through a naturally occurring control group and plausibly exogenous variation in which areas are chosen to receive electricity (as in the natural experiment literature) or through a parallel trends assumption which facilitates comparisons between the treatment and control even if assignment to treatment is not random (as in the difference-in-differences literature).

Prominent among these studies is Moretti (2014) which examines the Tennessee Valley Authority as a natural experiment (using proposed but failed authorities as controls) that built electricity

infrastructure (along with other infrastructure investments) and provided of electricity to a specific region of the United States. They find that the program effectively induced structural change in the long-run, raising aggregate income and manufacturing employment permanently. Similarly, Lewis and Severnini (2020) study the roll out of the power grid in the United States and find that electricity boosted incomes in remote rural areas and led to (sub)urbanization in rural areas near cities. Also in the United States, Vidart (2022) finds that electrification led to substantial increases in female labor supply and human capital.

Other papers employ difference-in-difference designs outside the US. Van de Walle et al. (2015) find that gaining electricity access increased consumption and employment in rural India. Khandker, Barnes, and Samad (2013) study Vietnam and find that being connected to the grid increases household income and education. Finally, Dasso and Fernandez (2015) find that electrification in Peru increased employment, female earnings, and the probability of engaging in non-agricultural work for females.

Excepting Moretti (2014) which takes the form of a natural experiment, our discussion of the causal effects of electrification has been limited only to studies employing instrumental variable or difference-in-difference techniques. In recent years, researchers have turned to experimental approaches to more precisely investigate the effects of electrification. We focus on Lee, Miguel, and Wolfram (2020b), who experimentally evaluate the effects of providing a grid connection to unconnected households in rural Kenya, as well as experimentally varying the cost of electricity to households in order estimate demand curves. Unlike the papers above, they find very limited economics impacts of electrification and nothing consistent with the idea of electricity as a driver of structural change. Although being connected to the grid does seem to change household behavior (they spend less on kerosene and are more likely to own appliances), there is no change in economic behavior. Households neither earn nor consume more, are no more likely to be employed or operate a business, and do not experience any gains in physical health or human capital (but do report higher life satisfaction). Altogether, these results seem to suggest that, at least for modern developing countries, electricity does not seem to have large effects, casting doubt on the idea that it can play a driving role in structural transformation.

One notable paper missing from our discussion so far is Burlig and Preonas (2021). Although not a randomized controlled trial, they estimate the effect of village-level electrification in rural

India using a regression discontinuity. Like Lee, Miguel, and Wolfram (2020b), they find almost no effect of electricity on economic outcomes (on average); electrified villages experience no change in average consumption or earnings, agricultural or non-agricultural employment, number of firms, or human capital. We defer further discussion of this paper to the next section.

Overall, despite a strong intuitive link between electricity and structural change, the evidence for such a relationship seems unclear. Cross-country relationships and historical episodes of development make it clear that the two happen in tandem in the aggregate. Quasi-experimental evaluations of these historical episodes support a causal interpretation of this link; however, recent rigorous evaluations call this link into question by failing to find any impact of electrification on economic outcomes for households or villages. These conflicting results serve as a starting point for our next section where we discuss promising paths for future research.

3 Promising Paths for Future Research

In this section, we lay out open questions about the relationship between electrification, economic growth, and structural change. We view these questions through the lens of the conflicting results found in the previous section, operating under the assumption that these studies, generally speaking, accurately identify the impacts of electrification (i.e. they are not the result of publication bias or misidentification) and discuss questions whose answers may be able to reconcile the conflicting results. We identify three broad paths forward, each of which is supported by some preliminary evidence. We discuss the recent research into each path and suggest how each research agenda could be pushed forward.

