Addressing the Challenges of Sustainable Electrification in Africa through Comprehensive Impact Evaluations

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List of abbreviations and acronyms

AERC	Africa Economic Research Consortium
AfDB	African Development Bank
CCEDA	Climate Change and Economic Development in Africa
COVID-19	Corona Virus Disease 2019
DiD	Difference-in-Differences
DRC	Democratic Republic of Congo
GAM	Gender Analysis Matrix
GDP	Gross Domestic Product
GW	Gigawatt
HOMER	Hybrid Optimization of Multiple Electric Renewables
IEA	International Energy Agency
IPWRA	Inverse Probability Weighted Regression Adjustment
MTF	Multi-Tier Framework
MVTEs	Multi-Valued Treatment Effects
NN-PSM	Nearest Neighbour Propensity Score Matching
NORAD	Norwegian Agency for Development Cooperation
OSeMOSYS	Open Source energy MOdelling SYStem
PAYGo	Pay-As-You-Go
PSM	Propensity Score Matching
QTE	Quantile Treatment Effects
RDD	Regression Discontinuity Design
SDGs	Sustainable Development Goals
SEFA	Sustainable Energy for All
SETI	Sustainable Energy Transitions Initiative
UNDP	United Nations Development Programme
WTP	Willingness-to-Pay

Abstract

Access to electricity leads to overall economic growth through improved agricultural and firm productivity, public service delivery, and enhanced household investment in human capital, net income, and general quality of life. Yet more than 540 million people in Africa still lack electricity today, and many more suffer from unreliable power supply. The considerable untapped renewable energy potential, and the associated rapid reductions in cost, make sustainable and decentralized electricity service a promising option for the continent, for transforming these deficits into opportunities. However, knowledge on how to finance and implement new models of electrification remains limited, because the results from prior impact evaluations are inconclusive and do not cover all relevant interventions or dimensions. Following a review of policy and research issues, we propose that five essential principles should guide future research efforts in this domain: (i) use of mixed/multi methods that adequately cover the varied implications of electricity access, (ii) choice of econometric methods that provide more credible estimates of impacts, (iii) use and combinations of more informative treatment data, (iv) careful theorizing and consideration of the potential for heterogeneous treatment effects, and (v) accounting for effects from treatments of different magnitudes. We demonstrate the last three of these with an illustrative application of the World Bank Multi-Tier Framework data for Kenya. New insights emerge as research moves from a focus on average treatment effects to heterogeneous and multi-valued treatment effects. Notably, the impacts of electrification may depend on the extent to which households and other economic agents can make complementary investments to benefit from an electricity connection. Thus, electrification may need to be combined with complementary programmes, for example, those that make appliances more accessible and affordable. A greater focus on holistic impact evaluation approaches is needed to make economic research on sustainable electrification more informative and policy-relevant.

Key words: *Africa; Climate change; Electrification; Gender; Multi-Tier Framework; Kenya.*

JEL classification codes: *C18; Q42; Q48.*

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1. Introduction

Modern energy is "the golden thread that connects economic growth, increased social equity, and an environment that allows the world to thrive" (United Nations Development Programme [UNDP], 2012). The centrality of modern energy in economic wellbeing is reinforced by the strong and positive cross-country correlation between electricity consumption and Gross Domestic Product (GDP) per capita (Burke et al., 2018). Thus, developed economies partly owe their current status and wealth to the available modern energy services. Despite recent declines in poverty, considerable untapped renewable energy potential, rapid cost reductions for solar and other new solutions, and incremental progress in electricity access in recent years, many agents (i.e., households, businesses, and public facilities) still lack access to sustainable electricity.

The focus of some of today's leading development policies globally is on increasing household electrification (Lee et al., 2020b).[1] The share of the global population with access to electricity increased from 83% in 2010 to 90% in 2018.[2] The population without access to electricity was 789 million in 2018, down from 1.2 billion in 2010 (IEA et al., 2020). At the same time, the International Energy Agency (IEA) estimates that, if society is to have a reasonable (>66%) chance of avoiding dangerous climate change, global energy-related carbon emissions should have peaked in 2020 and fall by more than 70% over the next 35 years (IEA et al., 2020).

The world's electricity access deficit is concentrated in sub-Saharan Africa, where electrification climbed from 34% in 2010 to 47% in 2018 (IEA et al., 2020).[3] About 548 million people currently lack access to electricity in sub-Saharan Africa, and nearly 80% of these live in rural areas. Fourteen African nations are among the global top 20 countries with access deficits.[4] With 85 million and 68 million people lacking access to electricity in 2018, Nigeria and the Democratic Republic of Congo (DRC) had the world's largest absolute numbers lacking access (IEA et al., 2020), but the continent is home to 30 countries having electrification rates below 50% (IEA, 2019). In addition, among those having connections to electricity, many confront poor reliability of supply and other problems, and household usage of electricity, therefore, tends to be very low. This situation of poor quality power supply has been identified as low-tier electricity access (Falchetta et al., 2020). To put the numbers in context, per capita annual electricity consumption in Africa averages 181kWh, compared to 6,500kWh in Europe and 13,000kWh in the United States (African Development Bank [AfDB], 2015).

Lack of access to electricity hampers a range of economic and social outcomes. In agriculture, power is needed for irrigation, mechanization (e.g., land preparation, cultivation, and harvesting), post-harvest storage and processing, and transport facilities. Power is needed to pump, transport, treat, and distribute water, particularly in the production of drinking water, and in water and wastewater treatment. Lack of electricity in over 90% of Africa's primary schools contributes to children's educational under-performance, and unelectrified households have inadequate lighting to support study after dark (AfDB, 2015). These deficiencies harm children's educational outcomes and reduce their opportunities to lead productive lives. The healthcare sector is also affected, as uneven power supply and power cuts prevent the use of life-saving equipment and affect the refrigeration of medications. In the home, the vast majority of Africans use stoves that rely on solid fuels, which are not just inefficient but emit pollution that is harmful for health and the environment—household air pollution causes an estimated 600,000 fatalities each year, half of them among children under the age of five (AfDB, 2015).

Power shortages cost Africa 12.5% of GDP in lost production time, compared with 7% loss in South Asia (AfDB, 2015). More than 30 African countries experience frequent power cuts and load-shedding (AfDB, 2015). Resultant opportunity costs amount to as much as 2% to 4% of GDP annually, and undermine sustainable economic growth, jobs, and investment (AfDB, 2015). The lack of reliable grid electricity in many countries often compels firms and households to use expensive diesel generators or water pumps that generate power at a cost of about US$D 0.40 per kilowatt-hour (AfDB, 2015) compared to a median cost of about US$D 0.10 per kilowatt-hour for grid electricity.

The electrification needs of the African continent remain unsatisfied, partly as a result of low generation capacity. Installed grid-based power generation capacity has been steadily increasing, reaching 194 GW in 2015, but is still not sufficient.[5] Fulfilling SDG 7.1.1 will require connecting 205 million households, and addition of at least 160 GW of new generation capacity (AfDB, 2015). For least-cost universal access, both centralized and decentralized solutions are needed (IEA et al., 2020): 130 million new grid connections and 75 million off-grid connections (AfDB, 2015).

Mass government-subsidized electrification programmes can be traced back to the "big push" development efforts of the previous century, particularly in the United States. Electrification can similarly be a key factor in Africa's structural transformation for economic development and attainment of the Sustainable Development Goals (SDGs). Accordingly, access to electricity has re-emerged as a key priority for policy makers and development partners in Africa. However, the evidence on how much, and in what ways, modern-day residential electrification contributes to economic development is not conclusive (Lee et al., 2020b). While it is true that more developed economies consume more electricity per capita than undeveloped ones, this correlation alone is not sufficient to establish a causal link between electrification investments and growth. To be sure, economic development is conditioned on a complex set of supply and demand impediments for a range of goods and services that extend well beyond energy services alone, including factors that influence actors' opportunities (e.g., income, knowledge, and data availability) and their decision context (e.g., rurality, policies, markets, and supply chains). Since investments in electrification are costly, a reductionist approach that ignores other development impediments may carry substantial opportunity costs, devoting scarce resources to a project that, on its own, will prove insufficient, and that therefore may end with electricity supply systems that lack long-term sustainability (McRae, 2015).

Accelerating the transition to electricity thus requires substantial new public and donor investments, as well as enabling policies. Just as essential, however, are data analytic products and impacts evaluations that support policy- making and also facilitate the diffusion of effective and transformational private innovations. Unfortunately, despite numerous investors and growing investment, knowledge on effective policies, interventions, and investment models remains limited (Pattanayak et al., 2019; Jeuland et al., 2021), and data that would aid planning and investment are scattered and not readily accessible. There is, therefore, an urgent need for research that involves and facilitates an interaction between scholars and practitioners working on access to electricity, and that uses a common language and holistic methods for influencing positive sectoral change. Accordingly, this paper investigates what we can learn from contemporary electrification policies and past research on the impacts of electrification, and how future research can become more innovative, timely, and relevant to real-world problem-solving.

The rest of this paper is arranged as follows: Section 2 reviews policy and research issues to inform a framework for future research. Section 3 proposes a framework for innovative future research. Section 4 demonstrates partial use of the framework in the case of Kenya. Section 5 presents the conclusions of this research.

2. A review of policy and research issues

Policy issues

Reducing electrification deficits will require concerted efforts that depend on sound policy. Policy frameworks will require consistent updates and enforcement to support innovation, such as off-grid solutions and new types of business models and public-private partnerships. AfDB (2015) highlights essential policy thrusts to catalyse, and remove obstacles to, universal high-quality electrification among unserved populations in Africa.

African governments will need to set up the right enabling policy environment. It is imperative to have an enabling environment in which the private sector can operate, either as Independent Power Producers or participants in public-private partnerships. The required reforms will mostly be around sector deregulation and price policies (cost-reflective tariffs) that attract private-sector investment, especially in renewable energy technologies such as wind, solar, and hydro. The unbundling of power generation, transmission, and distribution, and the involvement of the private sector in many of these aspects, especially where public-run utilities are unable to provide adequate services such as in rural off-grid communities, are necessary. There is a need to also ensure appropriate risk allocation to remove obstacles to electrification.

To be sure, African governments must proactively allocate much more funding to electrification. Yet power sector utilities already constitute a major fiscal burden for many countries. Utilities will need technical assistance to enable restructuring for loss reduction and revenue recovery. African governments need to consider a gradual withdrawal of subsidies to loss-making power utilities, and must redirect the subsidies to productive energy investment, social protection, and targeted connectivity for the poor and hard-to-reach last-mile consumers.

The adoption of energy-efficiency measures is a key enabler to power sector decarbonization. Reforms, such as the withdrawal of subsidies to oil-based products, such as kerosene and many other fossil fuels, are essential to allow power utilities to capitalize on investment in low-carbon technological innovation. On the other hand, when electrification or modern fuels confer positive externalities (e.g., for provision of better public goods, or enabling clean cooking with its substantial environmental and health spillovers), there is a strong efficiency argument for continued subsidization (Jeuland et al., 2018).

A constraint associated with the rollout of electrification by the public sector is the lack of a critical mass of bankable projects (AfDB, 2015). Aggregating project development capital, and channelling it through highly capable private-sector organizations involved in world-class project development, including private-sector-financing and legal institutions, will help increase the number of bankable projects.

A strong case can be made for a continental approach to electricity infrastructure. This will require strengthening the backbone of the pan-African smart grid. For example, many of the continent's water resources are shared (Wolf et al., 1999), so that damming and hydropower generation must typically be negotiated or financed regionally. Collective action would reverse blockages in situations where most regional power pools are hampered by a lack of funding, political instability, and weak cross-border regulations. Continental public goods could be insulated from the day-to-day conflicts between sovereign nations and selfish political leaders.

There is a need for the systematic implementation of full-country electrification programmes. This requires launching end-to-end energy system turnarounds. These programmes will include energy system planning, the restructuring of national regulatory environments, matching donors to targeted interventions, and bringing in the private sector to drive the development of capacity additions and new connections.

Given the high level of technological complexity in the electricity system, scientifically- and technologically-grounded mathematical models are often used to inform decision-making. Widely used broader energy models include MARKAL–TIMES, GCAM, LEAP and MESSAGE. Some energy models focus more narrowly on the electricity sector, for example, WASP, PLEXOS–LT, OptGen, PROMOD, EnergyPLAN, GridView, SWITCH, electrification pathways, OSeMOSYS, OnSSET, and HOMER. While these models collectively establish a diverse range of analytical capabilities that have been applied with success in recent years, one common theme across them is a general neglect of characteristics that are important in developing countries, such as resource constraints, supply shortages, the predominance of informal economies, and the preferences of local stakeholders (Baker et al., 2021).

There is also a clear trade-off between cost, reliability, and access (Baker et al., 2021), that is tightly tied to questions about tariff structures and subsidies. Subsidies make electricity more affordable to low-income residents, but reduce revenues that can support reliability and sustainability, thereby challenging long-term financial and technical performance (Burgess et al., 2020). This trade-off is important, as it relates to how infrastructure investments are prioritized, particularly when resources are limited. In brief, countries and decision-makers must choose between different potential capital investments, e.g., household connections, transmission lines, transformers, generation capacity in various regions, maintenance, environmentally sustainable technologies, among others. These choices will have implications for the extent and quality of access, and, therefore, for the economic and social development objectives that depend on modern energy services, but the precise implications of specific choices remain poorly understood and highly uncertain.

These policy issues indicate that there is scope for more economic research that clarifies stakeholder preferences and the specific trade-offs involved in different approaches to electrification, in order to generate new and more actionable knowledge than that which already exists. Baker et al. (2021) demonstrate how social science research at the intersection of energy justice, stakeholder preferences, and electricity policy can inform complex electricity planning models. In particular, stakeholder preferences for electricity solutions on local and national scales can be mainstreamed in economic and technological models of electricity. This work provides a bridge between the social knowledge and the technical knowledge needed to plan the evolution of the power system (Baker et al., 2021).

Research issues

Many aspects of electrification have received attention in the literature, and these are discussed in several recent and relevant review papers. For example, Bernard (2010) discusses the historical context of electrification initiatives in sub-Saharan Africa; Bonan et al. (2017), Bos et al. (2018) and Bayer et al. (2020) provide general reviews of electrification that focus especially on the experimental or quasi-experimental evidence for various types of household and firm or community outcomes; while Morrissey (2018) gives particular attention to the productive uses of electricity. There are also comprehensive literature reviews of electrification. For example, Peters and Sievert (2016) review studies using African data, van de Walle et al. (2017) provide a general review of literature on electrification, while Bayer et al. (2020) and Jeuland et al. (2021) conduct systematic reviews.

The focus of this review is to consider the implications of this broad literature for electrification efforts in Africa. Earlier research, mostly using cross-country panel regression models, suggests that access to electricity is a driver of GDP growth and economic development (Burke et al. 2018; Lee et al., 2020a.[6] On the strength of this evidence, the industrial and private sectors tend to get priority of access, largely because of the energy-intensiveness of their activities. At the regional level, electrification increases in parallel with manufacturing output and agricultural and manufacturing employment (Lee et al., 2020a). However, there are potentially also extensive economic opportunities to be gained from the provision of electricity to households and communities.[7] At the household level, electrification could lead to improvements in measures of income and well-being, the latter as reflected in expenditure and consumption, or increased leisure time (Lee et al., 2020b). Income improvements may be generated through higher educational outcomes, better health, and therefore increases in employment opportunities in value-added processing, as well as reduced agricultural sector losses to spoilage, to name a few. Many of these services rely on community-level public service quality as well, which may improve with electrification. Empirical evidence is crucial to guide decisions on further roll-out of electrification that supports important services for households, especially in rural areas.

Despite their potential importance, there are only a handful of studies that rigorously investigate the impact of rural electrification on the welfare of households and communities. These studies have found that electrification can: improve labour supply and the income of household members (Dinkelman, 2011; van de Walle et al. 2013; Grogan & Sadanand, 2013), increase productivity of the manufacturing sector (Rud, 2012), provide positive externalities even to neighbouring villages that are not electrified (van de Walle et al., 2013), improve schooling (van De Walle et al., 2013; Khandker et al., 2012; Khandker et al., 2013), increase time children can allocate to studying (Barron & Torero, 2014), improve human development and asset values such as housing (Lipscomb et al., 2013), reduce biomass use, and improve health (Samad et al., 2013). Almost all these findings come from studies undertaken outside Africa, with the exception of Dinkelman (2011), which investigated the effects of electricity network roll-out on rural employment growth and female labour market participation in South Africa. Studies in sub-Saharan Africa, in contrast, often find only muted impacts and benefits that are nowhere near the costs of investment that are needed to support universal electrification (Peters & Sievert, 2016; Jeuland et al., 2021). This highlights the need for improved understanding on the types of interventions that are most effective, to inform more efficient prioritization of resources.

The treatment effects can be estimated on a broader range of household outcomes than those highlighted in the foregoing, including aspects such as monthly electricity spending, how many different appliance types are owned (such as mobile phones, radios, televisions, among others), monthly spending on kerosene, the share of household members who are employed or own businesses, household asset value, and health status.

Refining past research approaches

As noted in the foregoing, past studies of the impacts of electrification, for example, on income, labour employment, and education-related outcomes, have yielded a wide range and sometimes contradictory measures of effects (Lee et al., 2020a). To make sense of the results, coming as they do from numerous studies over many years, requires that their results be systematically analysed and categorized across specific dimensions.

Consider education-related outcomes, for example. In theory, electrification enables higher quality and more reliable lighting, which allows children to study for longer in the evening, and this can result in improved test scores and higher schooling attainment. Early studies suggested that electrification has large, positive impacts on education-related outcomes, for example, in Vietnam (Khandker et al., 2013 [Instrumental Variables Method]), but more recent studies, particularly from African settings, find no statistically significant changes in school enrolment or test scores (van de Walle et al., 2017 [Instrumental Variables Method]; Burling & Preonas, 2016 [Regression Discontinuity Method]; Lee et al., 2020b [Randomized Control Trials Method]). As results have been observed to vary in similar ways for other outcomes, such as income and labour employment, there is a need to better understand the drivers of these mixed results and to help inform more relevant future research, that would, for example, provide insight on how electrification should be targeted.

To understand the inadequacies of past research, we follow Lee et al. (2020a) in discussing the existing set of studies, focusing on potential validity problems, econometric issues, the nature of the interventions being studied, the potential for spillovers, and differences in regions and populations (or context-specific heterogeneity) as the key drivers of their results.

Internal validity of research designs and potential for spillovers

Electricity grid infrastructure is costly and long-lived, rarely randomized, and likely to be endogenous to a variety of economic and political factors. Many studies on electrification, therefore, use an instrumental variable approach to isolate the variation in the electrification variable that can be attributed to a set of exogenous cost considerations (Lee et al., 2020a). Examples of instruments that have been used in this literature include: land gradient (Dinkelman, 2011; Bensch et al., 2019); a variable simulating how the grid would have evolved had investments been based solely on geographic cost considerations (Lipscomb et al., 2013); distance between the unit of analysis and the nearest grid infrastructure (Khandker et al., 2012; van de Walle et al., 2017; Chakravorty et al., 2016).