3.1 Electricity reliability

Electricity reliability may be as important as electricity access in driving structural transformation. As documented in Figure 3, gaps between lower income and higher income countries are stark not only for electricity access but also for electricity reliability. If the link between structural change and electrification is driven primarily by the use of electricity-intensive production machinery, then unreliable connections that experience regular outages, unstable voltage, or insufficient power to operate such machines may rationalize the small experimentally estimated effects of being provided

a grid connection. Consistent with this, data from the World Bank Enterprise Survey indicates that firms frequently perceive unreliable electricity as a key constraint (McCulloch & Zileviciute, 2017), and household surveys have found that households are willing to pay more for more reliable electricity (Alberini, Steinbuks, & Timilsina, 2022; Deutschmann, Postepska, & Sarr, 2021). In this section, we discuss two sets of questions related to electricity reliability. First, how important is reliable electricity for outcomes associated with structural change? Second, what causes poor reliability and what policies can help? Better understanding both the consequences of improving reliability and the root causes of unreliable grid power is important for policy. The answers may influence how policymakers wish to optimize investments to improve the grid (e.g. extending the grid and creating new customer connections versus improving the quality of the existing grid) and how to prioritize power supply during times when capacity is insufficient to supply all sources of demand.

3.1.1 How important is improved electricity reliability?

Fried and Lagakos (2021) explore the general equilibrium impacts of improved electricity reliability in quantitative macroeconomic model of electricity production and usage. Central to their analysis is the point that even if microeconomic estimates of the effects of electricity shortages are small (as in e.g. Allcott, Collard-Wexler, and O’Connell, 2016; Cole et al., 2018; Fisher-Vanden, Mansur, and Wang, 2015) the general equilibrium macroeconomic effects can be large. The core mechanism is that unreliable electricity substantially reduces firms’ incentives to invest in electricity-complementing capital; even relatively short outages require idling electrified machinery, leading to under-investment.

This research suggests that the link between electricity reliability and investment and long-run firm output is potentially large. Work aimed at confirming and quantifying this link causally is a promising path forward in and of itself and would be extremely useful in providing quantitative discipline to future models. Exploiting a permanent change in electricity reliability is key to accurate measurement of these effects as investment is forward looking and beliefs about future reliability are the key driver of investment decisions in the current period. Similarly, measuring outcomes at a sufficiently long follow-up time is important as the capital stock is a slow-moving object, particularly in developing countries where financial frictions are severe. More broadly, future research could

further investigate which aspects of grid reliability are most important in increasing electricity usage. Are shorter more frequent outages preferable to longer but less frequent ones? Do voltage surges play a key role? Do outages matter for firms more than households? The answers to these questions are unclear but would suggest immediate actions for policy makers to mitigate the consequences of unreliable grid power. In this vein, the only study we are aware of is Meeks et al. (2021) which finds that elimination of household voltage surges (through the installation of smart meters) increases household appliance purchases and usage.

A related channel is that the productivity of many uses of electricity seem to be non-linear in electricity reliability. By this, we mean that some machines would more than double their usefulness if electricity reliability increased from 50 percent to 100 percent. As a simple example, a fridge is substantially more useful if electricity is fully reliable as any outage risks spoiling the contents of the fridge — perhaps a minor issue in the case of food but a large issue in other cases, such as storage of vaccines and medical supplies. Other examples include incubators of premature newborns, food preservers (e.g. electric dryers), or electric irrigation pumps (unwatered crops may die). Unlike a piece of production machinery, such as a thickness planer used for producing wood products (as in Bassi et al., 2022), which would be half as productive on average if electricity was only available half of the time, these machines and many others may be entirely unfeasible for certain uses if electricity is sufficiently unreliable. Research, either empirical or structural, on this phenomenon is scant and could prove a promising path.

In addition to this work, more macro work exploring and quantifying the potential link between electricity reliability and macroeconomic outcomes is necessary. Unreliable electricity may reduce incentives (or ability) to invest in human capital, similar to the effect for physical capital described in Fried and Lagakos (2021). If incumbent firms receive preferential access to rationed electricity — either through straightforward political preference or through Special Economic Zones — this creates a wedge in the cost of using electricity that can lead to misallocation of the Hsieh and Klenow (2009) variety. In a similar vein, recent work finds that the impact of electrical outages depends on firm size; microenterprises (i.e. those without employees) experience large reductions in output during outages while large firms experience small, if any, decline (Hardy & McCasland, 2021). Such heterogeneity would also have implications for how unreliable grid power interacts with misallocation and aggregate output.