The ideal instrument is, on the one hand, generally correlated with the average cost of getting a household connected and, therefore, the probability of electrification, and, on the other hand, not correlated with the outcome variable. However, it is hard to rule out the possibility that the correlation between the instrument and the dependent variable runs through other channels besides electrification (Lee et al., 2020a).[8] For example, economic activity in mountainous regions is distinctly different from that in flat areas, calling into question the use of an instrument such as topography. The variables typically used as instruments do influence, not only the cost and placement of electrical infrastructure, but they also likely influence the placement of other needed infrastructure (e.g., roads, telecoms, etc.), with important implications for the correct measurement of causal impacts on the outcomes of interest. The validity of any geographic cost-based instrument is always questionable *prima facie*. Coming up with a new breed of more appropriate, practical, and robust instruments would be helpful for researchers working on evaluations of electrification interventions.

Other common approaches to impact evaluations of electrification interventions also often suffer from internal validity problems. Among quasi-experimental methodologies, prior studies have used difference-in-differences or matching approaches (Bensch et al., 2011; Khandker et al., 2013), or exploited geographic or other discontinuities (Burlig & Preonas, 2016; Fetter & Usmani, 2020), in order to minimize threats to causal identification. Each of these designs faces different validity threats that can be hard to fully remove. For example, difference-in-differences designs remove confounding by time-invariant unobservables, but do not remove the time-varying equivalent. Matching methods, meanwhile, allow accounting for observable differences between treated and comparison observations, but are vulnerable to confounding by unobserved heterogeneity. Comparisons based on discontinuities may be locally valid near an eligibility cutoff, but their validity becomes questionable as units having greater distance from that cutoff are included in the comparison (Angrist & Rokkanen, 2015).

Meanwhile, even fully-randomized experimental interventions may face internal validity threats due to spillovers. The design or scale of an electrification programme can also result in local spillovers that are not easily measurable using household data. Many historical initiatives to expand electricity access were, not only large in scale, but also included investments in generation capacity, transmission lines, and other forms of public infrastructure. Studies that measure impacts at the household level will not capture spillovers to the same extent as studies that observe outcomes at the regional level (Lee et al., 2020a). For example, the impacts of an electrification programme that electrifies schools, health clinics, and local enterprises, is not comparable to some recent electrification efforts that have targeted only households. Programmes that involve large upgrades in transmission capacity and increased connections, may have very different spillovers depending on whether or not they are accompanied by increased generation that supports greater energy consumption overall. In general, there is a need for better categorization of the types of electrification interventions, and for nuanced interpretation of treatment effects that is consistent with their particularities.

The upshot of the validity issues is that, any given estimate of the impacts of electrification should be treated with a fair amount of scepticism, and that researchers should be transparent about the strengths and limitations of their work. At the same time, an obsession with internal validity, at the cost of relevance and other considerations, is also unlikely to be helpful given the constraints with infrastructure evaluations of this type. The research community should, therefore, work to synthesize and contextualize findings better. This recommendation is in line with our prior argument that more be done to systematically analyse and categorize electrification impact study results across specific dimensions that are of policy interest.

Incomparable interventions

A major complication in interpreting the varying estimates of the impacts of electrification across studies is the lack of comparability across interventions and measures. These aspects affect the generalizability—or external validity—of the results from specific studies. For example, electrification impact studies in Africa and elsewhere have often considered grid extension into rural or unconnected communities, but the nature of the electricity supply that is delivered varies considerably. For example, the quality of an electricity connection typically varies across programmes, and can be measured in terms of the reliability, capacity, legality, and other aspects of the power supply, all of which influence the energy services that can be supported. Importantly, grid extension will deliver electricity that is very different from that provided by decentralized stand-alone solar home systems, or solar and other types of mini-grids. The majority of impact evaluations consider rural electrification from grid extension, rather than increased investment in existing grid infrastructure or improved service delivery to those already connected. Distributed renewables are hardly considered, despite the fact that these are increasingly seen as the least cost approach to electrification in many parts of sub-Saharan Africa.

Different regions and populations

A second aspect related to external validity is contextual: In brief, the impacts of electrification depend on what individuals are able to do with that electricity. Across regions, differences may arise due to the presence or absence of complementary infrastructure and amenities (Fetter & Usmani, 2020). Electrification may yield greater impacts in regions with better access to complementary infrastructure such as roads and linkages to neighbouring markets and commercial centres. Impacts may also be greater in areas with existing industries that can benefit from cheaper sources of power or in regions that are experiencing rising income levels owing to favourable commodity price shocks (Fetter & Usmani, 2020; Lee et al., 2020a). Note that these aspects may also be subsumed into instrumental variables estimates of impacts, if, for example, the so-called exogenous variables that affect the likelihood of electrification also pick up these complementarities.

Even across individuals within the same society, effects may differ because of variation in individual income levels or access to credit. Wealthier households are, by virtue of their ability to purchase more appliances, likely to be better positioned to benefit from access to electricity, especially in the short term.

Though past studies have used creative and novel ways to address the endogeneity of the electrification variable, it is also important to consider more systematically these complementarities and to entertain the possibility of heterogeneous treatment effects, as these factors could influence the interpretation of estimated impacts (Lee et al., 2020a).

Unexplored research frontiers

Building on these comments, we note that there are several areas of research enquiry that have not been explored to any significant extent in the context of electricity access on the African continent. Cutting-edge research on electricity access, use, and reliability should be informed by approaches deployed in the broader energy space.[9] Recent methodological advances are now available for deployment to emerging regions such as Africa.

The adoption of electrification technologies (e.g., connections to the grid) and the factors driving adoption are important issues, both from a policy and an academic perspective. Justifications for low connection rates—including liquidity and credit constraints, risk attitudes, and lack of information about the benefits—rely on insights from the more general technology adoption literature, but the case of grid electricity has only minimally been studied. It can by no means be taken for granted that all households and enterprises in newly-connected areas connect to the grid (Lee et al., 2016b).

In fact, in some grid-covered areas, connection rates remain extremely low (see, for example, Lee et al., 2016c and Lenz et al., 2017). A grid connection might not be a cost-effective investment for some beneficiaries, because of low energy consumption or a lack of opportunities to use electricity commercially. Likewise, adoption plays an important role for solar technologies, since households, especially, in remote regions and poor strata—the natural target region for off-grid technologies—will in many cases not be able to afford their high upfront investment costs.

Grimm et al. (2017), for example, observed in a Randomized Controlled Trial that, freely distributed solar kits are intensively used by recipient households (which proponents of the people-only-value-what-they-paid-for argument would not expect), but that energy usage patterns suggest an amortization period of 10-12 months. For most poor households, this will be too long to justify the investment, due to very tight liquidity constraints and high discount rates. The very low willingness-to-pay (WTP) for solar lanterns observed by Urpelainen and Yoon (2015) in India supports this observation.

For on-grid electrification, Greenstone (2014) notes that "rural uptake of electricity sometimes remains low once the region is connected". This is because rural consumers often use a portfolio of fuel sources, even when electricity is available owing to low incomes, the high cost of switching fully to electricity (e.g., the need to purchase appliances), and concerns about reliability and over-reliance on single energy sources. It is, therefore, also important to explore how to encourage uptake once the connections are established. In fact, connecting to the grid is not always a privately beneficial action if connection fees are too high to be amortized within a reasonable period.

While the literature on impacts of electricity is growing, the evidence that exists on the adoption behaviour of economic agents in newly-connected areas is mostly limited to studies that consider connection costs and payment schemes. For example, Bernard and Torero (2017) exploit the random provision of household discount vouchers in Ethiopia and find positive effects of greater discounts on connection rates. Furthermore, they observe that social interactions play an important role in a household's choice to connect to the grid, as neighbours of voucher receivers are also more inclined to connect. Lee et al. (2016c) observe very low connection rates, between 5% and 22% in Western Kenya (where connection fees are very high), and suggest that subsidies and new approaches to financing connections are needed in order to exploit the full potential of existing infrastructure. Lenz at al. (2017) observe only modest connection rates (around 60%), and low consumption levels by connected customers, in newly-electrified areas in rural Rwanda, despite the existence of instalment schemes that spread connection fees over one year. For micro-enterprises, Peters et al. (2011)

observe modest connection rates in Benin and note that connecting to the grid is not profitable for all firm types.

Across the continent, there appears to be substantial potential for lower-cost, green distributed energy resources, such as solar mini-grids, to advance socio-economic development among lower-income rural households (e.g., job creation, gender equality).[10] Yet evidence on effective approaches is thin, and given these potential customers' sensitivity to costs and low energy use patterns, the literature raises doubts about the income-, health-, and education-enhancing impacts of the investments. Specific linkages, e.g., displacement of harmful kerosene and paraffin lighting, the supply of power to healthcare equipment and cold storage, etc., should be investigated carefully, yet interventions must also be evaluated holistically. Policy makers often assert that productive energy uses will (i) allow sustainable provision of energy, (ii) facilitate bill payment, and (iii) raise both income and the willingness to pay (WTP) for energy, without providing evidence on the conditions and complementary infrastructures that facilitate such productive uses, outside of urban or industrializing areas and sectors.

Moreover, the energy access problem inherently calls for interdisciplinary solutions. STEM disciplines and perspectives are important for designing, building, and continuously upgrading the quality and reliability of infrastructure, supported by new measurement techniques and devices. However, the traditional engineering and technology bias in this sector ignores many challenging issues related to cultural acceptance of new technology, innovation in business models and cost-reducing supply chains (Bhattacharya & Palit 2016; Krithika & Palit 2013), the enabling environment, and the need for policy action. The latter can stimulate demand, especially among the rural poor, as well as help society to internalize social costs and benefits efficiently and equitably (Jeuland et al., 2021, Sovacool et al., 2018). It is critical that engineers appreciate this complexity when they work to devise solutions that fit in an intervention ecosystem, while social scientists and public health scholars must understand technical nuances and constraints when designing effective policies. Equally important is the need to understand the nature of structural inequality that impedes development and better outcomes among disadvantaged populations in sub-Saharan Africa and across the globe.