3.1.2 What explains poor reliability, and what policies may help?

While research into the effects of unreliable grid electricity is important, equally important is improving our understanding of the fundamental reasons for poor reliability and what can be done to improve reliability. From a technical standpoint, poor reliability can arise for two reasons. First, demand may exceed supply, leading to rationing of power. Second, even if generation capacity is sufficient to meet demand, failure in transmission between generation and the end-user can cause low quality power supply. While both types of problems have technical explanations which may relate to underinvestment and insufficient or substandard grid infrastructure, recent research suggests that poor grid reliability may be thought of as a political economy problem arising from limited state capacity and policy choices to pursue lower-price-lower-reliability service.

The largest body of research in this direction focuses on how political constraints that cause low prices for electricity may explain poor reliability. Burgess et al. (2020a) present evidence that subsidies to household electricity prices — either explicitly or implicitly through tolerance of non-payment (an issue which we will further discuss) — lead to operating losses for public electricity distributors and that distributors respond by rationing power. The result is unreliable grid electricity from frequent outages due to rationing. Other research supports this explanation; for example, Kabir Malik and Singh (2015) finds that the unbundling of State Electricity Boards in India led to an increase in capacity utilization, suggesting that plants were previously idling capacity rather than failing to supply electricity due to capacity constraints.

The key political difficulty is that free or heavily subsidized electricity is a common and popular stance. Huenteler et al. (2020) document that in many lower-income settings, electricity is priced below cost. This may be due to the acceptance of the idea that electricity is a human right (as suggested by Burgess et al., 2020a) or could simply be due to the fact that households in developing countries enjoy the amenities of home electricity (e.g. phone chargers, light bulbs, and television) but cannot pay unsubsidized rates. In other words, unreliable but affordable electricity may simply be preferable (in partial equilibrium) to reliable, expensive electricity for voters. Beyond low officially sanctioned prices, de facto prices may be even lower due to acceptance of non-payment. For example, Mahadevan (2019) and Min and Golden (2014) find patterns that suggest politicians in India successfully take actions such as manipulating billing data to provide free electricity for

political gain.

The political economy problem is made worse by the fact that grid reliability, unsurprisingly, appears to be a large determinant of demand for electricity and political support for higher electricity prices. In essence, people are unwilling to pay higher prices for unreliable electricity — or support local leaders who advocate for this — which leads to revenue shortfalls for public utility providers who then must ration power to control losses (as discussed above) which leads to unreliable grid power, a so-called "revenue trap". Dzansi et al. (2018) document this cycle in Ghana; households exposed to more power outages are more likely to have unpaid electricity bills. Similarly, Khanna and Rowe (2020) find that non-payment rates increase substantially in response to higher electricity prices in India.

If these forces are sufficiently strong (i.e. enough to induce multiple equilibria), temporarily accepting higher losses may be enough to break public utilities out of this revenue trap or at least reduce losses even in the long term. This notion is strengthened by the fact that improved electricity reliability can lead to large increases in investment and output, suggested in Fried and Lagakos (2021), as higher long-run output can be taxed and these funds can be used to further escape the revenue trap and/or pay off debt accrued while running the utility at a loss. Together, these factors suggest that carefully crafted policy may make it possible to escape a revenue trap at relatively little cost (in present discounted values terms) and accelerate the process of structural change. Further research into these issues, both macroeconomic analysis of such a policy and microeconomic research investigating the presence and strength of a revenue trap, seems a productive path.

These political economy problems may also be partially addressed by technological solutions, through advancements that make revenue recovery more effective and reliable. Prepaid electricity meters, which must be loaded with credits, dramatically increase repayment rates and decrease the cost of revenue recovery (Jack & Smith, 2020). Home solar systems, financed over time, may also help improve access to reliable electricity as these systems operate entirely off grid (see e.g. Lang, 2020); however, it's important to note that even in the presence of off-grid solar, there are still many households who benefit from access to grid power (Burgess et al., 2020b). Carranza and Meeks (2021) examines how load-reduction from adoption of energy-efficient appliances may improve electricity quality. Other work (Gonzales, Ito, & Reguant, 2022; Jha, Preonas, & Burlig, 2022; Ryan, 2021) examines how investments in transmission lines could promote within-country

trade in electricity, influencing the price and quality of electricity that utilities make available. On another note, it is possible that non-technological interventions such as threat of consequences for non-payment or targeted messaging can be effective in changing payment norms (Coville et al., 2020; Pomeranz, 2015). Similarly, if stolen electricity or politically-motivated bill manipulation are a large reason that de facto electricity prices are too low, improved monitoring and strengthened sources of accountability (discussed further below) can help counter these dynamics that lead to lower prices and, consequently, lower quality electricity.

A second body of related literature focuses on how limited accountability can lead to low-quality public service provision. This is relevant to electrification, as the national electricity utility is heavily subject to government regulation, if not state controlled, in many countries. Given well-understood technical specifications for electricity transmission, the immediate causes for chronically poor electricity reliability is expected to be closely related to enforcement of existing regulations and specifications for infrastructure construction and management. If poor accountability allows corruption to divert funds away from their intended activities, this can cause poor quality services. Some work has shown that lack of observability in the provision of public goods and services can cause poor quality public goods (Ferraz & Finan, 2008, 2011; Olken, 2007). This is suggestive that in the context of electrification, improving transparency may similarly help improve power quality. These types of policy solutions may also help address concerns that electoral incentives may skew the allocation of public goods (Briggs, 2021; Burgess et al., 2015; Harris & Posner, 2019). Wolfram et al. (2023) examines contracting conditions imposed by foreign aid funders and third-party monitoring as sources of accountability for private contractors employed by the national utility in Kenya to do construction for mass electrification; they find that these mechanisms can in fact play a role in improving initial construction quality. Future research could usefully examine the relative importance of these causes of poor reliability, and examine what policies can improve accountability and service delivery. For example, improved transparency could improve service quality through electoral accountability. On the other hand, improved transparency could also be seen as improving state capacity, say by allowing managers to better monitor workers or allowing law enforcement agents to better monitor utility actions.

3.2 Complementary inputs

Electricity may be necessary for structural transformation, but its effects are likely to depend on additional investments or inputs. In this section we discuss possible complementarities between electrification and public investments, such as roads and ports. Such investments may influence the returns to using electricity by improving market access. We also discuss complementarities with private investments, such as electrical equipment, as returns to electrification may depend heavily on the presence of these complementary inputs. It is useful to examine what constraints may lead private actors to underinvest, and what kinds of policies can help counteract those constraints. Developing better answers to these questions is important for policymakers — electrification efforts may be targeted differently based on the presence of key complementary inputs or bundled with complementary programs in ways that can increase their impacts.

3.2.1 To what extent are complementary public investments important?

"Big push" infrastructure projects that invest heavily in electrification tend to also invest heavily in other infrastructure. If there are complementarities between electricity and other infrastructure, the effects of such a project could be larger than the effects of electrification alone. This could explain why evaluations of large-scale projects have measured links between electrification and structural change while individual-level experiments have not.

Early work along these lines suggests that these complementarities may be large. Moneke (2020) studies the expansion of the electricity network and road network in Ethiopia and finds dramatic increases in manufacturing employment as well as various measures of income (e.g. household expenditures, durable ownership, and nightlights) for areas that received an expansion of both. Although the focus on the paper is on the effects of roads with and without electricity rather than the other way around, this is suggestive evidence that the effects of "big push" investments may be large. Improved roads may facilitate market access for outputs produced by firms using electricity. They may also lower the cost of constructing and maintaining electricity infrastructure.