The importance of considering governments' policy support and public investment also cannot be ignored (Bhattacharya, 2012), especially when considering integration between grid and off-grid electrification (Urpelainen, 2014). Various disciplines (including economics, political science, and public policy) provide insight on approaches for tackling spillover effects, and reducing inequality and its harms.

Finally, there are trade-offs across objectives (reaching more people vs. reaching fewer people better) that likely vary with local opportunities and institutions, in terms of social costs and benefits, innovation dynamics, and sustainability. As such, there is a need for a measurement and evaluation toolkit to understand outcomes better, and to learn how to improve interventions.

3. Innovative framework for future research

To account for the issues raised in Section 2, we propose a framework for the production of novel research on electrification in Africa.[11] Foundational examples that can inform new research on electrification in sub-Saharan Africa include: individual studies and syntheses of research on the impacts of rural electrification (Jeuland et al., 2021; Peters & Sievert, 2016; Morrissey, 2019; Jeuland et al., 2020a); analyses of the coping costs of unreliable electricity and the willingness to pay for improved electricity provision (Meles, 2020; Meles et al., 2021); work on the demand for off-grid energy technology, appliances, and services (Grimm et al., 2017; Lukuyu et al., 2021), including gendered aspects (Alem et al., 2018; Klege et al. 2021); and measurement of the distributional implications and impacts of tariffs and the pricing of products (Hassen et al., 2021), and of income transfer effects on energy consumption (Gelo et al., 2021). Five new areas proposed for future research on the impacts of electrification are considered below.

Innovations in the type of data used for access to electricity

Nearly all existing studies on the impacts of electrification in Africa use data from primary surveys conducted by economists (Lee et al., 2020a). The key explanatory variable (access to electricity) has historically been characterized as binary, i.e., households are considered to either be connected to the grid (on-grid) or not (off-grid). A binary indicator for access to electricity has many shortcomings, which could be addressed in at least four ways.

Under-grid option

While households may either be connected to the national grid or not, some unconnected households close enough to a low-voltage line could be connected at relatively low cost and should be considered to be in a separate category (under-grid) to those who are prohibitively far away from the national grid. This distinction matters because the appropriate policy responses for under-grid agents or households (which could relatively easily be connected to the grid) may be different from those for truly off-grid communities, which may require the large-scale expansion of the national grid or alternative electrification solutions (Lee et al., 2020b). For congruence with policy options, non-binary variables, perhaps based on distance of actual connection cost, should be used to capture the ease of connection to electricity, for those presently unconnected.

Reliability of access to electricity

Another dimension of access to electricity is the reliability or quality of service, an issue that plagues grid-connected households in Africa. The World Bank's Energy Sector Management Assistance Programme has introduced a new approach called the Multi-Tier Framework, in which the measured level of electrification gradually increases with the capacity, duration, reliability, quality, affordability, legality, and safety of electricity access. As more data describing these various features in representative country-level samples is rolled out, as has been done for Ethiopia, Kenya, Rwanda, and Zambia, options to move beyond simple connection status in the analysis of impacts will emerge, allowing for increased insight on how the nature of electrification technology determines different outcomes. For example, it would be reasonable to expect that basic access is sufficient for low-power services like electric lighting, while refrigeration and other more energy-intensive services that enable reduced spoilage necessitate a higher level of access.

Use of remote-sensed data sets such as nightlights

Electrification of non-residential customers such as factories, small businesses, schools, and health centres has largely remained uncaptured in access-to-electricity measures collected in economic surveys, which most typically indicate the proportion of households in the population with connections. Such omissions and aspects related to reliability may be captured through the use of satellite data on nightlights, however, or by using satellite image recognition methods for detection of energy-related infrastructure such as transmission lines, solar panels, or water pumps. Previous seminal applications have shown that combining nightlights and human settlement data sets can proxy electricity access levels and track the rollout of electrification at a local scale. These data have also been used to model changes in electricity consumption within provinces (in countries where disaggregated data are available for validation purposes), detect power supply disruptions and outages, map power transmission and distribution infrastructure, and measure economic development and inequality sub-nationally (Falchetta et al., 2020).[12] Lee et al. (2020b) use local population density and the brightness of nightlights to generate a measure of access to electricity for Kenya. Falchetta et al. (2020) process six years of high-resolution population, nightlights, and settlement data for sub-Saharan Africa to derive multi-dimensional estimates of access to electricity. Today, new and improved satellite data products that are being frequently updated allow for considerably greater precision through improved sensitivity and spatial resolution. Use of such measures is likely to capture access better and also allows for tracking of changes over time, opening up new avenues for examining the extent to which economic transformation lags or foretells changes in electrification.

Differentiating grids from microgrids and stand-alone solar

The grid is just one way to expand electricity access. Microgrids[13] or mini-grids have also generated substantial interest, especially for geographically remote communities that are prohibitively expensive to connect to a national grid. On the one hand, demand for connections to private microgrids is strongly influenced by the availability and quality of the national grid, and is likely to be low in locations where the national grid is anticipated to provide subsidized access in the near future (Fowlie et al., 2019; Burgess et al., 2019). On the other hand, a number of private operators have built microgrids that are operational and generating revenue, suggesting that demand is positive in some settings (Lee et al., 2020b). Moreover, an increasing number of African countries are incorporating microgrids as a key component of their national electrification strategies, e.g., Ethiopia's National Electrification Policy 2.0 and Benin's Plan Directeur.

Decentralized, renewable energy technologies, not only allow off-grid households to potentially leapfrog the conventional grid, but their business models also typically necessitate collection of high frequency data on energy consumptions, to allow alignment of generation capacity from solar irradiation with adequate sizing of batteries to support consumption during peak demand periods. Similarly, the home solar sector (solar lanterns and solar home systems) has seen its estimated penetration rise rapidly across sub-Saharan Africa (Lee et al., 2020b). Solar lanterns offer just enough power to meet the basic standard of electrification in the World Bank's Multi-Tier Framework, but solar home systems supported by battery power are becoming increasingly attractive for off-grid remote households, and beginning to operate under PAYGo models that require high frequency measurement of consumption. Therefore, access to electricity through microgrids and standalone home solar systems ought, not only to be accounted for in measures of access, but may also provide new insights on how households, small businesses, and other actors consume energy.

Innovations in econometric analysis

Impact evaluation studies of electrification efforts typically estimate versions of a regression equation in which the dependent variable is a key outcome of interest, such as labour supply or schooling years for an observed unit (typically a household or a region) at a certain point in time, and the key explanatory variable is a measure of electrification that is usually binary (Lee et al., 2020a). See Figure 1 for a generalized impact evaluation approach to electrification. Obvious issues arise if the coefficient on the electrification variable is interpreted as capturing the causal effect of switching from no connection to an electricity connection. The primary challenge is that electrification is likely to be correlated with other factors that jointly determine current and expected levels of the outcomes of interest. For example, consider a setting in which there were no subsidies for electricity connections. The households that are connected to power are probably those with higher incomes, wealth, access to credit, and education, or those who believe they would benefit most from an electricity connection (Lee et al., 2020a).

Figure 1: The impact evaluation approach to electrification

Treatment
The key intervention to be evaluated is an electrification intervention in a specific country or region.

Outcome
The key outcomes include intermediate (e.g., employment) and final measures of welfare (e.g., income, health)

Theory of change
Electrification affects the outcomes of the connected via specified channels. One can enumerate and show linkages across inputs, outputs, intermediate outcomes, and impacts following the intervention.

Evaluation design
To estimate the various impacts of electrification, one uses true experiments or ex-post quasi-experimental observational design with matching-based estimators. Purposively collected survey data are required.

Identification strategy
Impact evaluations are typical based on one of the following approaches: instrumental variables regression, simple difference-in-means of treated and control observations, difference-in-differences, regression discontinuity design, and randomized controlled trial. These are all used to estimate the difference in outcome indicators between treatment and control groups. Average and heterogeneous treatment effects can be recovered, subject to statistical power considerations.

At a higher level, electric-grid investments or programmes that favour off-grid connections may be targeted towards districts that are favoured by a governing political party, and these same districts could also be in line to benefit from a myriad of other government assistance programmes. Alternatively, investments may be targeted towards areas that are predicted to face greater access deficits or have greater potential for economic growth, perhaps due to the presence of a valuable local commodity or the establishment of a new industry that will attract additional labour, further boosting local economic activity. Clearly, it would be misguided to conclude that extending electrification to areas lacking this potential would generate the same effects. Here, the electrification variable could capture a broader pattern of government favouritism (Lee et al., 2020a), or simply reflect contextual realities that challenge attempts to generalize from the observed impacts.

In these examples, omitted variable bias would lead the analyst to overestimate the causal effect of electrification. These issues can be addressed using various well-known econometric strategies, including instrumental variables, difference-in-means, difference-in-differences, regression discontinuity designs, and randomized controlled trials.[14]

Instrumental variables (IV)

The IV strategy relies on identifying a variable that is correlated with the treatment variable but otherwise independent of the outcome being evaluated. This variable can then be employed within a two-stage least squared (2SLS) regression. The difficulty lies in finding a suitable variable, since "weak instruments" can lead to bias (Sovacool et al., 2018), while the validity of the exclusion restriction from a theoretical perspective is often an article of faith. There is growing scepticism in the empirical economics community about the validity of many IVs; recent studies have tried to avoid this issue by using the alternative econometric strategies enumerated above.