Further work examining the complementarities between electricity investment and other infrastructure would help shed more light on this question. In addition to roads, governments often make large investments into ports, railways, and water supply and knowing how electricity interacts with

these other investments can help policymakers prioritize and target investments to have the largest effect on growth.

In addition to physical public infrastructure, the effects of electrification may depend heavily on the level of financial infrastructure. Although micro-credit initiatives have been expanding rapidly, it is well known that households and firms in developing countries face substantial financial frictions which may mitigate the effects of electrification. For example, if electricity is provided to firms but firms are unable to finance electricity-using machinery, the effects may be limited. Similarly, if newly electrified smallholder farmers are unable to finance new equipment (e.g. electric dryers, pumps, or grain mills), the effects may be limited.

As far as we know, there is no research into the interaction of electrification and financial frictions at either a household or a firm level on macroeconomic outcomes such as structural change. This is likely due to the computational difficulty of solving multiple-asset models — as would arise when modeling firms with electrically powered capital and non-electrically powered capital or households with savings and electricity-using durable goods — in the presence of credit constraints. However, increases in computing power as well as recent computational techniques (e.g. Auclert et al., 2021, particularly Appendix E) mean that such models can now be solved fairly easily on a typical laptop. Additionally, the emergence of canonical models of financial frictions, microenterprise, and development (e.g. Buera, Kaboski, & Shin, 2011; Itskhoki & Moll, 2019) provide a strong framework upon which to build models that study how the interaction of financial frictions and electrification impact development outcomes. Empirical work on these interactions would also be extremely useful, both for its own sake and also to provide motivation and discipline to such models.

3.2.2 To what extent are complementary private investments important?

While complementarities with public infrastructure may be important, electricity is also complementary to private investment in physical capital (e.g. electrical appliances and machinery) and human capital (e.g. the skills necessary to operate and maintain complex electric machines). If electricity is provided but physical and human capital are in short supply, the full gains and structural change may not be realized. Recall Figure 1 which showed that the historic expansion of electricity in the United States took place at a much higher level of GDP than today's expansions in low income countries. In other words, modern evaluations of electrification are necessarily studying

poorer countries than historic evaluations. Rich countries possess more physical and human capital than poor countries (Hsieh & Klenow, 2010) and if electricity is strongly complementary to both of these, it's possible that the returns to electricity in these countries are simply smaller than the returns evaluated in historic analyses.

Direct evidence on the complementarity of electricity with other inputs is scarce and more research here would be useful. Ryan (2018) uses experimental assignment of energy consulting, which boosted energy efficiency, to Indian manufacturing firms to estimate a production function and finds that capital and high-skill labor are strongly complementary with electricity (while low-skilled labor and intermediates are substitutes). Vidart (2022) builds an OLG model and finds, among other things, evidence consistent with a skill-bias in electricity.

Relatedly, future research can usefully identify market frictions that distort levels of private investment. As a technology that is useful only in combination with electrical equipment and appropriate building wiring, any inefficiencies affecting these strongly complementary goods can impact the expected benefits of using electricity. For example, low levels of investment in electrical equipment by households and firms may be affected by poor access to credit or poor information about the costs and benefits of different equipment – including their existence, quality, and cost of usage. While large a body of research on such barriers to adoption exists for other technologies and suggests types of information and methods of propagation that may matter (see Jack, 2013, for a review of related work on agricultural technologies), to our knowledge little comparable work has been done in electrification.