Matching and difference-in-means

Matching involves finding subjects in the treatment and control groups who are as similar as possible on the basis of relevant, observed variables (e.g., energy consumption, building type, location). Approaches vary considerably, from very rudimentary exact matching based on relatively few characteristics (as in epidemiological case-control studies), to statistically-based approaches, such as propensity score matching or synthetic control. Depending on data availability, the plausibility of similarity across sample groups can vary (Sovacool et al., 2018) but none can fully account for confounding by unobservables; matching can also be combined with other approaches, namely, difference-in-differences, to improve the validity of this design (Jeuland et al. 2015).

Difference-in-differences (DiD)

DiD estimation is a very common impact evaluation strategy that exploits the availability of panel data, where repeated observations are made on the units of analysis at two or more points in time. Neither of the units of analysis receives the treatment in the first one or more periods, and only some receive it in the subsequent follow-up periods. The latter become the treatment group while the remainder are the control group. The approach is versatile and can be applied to many intervention contexts, and relies on the assumption that, after controlling for relevant variables, the outcomes in the two groups would have changed identically in the absence of the treatment (Sovacool et al., 2018).[15]

Regression discontinuity design (RDD)

The RDD design leverages a feature of some interventions that assign subjects to treatment and control groups according to whether an observed, continuous variable lies above or below a specific eligibility threshold. For example, the threshold may be an income or poverty measure that is used by regulators to define eligibility for a subsidy scheme. The variable may or may not be associated with the relevant outcome, but provided the association is smooth, no bias should result (Sovacool et al., 2018). For example, Burlig and Preonas (2016) exploit a population-based eligibility cutoff in India's massive national rural electrification programme launched in 2005, whereby only villages above a certain population level were eligible in the initial programme phase. When assignment rules (in this case, a cutoff based on village population) are followed diligently, the regression discontinuity design method removes selection bias (Lee et al., 2020a). In cases where the criteria are not as strict, a fuzzy RDD approach may remain possible (Hahn et al., 2001).

Randomized controlled trials

Randomized controlled trial experiments involve assigning participants prospectively to treatment and control groups using some random method, which guards against confounding by selection bias and unobservable variables (since treatment and control observations are statistically identical). True experimental designs are distinguished by: a) random selection and/or assignment of participants; and b) researchers having control over extraneous variables (Sovacool et al., 2018).[16] Experimental designs can be implemented in lab or field settings, as well as via trials, games, and simulations. Recent examples of true experiments are Barron and Torero (2017) and Lee et al. (2020b). In an experiment, researchers also often (though not always, since they may be involved in such aspects in quasi-experiments as well) have greater control over data collection procedures, for example, designing the questions administered through household surveys. As a result, it is often possible to collect data on a wider range of outcomes and potential mechanisms than are typically available in administrative or secondary data sets that are often used in non-experimental studies (Lee et al., 2020a).

The obvious hurdle to implementing a randomized controlled trial of electricity infrastructure is that researchers may find it hard to persuade policy makers to randomize the placement of infrastructure. On the other hand, randomized controlled trials have been more successfully used to measure the impacts of off-grid systems, for example, in looking at the effects of home solar access on child study times and test scores (for example, Furukawa (2014) in Uganda, Rom et al. (2017) in Kenya, and Grimm et al. (2017) in Rwanda).[17] Encouragement designs that randomly vary electricity connection prices are also an example of experimental approaches to evaluation of energy access (Lee et al., 2016b).

Innovations on heterogeneous treatment effects

Systematic research investigating the possibility of heterogeneous electrification treatment effects would be useful, both to clarify the reasons for the divergent evidence observed in existing literature, and to enable better targeting and planning of interventions. Impact evaluation methods can deal with heterogeneity of impacts according to specific variables. For example, Quantile Treatment Effects (QTE) can be estimated to investigate whether a particular treatment favours or penalizes specific groups across the population distribution as specified in some variable of interest. Khandker et al. (2014) estimate a quantile regression of overall household income and expenditure on household electrification. New approaches to analyse heterogeneity compare households based on how much they are willing to pay for an electricity connection, a household characteristic that is rarely, if ever, captured in observational data sets. Lee et al. (2020a) estimate heterogeneous treatment effects of electrification and show evidence of substantial heterogeneity in treatment effects, even within a sample of poor rural households that were all without electricity at baseline. The main point is that the impacts of electrification can vary substantially across different types of individuals, even within a relatively homogenous sample of poor rural households in neighbouring villages, in ways that are difficult to observe.

The question of how the impacts of electrification may vary across countries, or regions within a country, is likely to be of keen policy interest, as:

- understanding which households and areas are most likely to benefit from grid connections can help policy makers to better target grid investments; and

- if wealthier households are more likely to utilize and benefit from access to electricity, then expansion of the rural grid infrastructure could exacerbate economic inequality in rural areas of low-income countries, an outcome that is seldom discussed in the current policy debate.

Moreover, heterogeneity may arise due to the nature of the investment or intervention. If the policy focus is on connecting households rather than centres of economic production and activity, impacts may be quite different. Similarly, an approach that subsidizes connections may benefit some households who are eligible and capture those subsidies, but may still not reach a level of access needed to spur economic development. Or there may be very distinct treatment effects from providing higher levels of electricity access (e.g., tiers 4 or 5 in the Multi-Tier

Framework) compared to basic access. As the body of empirical evidence on the impacts of electrification has increased, several existing reviews (e.g., Bonan et al., 2017; Bos et al., 2018) offer a path forward for articulating testable hypotheses that systematic studies of heterogeneity could help clarify.

Innovation with multi-valued treatment effects

Building on this last point, impact evaluation also acknowledges that treatments could be multi-valued in nature, i.e., different doses of treatments are administered, leading to distinct impacts. Important phenomena such as non-linearities and differential effects across treatment levels cannot be captured with a traditional dichotomous treatment econometric approach. Considering multi-valued treatment effects (MVTEs) allows for potential efficiency gains in estimation. It also allows for joint inferences across and between multiple treatment levels (Cattaneo, 2010).

Innovation with mixed/multi methods

Even more generally, there is great potential for research studies that would combine methods to obtain enhanced understanding of what changes in communities and regions following electrification programmes. Here we are advocating for much more cross-fertilization that combines frameworks and methods from multiple disciplines or domains of research. In some cases, this mixing will lead to new methods, or methods that are only beginning to emerge among researchers.

In particular, quantitative (surveys, statistics, modelling) and qualitative (interviews, focus groups, observation, case studies) methods have different strengths and weaknesses. Quantitative methods are best for testing hypotheses or estimating the magnitude of the relationships between variables (e.g., correlation), while qualitative methods are best for exploratory studies or accessing more in-depth information, such as how social actors construct meaning (Sovacool et al., 2018). Even among quantitative methods, impact evaluations are typically aimed at precise estimation of specific relationships between variables, whereas structural modelling or systems approaches are more common in the engineering sciences aimed at general understanding of complex interconnections between variables. An example of a multi-methods evaluation that combines both quasi-experimental impact evaluation with systems modelling and mixed survey methods is Jeuland et al. (2020b), which aimed to provide a holistic picture of the consequences of a large-scale water and sewer infrastructure project in Jordan.

Gender is a running theme in debates around electrification and, as such, Gender analysis is a complementary method for impact evaluations in this domain. Numerous studies have examined whether electrification affects the allocation of household labour resources. The leading hypothesis is that the availability of electricity inside a home reduces the amount of time required for certain household tasks, and that this primarily frees women to pursue and benefit from external employment opportunities (Lee et al., 2020a). Earlier studies using IV methods have found that rural electrification led to large increases in local female employment (Dinkelman, 2011 [South Africa]; Lipscomb et al., 2013 [Brazil]; Grogan & Sadanand, 2013 [Nicaragua]). However, such impact has not been apparent in more recent studies; for example, van de Walle et al. (2017) (Instrumental Variables) and Burlig and Preonas (2016) (Regression Discontinuity) in rural India; and Lee et al. (2020b) (Randomized Control Trials) in rural Kenya. Given this ambiguity, there would be novelty in combining mixed/multi methods of impact evaluation and Gender analysis, to better explore the apparent nuances.

Gender analysis

Digging deeper, it is well documented that women in developing countries spend 2-3 hours a day collecting biomass energy (UNDP, 2012). This makes women in such countries, not only more vulnerable to energy scarcity, but also exposes them to risks and marginalization that limit the unlocking of their full potential. These risks are even higher when remote and rural areas experience weather and rainfall variability due to climate change. Research should study the extent to which investment in the rural energy sector has benefited women living in the rural areas. At the micro- and meso-levels, for example, it will be useful to look at how changes in different electrified areas are interconnected and influencing gendered behaviours, i.e., to assess how energy interventions link to time use and incomes; and at the macro-level it will be useful to look at the role of political systems and community participation as these relate to gender. Other issues include the norms surrounding women who act as professionals or entrepreneurs in the energy sector, manage energy at local and household levels, consume energy, etc.

Gender analysis includes a review of social, economic, and political power dynamics, and provides an analysis of the division of labour, and access to and control of resources. One will also be able to review women's priorities, women's practical needs and strategic interests, and ways to address them. The analysis provides an understanding of gender relations and their implications for development policy and implementation. In order to do a Gender analysis, gender-disaggregated statistics are required (Shankar, 2015).

Gender analysis can be done using any of several frameworks.[18] Gender Analysis Frameworks help conceptually structure gender research, and frame its content. The frameworks are in turn supported by specific tools. Thus, they help define the focus of the research and the methods needed to gather information. A Gender Analysis Framework is usually chosen once there is a clear idea of the scope of the analysis, available time, and resources.

For example, the Harvard Gender Roles Analytical Framework concentrates on women's and men's activity profiles, and the differences in access to and control over resources. It focuses on the roles of women and men and not on their different relations. The Moser (Practical and Strategic Needs) Framework, in contrast, examines women's productive, reproductive, and community management roles in society. It identifies disparities between practical (immediate) and strategic (longer-term) gender needs. Finally, the Gender Analysis Matrix (GAM) is based on four levels of society (women, men, household, and community) and four types of impact (labour, time, resources, and socio-cultural factors).

Behavioural realism

Another area where methodological novelty is needed is in adding behavioural realism to quantitative energy models, such as those commonly used by engineers (Sovacool et al., 2018). Energy modelling includes techniques that quantitatively represent and analyse the technical, economic, and (to a lesser degree) social aspects of energy systems, typically in a forward-looking manner. These models are influential in determining the way electrification is rolled out on the ground. They often rest on strong behavioural assumptions (e.g., full or bounded rationality) and mathematical techniques (e.g., systems dynamics, agent-based), and may be integrated to a greater or lesser degree with broader economic models. For the most part, all modelling exercises boil down to translating a series of assumptions into mathematical form (equations, algorithms, parameters) and then testing the logical consequences of those assumptions. Many such models have been criticized for their lack of realistic assumptions about human behaviour, including optimization models that assume that actors are hyper-rational and fully informed; and agent-based models that lack an empirical foundation for many of their assumptions.

Behavioural realism broadly refers to improvements in the representation of agents or decision-makers in these models, especially consumers, to better match real-world behaviour in the target population—which of course can vary by region and culture and over time. This realism can come from better use of empirical data, the representation of both financial and non-financial motivations, and the representation of diversity or heterogeneity in behaviours and motives. There are clear opportunities for innovative research that combine results from surveys, laboratory experiments, case studies and other sources, and commonly used in impact evaluations, to inform the selection of planning model parameters (Sovacool et al., 2018).

4. Demonstrating comprehensive treatment effects of electrification in Kenya

This section offers an illustrative demonstration of how future research can use the proposed framework, and moreover draws attention to the extensions that were not possible in a first and largely desk-based iteration. The first consideration should be the use of mixed or multiple methods, as that choice has a bearing on data collection and the search for more appropriate and relevant data. Impact evaluation requires that at least one of the methods leverage be an econometric investigation that hinges on observations' different treatment status. Rigorous econometric methods should be chosen to suit the research objective and data availability. For example, the use of experimental methods would be the first best choice for identifying causality. With quasi-experimental methods, data considerations and careful assessment of the most significant threats to inference will determine the most appropriate variant. Studies should endeavour to use more informative data pertaining to treatment status, e.g., the Multi-Tier Framework data that captures electricity capacity, reliability, etc. Future research should not limit itself to investigating traditional average treatment effects, but should also investigate heterogeneous and multi-valued treatment effects as appropriate.

Using the 2018 World Bank Multi-Tier Framework data for Kenya, we illustrate the exploration of average, heterogeneous and multi-valued treatment effects on household welfare outcomes. This exploration begins with considering the impact of access to electricity (i.e., electrification) on household welfare (as exemplified by total household expenditure) in Kenya. Total household expenditure includes all spending on things such as energy, groceries, and other items. Two measures exist in the data set: monthly total household expenditure and annual total household expenditure, in local currency (Kenyan shillings).

Access to electricity is defined and measured in many ways in the data set; we consider the definitions shown in Table 1.

Table 1: Definitions of access to electricity

Access Variable	Definition
Grid electricity	A household is connected to grid electricity
Solar (home systems) electricity	A household is connected to a solar off-grid electricity system
Any electricity	A household is connected to either the grid or solar electricity
Electricity availability	Availability (hours) of electricity in a typical day
Electricity usage	Usage (hours) of electricity in a typical day
Electricity availability tier	One of five MTF data tiers of electricity availability, namely, 0 hours, 4 hours, 8 hours, 16 hours, and 23 hours
Electricity usage tier	One of five MTF data tiers of electricity usage, namely, 0 hours, 4 hours, 8 hours, 16 hours, and 23 hours

The data is cross-sectional, and therefore requires us to use the quasi-experimental matching method to create comparable treatment and control observations. A pre-matching t-test is conducted for a range of different household characteristics to ascertain whether there are significant differences between unconnected and connected households. The null hypothesis is that H0: Mean (0) – Mean (1) =0. Results are reported in Table 2.

Table 2: Pre-matching t-test

	t/z- value		
Covariates	**Solar Electricity**	**Grid Electricity**	**Any Electricity**
Business ownership (Yes)	-3.778***	-1.962**	-4.118***
Land ownership (Yes)	-11.556***	21.250***	7.514***
No. of years in school	-0.335	-26.430***	-22.148***
Gender (Male)	-3.819***	1.815*	-1.448
Marital (Married)	-8.189***	5.316***	-1.237
Access to financial services	-3.475***	-18.012***	-18.767***
Household size	-9.640***	10.084***	2.064**
No. of household rooms	-5.318***	-2.180**	-5.534***
Household dwelling walls (blocks or burnt bricks)	9.177***	-33.654***	-19.664***
Age	-5.546***	12.114***	6.667***
Age squared	-4.937***	11.531***	6.522***
Household drinking water (piped/vendor/bottled water)	3.164***	-33.018***	-24.413***
Household monthly income (log)	-1.580	-13.586***	-12.555***

Note: *, **, *** indicate significance level at, respectively, 10%, 5%, and 1%.

As shown in Table 1, there are important differences in the profiles of unconnected and connected households for each of the three electricity access measures. In some cases, the differences across electricity types are sizeable. For example, there are large differences between grid-connected and unconnected households, in the household head's years of schooling, but no differences in schooling for those with and without solar electricity. These naïve comparisons are not very informative about the causal effects of electricity access, however, which require ensuring that the compared households are similar except in terms of such connections. Given the nature of the data, we next create a matched sample based on propensity scores specified using a probit specification (results of this matching step can be found in Table A1 in the appendix).

Average treatments effects of electrification

The average treatment effects were generated using three methods, namely, propensity score matching (PSM), nearest neighbour propensity score matching (NN-PSM), and the inverse probability weighted regression adjustment (IPWRA).[19] Under the three methods, the average treatment effect on expenditures was calculated for each electricity access outcome with both monthly total household expenditure and annual total household expenditure. Tables 3, 4 and 5 report these average treatment effects.

Table 3: Impacts of grid electricity on total household expenditure

Outcome variable	Method		
	PSM	NN-PSM	IPWRA
Monthly total household expenditure (log)	0.4007***	0.3680***	0.3333***
	(0.0617)	(0.0429)	(0.0398)
Annual total household expenditure (log)	0.3977***	0.3634***	0.3293***
	(0.0617)	(0.0427)	(0.0397)

Notes: *, **, *** indicate significance level at, respectively, 10%, 5%, and 1%; standard errors are in parenthesis.

Table 4: Impacts of solar electricity on total household expenditure

Outcome variable	Method		
	PSM	NN-PSM	IPWRA
Monthly total household expenditure (log)	0.2975***	0.3284***	0.2748***
	(0.0578)	(0.0521)	(0.0457)
Annual total household expenditure (log)	0.2937***	0.3240***	0.2710***
	(0.0580)	(0.0521)	(0.0456)

Notes: *, **, *** indicate significance level at, respectively, 10%, 5%, and 1%; standard errors are in parenthesis.

Table 5: Impacts of any electricity on total household expenditure

Outcome variable	Method		
	PSM	NN-PSM	IPWRA
Monthly total household expenditure (log)	0.2975***	0.3284***	0.2748***
	(0.0578)	(0.0521)	(0.0457)
Annual total household expenditure (log)	0.2937***	0.3240***	0.2710***
	(0.0580)	(0.0521)	(0.0456)

Notes: *, **, *** indicate significance level at, respectively, 10%, 5%, and 1%; standard errors are in parenthesis.

From tables 3, 4 and 5, we might conclude that electrification has a positive impact of at least 0.3 on total household expenditure. However, there does not seem to be any impact from solar electrification. This may reflect the need for a threshold of access to electricity before impacts can be generated. On its own, solar electricity, as captured here, appears to not provide sufficient capacity to generate electrification impacts.[20] There is merit in studies that look at the different levels of electrical capacity under the various modes of electrification.

Of course, an important caveat to all these results is that the matching algorithm only controls, in different ways, for differences included in the matching algorithm. Despite the matching, other differences across treated and control observations may remain, and these could bias the above results in various ways. For example, if grid-connected households select into these connections based on other unobserved factors that are positively (negatively) correlated with outcomes, the impact estimates will be biased high (low). The same applies for the off-grid solar-connected households. In general, one might expect that unobservables might bias grid-connected household impact estimates upwards, because such households are also more likely to be located close to other economic opportunities, whereas the opposite may be true for off-grid connected households who live in the most remote areas.

Heterogeneous treatment effects of electrification

The average treatment effects generalize impacts across the income distribution. As argued earlier, electrification impacts may be heterogeneous, and such heterogeneity can be examined by estimating quantile treatment effects. Table 6 presents quantile treatment effects of electrification with any technology on monthly total household expenditure and annual total household expenditure, controlling for covariates such as business ownership, land ownership, schooling, gender, marital status, access to financial services, household size, size of dwelling, type of dwelling walls, age, and drinking water source.

As thresholds of electrical capacity matter, we redefine access to electricity in this quantile regression based on two categories for the level of usage of electricity from any source (grid or off-grid solar). This new access variable is based on the amount of electricity used as a fraction of electricity available. The mean value of this variable (0.6) is used to define a dummy variable indicating above-average access (1) and below-average access (0).

Table 6: Heterogeneous impacts of above-average combined grid and solar electrification on total household expenditure

Outcome variable	Quantiles								
	1	2	3	4	5	6	7	8	9
Monthly	0.03	0.04	0.06	0.15***	0.16***	0.12***	0.15***	0.13	0.12
	(0.07)	(0.04)	(0.05)	(0.05)	(0.05)	(0.05)	(0.04)	(0.07)	(0.07)
Annual	0.04	0.04	0.06	0.16***	0.16***	0.14***	0.16***	0.14	0.12
	(0.06)	(0.04)	(0.05)	(0.05)	(0.05)	(0.05)	(0.03)	(0.07)	(0.07)

Notes: *, **, *** indicate significance level at, respectively, 10%, 5%, and 1%; standard errors are in parenthesis.