It is unclear to what extent physical and human capital complementarities can fully explain the differential effects of electricity measured in the empirical literature. While the empirical results above suggest that electricity is complementary to physical and human capital and thus lower levels of capital will lead to lower (marginal) returns to electricity in partial equilibrium, it is hard to see whether or not this explanation continues hold in general equilibrium or can generate a large enough quantitative effect to fully explain the measured differences. If electricity is truly less productive on the margin due to fewer complementary inputs in today's low and middle income countries, simple neoclassical theory predicts that electricity prices should be substantially lower (as marginal benefits and marginal costs must be equal) and, as a result, electricity access may lead to larger increases in output despite small marginal gains per unit due to lower per unit prices. In a such a

model, how would the effect of electricity access differ between lower and higher income countries and what assumptions are necessary to ensure that the general equilibrium effect of lower prices does not undo the lower marginal return to electricity? The answers are not straightforward.

It is also unclear whether or not the prediction of such a model that electricity prices should be lower in poorer countries is true. Rigorous documentation of how electricity prices for households and firms vary with development would be a useful contribution itself, complicated by the fact that *de facto* and *de jure* prices may differ. An alternative — and opposite — theory could posit that electricity production in lower income countries is extremely inefficient, leading to high electricity prices that limit the transformative effect of being provided an electrical connection. Such a notion sounds equally plausible but operates on opposite principles. Further theoretical and empirical work is needed to help illuminate which of these aspects is more consistent with data. Additionally, conventional wisdom holds that electricity markets are highly regulated and that many of the issues with electricity in developing countries stems from a breakdown of markets entirely (see again Burgess et al., 2020a). In light of this, it's possible that a neoclassical approach may not have much explanatory power and research expanding such a framework to account for the realities of energy markets would also be productive.

3.3 Migration, Agglomeration, and Effects at Scale

Another possible explanation that requires more research is whether the effects of electrification vary based on the scale of the intervention and, if they do, the channels through which scale matters. As we mentioned in Section 2, one key difference between the early literature that found a positive causal relationship between electrification and structural transformation and the modern literature finding small effects is that the former tended to examine large-scale "big push" instances of electrification that impacted entire regions while the latter studied the effects of providing an electrical connection to a single household in a village.

Preliminary evidence supports this idea that the scale of electrification may be important. For example, Burlig and Preonas (2021) exploit a regression discontinuity and diff-in-diff introduced by India's national electrification program to estimate the effects of electrification at the village level. Importantly, their quasi-experimental design allows estimation of electrification's effects for small (median size about 1000) and large (median size about 2000) villages separately and finds that while

electrification seems to have no effect on small villages, large villages experienced an increase in per-capita expenditure. Although the effect is noisy (and not quite statistically significant), the point estimate is large and suggests that electrification almost doubled expenditure per capita. While not conclusive, this is suggestive evidence that scale is an important determinant of the effects of electrification and is consistent with broader patterns across settings as discussed in Section 2. Overall little is known about what channels may drive such a scale effect. Research aimed at confirming the effect and investigating the driving forces behind it would be productive.

Composition and selection effects are one potential channel that could explain why larger electrified areas seem to benefit more than smaller areas or individual households, and more generally may be important for understanding heterogeneous effects of electrification across settings. Compositionally, larger villages and towns may have more existing complementary public infrastructure (and may be large precisely for this reason), may have more and better skilled workers, and may have better financial and educational infrastructure required to make private investments in physical or human capital that complement electricity. They may also feature different pre-existing industries, including higher or lower prevalence of small-holder farming. Thus it may not be the largeness of the areas, per se, that drives the large increases in incomes from electrification, but rather these differences in composition that are effectively proxied by size.

Geographic selection and migration may also play a substantial role in explaining such a compositional effect. Grid expansion is expected to be non-random. If utilities first connect larger towns and villages, or areas with certain industries or public sector agencies, with the understanding that higher-return areas should be prioritized, then any additional grid expansion may simply be targeting areas with lower and lower marginal returns. In this view, it is possible that in many countries most of the gains from expanding electricity access have already been realized and additional electrification has little to offer in terms of structural transformation.