The results indicate that, among those with access to electricity, above-average access to electricity has heterogeneous impacts on household expenditure. While all coefficients are positive, the bottom three and top two quantiles do not experience significant impacts. Above-average access to electricity only significantly benefits the middle four quantiles by between 0.12 and 0.16. This is likely because benefiting from electricity requires complementary electrical devices (e.g., a sewing machine) and allocating them to productive uses (e.g., a tailoring enterprise), something that the bottom quantiles cannot afford. And while the top quantiles do not appear to significantly benefit from electricity, the coefficients for those groups are not statistically distinguishable from those of the middle four quantiles. Somewhat less precise impacts for them may be due to power limitations, or could be due to greater variation at the top of the distribution for those with better professions or enterprises that are able to cope with electricity shortfalls for other reasons (e.g., teaching, ICT enterprises).

Indeed, the impacts of electrification may depend on the extent to which households can take actions and/or make the complementary investments that enable them benefit from an electricity connection. Electrification ought to be combined with complementary programmes that will make electrical appliances more accessible. In addition, it may need to be targeted towards regions that already benefit from complementary factors.

This also suggests that demarcating electricity capacity in impact studies using mean usage might not be the first best strategy. As indicated earlier, the World Bank Multi-Tier Framework has defined electricity capacity thresholds in other ways, and these different dimensions should be further explored. Thus, the analysis presented here, though improving somewhat on the connected/not-connected approach, still has the disadvantage of using a less informative binary electricity access variable approach.

Multi-valued treatment effects of electrification

The impacts of electrification on outcomes, including total expenditure, might also differ because of the different magnitude of the treatment that they receive. In this case, different quantities of electricity might generate differential impacts, and these would be governed by a range of factors such as capacity, reliability, etc., that affect the dose (i.e., number of hours) that households receive. The World Bank Multi-Tier Framework is based on this consideration. Following these principles, the current data set allows redefinition of the access variable to portray five tiers that indicate the hours that electricity is available for use by a household, namely, 0 hours, 4 hours, 8 hours, 16 hours, and 23 hours. This is defined for a typical 24-hour period.

Table 7 considers the multi-valued treatment effects of electricity usage, defined as the number of hours a household used electricity in a typical day. Note that, a household might decide not to use all the available electrical capacity hence they were asked for the number of hours when they used electricity. Impacts on the following outcomes are calculated: monthly total household expenditure, household expenditure on alternative energy sources (for lighting, and mobile phone and battery charging), time children spend studying (defined in minutes), and the head of household's employment in the non-agricultural sector.

Table 7: Multi-valued (usage) treatment effects on household outcomes

Tiers (treatment levels)	Outcome Variables			
	Monthly total household expenditure (log)	Household head's employment in the non-agricultural sector	Household expenditure on alternative energy sources (log)	Time children spend studying
4 hours	9.534***	5.446***	0.9824***	0.6747***
	(0.0354)	(0.059)	(0.0065)	(0.0149)
8 hours	9.713***	5.314***	0.983***	0.7131***
	(0.0183)	(0.0354)	(0.0035)	(0.0217)
16 hours	9.901***	5.233***	0.9853***	0.7555***
	(0.0268)	(0.0367)	(0.0048)	(0.0281)
23 hours	9.876***	5.365***	0.9852***	0.7580***
	(0.035)	(0.0513)	(0.0051)	(0.0337)

Note: ***, **, * indicate, respectively, 1%, 5%, and 10% level of significance.

The results generally show differential impacts of the multi-valued treatment. The impact on the probability of employment outside the agricultural sector (0.67 to 0.76) increases monotonically with higher doses of electrification. The impact on monthly total household expenditure is also generally increasing (9.5 to 9.9). Household expenditure on alternative energy sources (5.4 to 5.2) decreases with higher doses of electrification. However, electrification does not completely eliminate household expenditure on alternative energy sources. Even though electrification has positive impacts on the time children spend studying, this outcome does not vary (roughly 0.98) with higher doses of electrification. For the interested reader, the derivative treatment function estimates, showing marginal effects within tiers, are reported in the appendix (Table A2).

Electricity usage is partly under the control of the household, who might decide not to use all the available electrical capacity. It might be argued from this to be an inappropriate treatment variable. An access variable that is likely not to be under the control of the household is availability or supply of electricity. Next, in Table 8, we consider multi-valued treatment effects of electricity availability, defined as the absolute number of hours when electricity is available to a household in a typical day.

Table 8: Multi-valued (availability) treatment effects on household outcomes

Tiers (treatment levels)	Outcome Variables			
	Monthly total household expenditure (log)	Household head's employment in the non-agricultural sector	Household expenditure on alternative energy sources (log)	Time children spend studying
4 hours	9.475***	5.763***	0.951***	0.668***
	(0.072)	(0.162)	(0.019)	(0.0435)
8 hours	9.609***	5.865***	0.973***	0.7174***
	(0.0522)	(0.1021)	(0.013)	(0.0020)
16 hours	9.775***	5.763***	0.985***	0.750***
	(0.0477)	(0.0601)	(0.0077)	(0.0345)
23 hours	9.807***	5.343***	0.984***	0.7152***
	(0.0309)	(0.045)	(0.0023)	(0.0176)

Note: ***, **, * indicate, respectively, 1%, 5%, and 10% level of significance.

The results generally confirm differential impacts for different doses of the treatment. The monthly total household expenditure now increases monotonically from 9.5 to 9.8 across levels of availability. Employment outside the agricultural sector presents qualitatively similar results, though the last tier shows a decrease in impact. For expenditure on alternative energy sources, other than for the second tier, electrification is found to encourage reduced spending on other sources of energy. The studying variable shows a general upward trend, implying that children are likely to study more with higher levels of electrification. In general, there does not seem to be much difference in the results whether one uses electricity usage or electricity availability. For the interested reader, the derivative treatment function estimates, showing marginal effects within tiers, are reported in the appendix (Table A3).

There are new insights to be gained as research incrementally moves from a focus on average treatment effects to heterogeneous and multi-valued treatment effects. These are likely to be more useful for policy debates and action on sustainable electrification on the continent. Furthermore, if conducted in the context of multi/mixed methods, economic research on sustainable electrification could become more relevant to future policy decisions.

5. Conclusion

Access to electricity leads to enhanced educational, business, and healthcare opportunities, and to an overall improvement in quality of life; yet more than 540 million people in sub-Saharan Africa still lack any electricity, while many millions more suffer from unreliable access. It is clear that, in order to make progress, numerous hurdles must be overcome throughout modern power systems in sub-Saharan Africa, including meeting electricity demand, maintaining reliability, and limiting negative environmental impacts.

Knowledge about effective policies, interventions, and investment models remains limited, and data that would aid planning and investment are inaccessible and scattered. Furthermore, there is a persistent "know-do" gap that arises when decision-makers and practitioners do not: (i) draw sufficiently and meaningfully on what researchers "know" about the design and evaluation of policies, institutions, and business models, or (ii) address the social and cultural context of targeted communities. There is, therefore, an urgent need for research that involves and facilitates an interaction between scholars and practitioners working on electricity access, and uses a common language and methods to influence positive sectoral change.

While technological constraints are fairly well-represented in electricity planning models, consumer behaviour and preferences are not. There is ambiguity and inconsistency in existing estimates of the impact of electrification on a wide range of development outcomes for households and firms, as well as regions. More and better economic research on the impacts of electrification is needed in order to inform future policy making. Such research would be particularly valuable for guiding electrification choices and decisions in Africa, where most of those without access globally, and many lacking high quality access, are most concentrated. Moreover, African governments face new choices that were previously not available, as off-grid electrification technology is only now becoming technologically and financially viable.

Following a review of policy and research issues undertaken to provide lessons for better future research, five areas where researchers should focus future work and innovations were proposed: (i) the type of data used for electricity access, (ii) econometric methods, (iii) handling of heterogeneity, (iv) more nuance on intervention types, and (v) leveraging of mixed/multi methods.

An exploration using the World Bank Multi-Tier Framework data on Kenya then demonstrated several of these aspects (namely, related to data, discussing limitations of econometric methods, estimation of heterogeneous impacts, and finally of impacts at different levels of treatment), to show that such systematic investigations can yield new insights. While this investigation was highly exploratory and suffers from some obvious shortcomings, it is intuitive that the impacts of electrification would depend on the extent to which households can take actions and/or make the complementary investments that allow them to benefit from an electricity connection. Electrification efforts may, therefore, need to be combined with complementary programmes that also make electrical appliances more accessible, and may need to be targeted towards regions with particular characteristics and features. If impact evaluation can be made more holistic and leverage mixed methods, economic research on sustainable electrification could become much more valuable as an input that guides strategic decision-making and sector investment.

Notes

1. For example, Sustainable Development Goal 7.1.1 targets universal electrification by 2030, and the US Power Africa initiative seeks to add 60 million new electricity connections across Africa.

2. Despite accelerated progress in recent years, 100% access to electricity by 2030 will be difficult to achieve. For universal access, the annual rate of electrification would have to rise from the current 0.82 percentage points to 0.87 percentage points for the years 2019 to 2030, and increasingly remote and poor locations would have to be served, even before disruption from COVID-19 is factored in (IEA et al., 2020). COVID-19 will likely slow or reverse advances in electrification, as utilities and off-grid service providers face financial difficulties, though there is also a growing call for new infrastructure investments that would help assist and speed economic recovery.

3. Latin America, the Caribbean, Eastern Asia, and South-eastern Asia approached universal access to electricity with over 98% access by 2018, while Central Asia and Southern Asia achieved more than 92% access by 2018 (IEA et al., 2020).

4. The countries are Angola, Burkina Faso, Chad, DRC, Ethiopia, Kenya, Madagascar, Malawi, Mozambique, Niger, Nigeria, Sudan, Tanzania, and Uganda.

5. Estimates suggest that gas-fired generation capacity is now 38% of the continental total, followed by coal-fired (24%), oil-fired (18%), renewables including hydropower (17%), and nuclear (1%) (AfDB, 2015).

6. The challenge is to disentangle the causal effects of electrification on development outcomes from other factors that may also be changing with electrification rates. There may also be lingering reverse causality issues, since economic growth—current or anticipated—is widely documented as a driver in greater electricity and energy consumption (Jeuland et al. 2021; Lee et al., 2020a).

7. Electricity provision should be welfare-enhancing (i.e., should leverage positive outcomes for other SDGs). Evidence-based knowledge to assist decisions about appropriate provision mechanisms and financing is required, but often lacking.

8. In technical terms, this is the same as saying that the "exclusion restriction" should hold. Note that the instrumental variable method requires that an instrument is *informative* (that is, $E(z_i E_i) \neq 0$, where z_i is the instrument and E_i is the electrification status for household *i* and *valid* (that is, $E(z_i \varepsilon_i) = 0$, where ε_i is the error term in the regression). The latter condition is referred to as the "exclusion restriction". It is difficult to be confident that all of the possible violations of the exclusion restriction have been eliminated (Lee et al., 2020a).

9. For example, studies on the determinants and impacts of clean cooking transition, including detailed gender dimensions (Das et al., 2020; Talevi et al., 2020); measurement of the demand for off-grid energy products (Bensch et al., 2019; Grimm et al., 2017; Peters et al., 2019); energy poverty measurement (Urquiza et al., 2019; Villalobos et al., 2019); aspects related to health and environmental quality (Barrington-Leigh et al., 2019; Lewis et al., 2016); and evaluation or modelling of the impacts of electrification (Litzow et al., 2019; Mahadevan, 2019).

10. Consumer preferences can also limit the take-up of alternative energy. Home solar does not satisfy a wide range of household energy needs, based on a survey of appliance ownership and aspirations (Lee et al., 2016a). Relative to households that primarily use kerosene, home solar users benefit from basic energy applications, including lighting, mobile phone charging, and, for some systems, television. However, once they have access to these basic end uses, the appliances they aspire to own next (for example, irons) require higher wattages that cannot be supported by most home solar systems, at least not based on current technologies (Lee et al., 2020a).

11. This research could leverage the rich body of policy-relevant research that has or is being generated through the Environment for Development's Sustainable Energy Transitions Initiative (SETI) network of researchers and affiliates. There is potential for leveraging more grants for country-level research through this network. SETI (https://efdinitiative.org/our-work/research-programs/sustainable-energy-transitions-initiative) is an interdisciplinary global collaborative that aims to foster research on energy access and energy transitions in low- and middle-income countries, and to better understand their impacts on health, social outcomes, economic growth, climate change, and natural resources. One potentially promising idea for scaling up energy research on the continent would be to tap this networks and associated institutions to train students and researchers to engage with real-world policy environments and innovation ecosystems that support the discovery, design, evaluation, and scaling-up of community-focused technological innovations and business models.

12. The main limitations of the literature using nightlights to keep track of electricity access in developing countries include the fact that light has been considered mostly in a binary fashion, without exploring the effective level of radiance detected and exploiting it to derive and validate proxy measures of electricity access quality for electrified

households in data-scarce regions. In addition, the focus has been mainly on static snapshots that do not explore the interdependencies of changing demography, growing urbanization, and nightlights distribution for electricity access assessment (Falchetta et al., 2020).

13. Microgrids are typically defined as small networks of users connected to a centralized and stand-alone source of electricity generation and storage. They are capable of providing longer duration and higher capacity than home solar and can also be powered with clean energy sources like solar, wind, and hydro. Technically, it is possible to integrate them into expanding national grids over the long run, but it is too early to tell how widely this will happen in practice (Lee et al., 2020b).

14. But even amongst studies that use these methods, the past decade of work on this topic has resulted in a wide range of estimated effects, implying that considerations other than econometric method are important.

15. This assumption is not always valid, but establishing parallel pre-intervention trends among treated and control observations goes a long way towards establishing that time-varying unobservable confounding is unlikely.

16. In some cases ("natural experiments"), the experimental conditions are outside the control of the investigators, but nevertheless provide sufficient degree of control to permit causal inference.

17. Here, too, there is no consensus about the educational benefits of home solar, despite countless rural households across the world increasing adoption of these products. However, at the very least, adoption reduces usage of kerosene and dry cell batteries for lighting, resulting in some benefits to health and the environment (Lee et al., 2020a).

18. The Oxfam publication, *A Guide to Gender Analysis Frameworks*, includes some useful examples and case studies.

19. The first two are matching algorithms, while the third uses a weighting approach. The PSM estimators differ in three aspects, including the way the neighbourhood for the household treated is defined, the common support available, and how weights are assigned to neighbours (Caliendo & Kopeinig., 2008). The NN-PSM involves matching with replacement, which creates a trade-off between bias and variance. The PSM is the default for propensity score matching, while the weighting method uses propensity scores to obtain balance between treated and untreated individuals.

20. Solar would have had the same impact as grid electricity if it was from substantial generation units connected to the grid.

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Appendix

Table A1: Probit model for the propensity score estimates

Variables	**Treatment: Access to Electricity**		
	Solar Electricity	**Grid Electricity**	**Combined Electricity**
Business ownership (Yes)	0.20186	0.1793	**0.3777**
	(0.10511) *	(0.1197)	**(0.1353)*** **
Land ownership (Yes)	**0.28695**	-0.5515	-0.1187
	(0.05970)* **	(0.0655)***	(0.0648)*
No. of years in school	0.02011	0.0460	0.0483
	(0.00689)***	(0.0076)***	(0 .0074)***
Gender (Male)	-0.07564	-0.1083	-0.1449
	(0.0996)	(0.1048)	(0.0103)
Marital (Married)	0.35098	-0.2562	**0.0600**
	(0.0938)***	(0.0966)***	**(0.0955)**
Mobile Money account	0.2559	0.0771	0.3448
	(0.9829)***	(0.1108)	(0.0928)***
Bank account	0.3715	0.4368	0.7155
	(0.1017)***	(0.1115)***	(0.0980)***
Household size	0.0678	**-0.0175**	0.0359
	(0.01424)***	**(0.0160)**	(0.0154)**
No. of household rooms	-0.00083	0.0171	0.0079
	(0.0165)	(0.0180)	(0.0179)
Household dwelling walls (blocks or burnt bricks)	-0.06998	0.8450	0.6180
	(0.0621)	(0.0633)***	(0.0663)***
Age	-0.0118	-0.0160	-0.0330
	(0.0139)	(0.0155)	(0.0148)**
Age squared	0.00019	0.00016	0.00038
	(0.0001)	(0.0001)	(0.0001)**

continued next page

Table A1 Continued

Variables	Treatment: Access to Electricity		
	Solar Electricity	Grid Electricity	Combined Electricity
Household drinking water (piped/vendor/bottled water)	-0.3480	0.7658	0.3396
	(0.06001)***	(0.0627)***	(0.0635)***
Household monthly income (log)	0.02450	0.0926	0.1152
	(0.02378)	(0.0265)***	(0.0256)***
K	-1.5205	-1.5996	-1.2542
	(0.3663)***	(0.4030)***	(0.3953)***
LR chi2(14)	215.04	1157.47	638.16
N	2,477	2,477	2,477

Note: *, **, *** indicate significance level at, respectively, 10%, 5%, and 1%.

Table A2: Derivative treatment function estimates for marginal (usage) effects within tiers

Tiers Treatment Effects (for delta= 0.1)	Outcome Variables			
	Monthly total household expenditure (log)	Household expenditure on alternative energy sources (log)	Time children spend studying	Household head's employment in the non-agricultural sector
4 to 6.4 hours	0.1147***	-0.0860***	0.0009	0.0246
	(0.024)	(0.0248)	(0.0041)	(0.0159)
8 to 10.4 hours	0.0803***	-0.0500***	0.00632***	0.0173**
	(0.0131)	(0.0146)	(0.0019)	(0.0075)
16 to 18.4 hours	0.0112	0.0240***	0.00009	0.0044
	(0.0115)	(0.0095)	(0.0011)	(0.0098)
23 to 25.4 hours	-0.0489	0.0885***	-0.00022	-0.0064
	(0.0316)	(0.0270)	(0.0213)	(0.0212)

Note: ***, **, * indicate significance level at, respectively, 1%, 5% and, 10%.

Table A3: Derivative treatment function estimates for marginal (availability) effects within tiers

Tiers Treatment Effects	Outcome Variables			
(for delta= 0.1)	Monthly total household expenditure (log)	Household expenditure on alternative energy sources (log)	Time children spend studying	Household head's employment in the non-agricultural sector
4 to 6.4 hours	0.0846***	0.0729	0.015	0.032
	(0.028)	(0.0472)	(0.011)	(0.027)
8 to 10.4 hours	0.0641***	0.0123	0.0063*	0.018
	(0.018)	(0.0281)	(0.0037)	(0.0148)
16 to 18.4 hours	0.0229**	-0.1095	0.0050**	-0.006
	(0.0117)	(0.1690)	(0.0019)	(0.0044)
23 to 25.4 hours	-0.0129	-0.2157	-0.0026	0.0266
	(0.0261)	(0.0496)	(0.0053)	(0.0174)

Note: ***, **, * indicate significance level at, respectively, 1%, 5%, and 10%.

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