Further, most low and middle income countries are characterized by high levels of rural-urban migration,¹ highlighting the fact that individuals themselves can select into regions and thus choose whether to migrate somewhere with or without electricity access. Recent studies on the effects of electricity access necessarily focused on electrification of rural areas, as urban areas have already

¹This certainly is true for India (studied by Burlig & Preonas, 2021) and Kenya (studied by Lee, Miguel, & Wolfram, 2020b) both of which have been experiencing growing urban populations for decades.

largely been electrified. Given the flow of population from rural to urban areas, it seems likely that individuals with highly productive ideas or skills that complement electricity (or those with a high amenity value of electricity) would migrate away from rural areas and towards urban centers, disproportionately leaving in rural areas those with lower valuations for electricity. Relatedly, even within rural areas, early adopters of electricity are likely to be self-selecting, as a result later adopters, who are the targets of today's rural electrification efforts, would be expected to exhibit low returns. Here, the implication for the potential effectiveness of modern rural electrification programs is disappointing; there could be relatively little output and income gains from rural electrification (at least in the short term) simply because those with high returns to electricity already had access through spatial migration or early adoption. Under this story, an unintuitive relationship is possible – namely that rural electrification could reduce the rate of structural change. If access to electricity is a driver of rural-urban migration, bringing electricity to rural areas could reduce these flows

Another potential channel not unique to electricity may be agglomeration effects of the Glaeser (2010) variety. Electrification of an entire area, as opposed to individual households, allows new business to form simultaneously and co-locate, may increase the education and the skilled labor pool from which businesses recruit locally, and could lead to increases in local demand as successful business owners spend their profits. If these agglomeration effects are strong, small observed effects from providing electricity to a single household does not rule out large aggregate effects of electrification at a regional or national level.

Thinking about electricity as an amenity may provide another related explanation for why the effects of electrification could differ with scale. Although our discussion so far has mostly treated electricity as an input into production for firms and farmers, households derive substantial utility from the use of electrified appliances, particularly radios, televisions, and lighting. A region that receives electricity and is now able to provide these amenities has a substantial advantage in attracting skilled labor, such as entrepreneurs, teachers, and technicians (needed to maintain electrical machines). While this infusion of skilled labor alone would accelerate the pace of structural change, it could also interact with the agglomeration effect discussed in the previous paragraph and further strengthen such an effect. To our knowledge, there is very little work looking into either of these questions, although both intuitively seem to be of first-order importance in understanding the impacts of electrification.

4 Conclusion

In this paper, we document some basic cross-country facts on the relationship between electrification and income and discussed the existing literature on the economic effects of electrification and how this literature informs our understanding of the role that electrification plays in driving structural transformation. We have also laid out paths for productive future research. Many of these paths are motivated by the desire to fill holes in the existing literature and address unanswered policy-relevant questions, but just as many arise from thinking about what questions need to be answered to develop a well-grounded macroeconomic theory of structural transformation and electricity.

We expect progress on this agenda in future research to benefit from both micro and macro approaches. For example, microeconomic studies that examine the consequences of relaxing constraints on improved reliability or access to complementary inputs can help establish crucial empirical facts. Studying heterogeneous effects of current and historical large-scale programs, or studying researcher-led interventions along these lines may be fruitful. At the same time, macroeconomic modeling is likely to be needed to better understand the general-equilibrium effects of relieving such constraints and more generally for understanding effects of electrification at scale.

Our hope is that this summary and these paths will provide a useful framework through which young researchers (i.e. graduate students) and researchers interested in electrification but new to the literature can view the existing results and paths in which they can make contributions. We also hope to convince researchers currently working on electrification that viewing their own work through the lens of structural transformation is important.

As a so-called general purpose technology, the applications of electricity are essentially endless. Many credit the development of electricity (and general purpose technologies more broadly) as fundamental to the long-run growth of the modern world (see e.g. Bresnahan & Trajtenberg, 1995; David, 1990; Ramey, 2020), making the relationship between structural change and electrification a clear area of interest for researchers interested in understanding economic development. This importance combined with its policy relevance today, overlap with other big questions in economics, and the fact that there is a lot about electrification that is unknown makes this an exciting area of research.

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