Conceptual and Institutional Prerequisites for Guiding Equitable Progress towards Universal Rural Electrification

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1. Motivations underlying the research

Rural electrification is a means to improving the socio-economic conditions and living standards of those living in rural areas. Yet, as global rural electrification efforts accelerate under the Sustainable Development Goals 7 (SDG 7), most policies and programs continue to solely target and be evaluated on extending connections, with mixed results.

Despite increasing efforts to improve access to modern energy services in rural areas, progress is lagging and, in some cases, falling behind population growth. In fact, recent research suggests that even while new connections maybe provided, household access to essential energy services will still be very unequal even by 2030 without additional efforts. The few studies that have assessed recent cross country and within country variation in rural electrification performance using econometric techniques find this is linked with political systems, indicators such as corruption and government effectiveness and the institutional environment. As we approach the 2030 mark set under the UN SDGs, the IEA continues to project a severe deficit under the current policy scenario. More work must be done to understand drivers of rural electrification successes and transfer these lessons to countries where the deficit prevails despite ongoing efforts.

Conceptual developments in energy access and energy poverty measurement encourage us to look beyond connection-based indicators towards improvement across distinct multi-dimensional supply attributes linked with energy services. Indeed, past work has shown that connection-based indicators fail to capture inequities in supply reliability, affordability and use. Moreover, there is very little precedent for linking rural electrification efforts with wider socio-economic and environmental impacts that ultimately justify the implementation of these policies. This is not limited to academic discourse, rather, the SDG 7.1 target itself speaks to the provision of reliable and affordable access to modern energy services for all. Further work is necessary to understand the limitations of connections-focused programs and suggest ways forward.

2. A short account of the research performed

We conduct both quantitative and qualitative analysis of longitudinal and cross-sectional electrification datasets and country case studies. We begin with exploring the importance of multi-dimensional energy access measurement approaches and the need to assess progress at the sub-national level using sub-national cross-sectional rural electrification datasets. We then analyze the relationship between the capacity of institutions and the efficacy of rural electrification policy using a linear regression model applied to longitudinal cross-country electrification data. Finally, we conduct a narrative review of three exemplary rural electrification policy country case studies to draw broad transferable lessons for policy development.

Our work shows that national connection rates describing rapid progress are complicated by inadequate supply reliability and sub-national disparity in infrastructure provision. Similarly, while policy implementation has objectively increased following the inclusion of energy access under the SDGs, effectiveness of these in driving progress in rural electrification is uncertain. Our analysis shows that rural electrification policy efficacy is positively modified by institutional capacity, aligning with prior work describing the effects of government quality and corruption on electrification outcomes. Reflecting on

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policy case studies in Brazil, India and Morocco, we find similarities in center-led efforts combined with regulatory controls and the integration of targeted pro-poor subsidies and decentralized electrification technologies. Nevertheless, even among these exemplary policies, evaluation remained weak beyond merely counting connections and financial oversight.

3. Main conclusions and policy implications of the work

Drawing on the quantitative and qualitative evidence presented, we argue that next generation rural electrification policy formulation must consider the following elements: (1) measurement of distinct multi-dimensional supply attributes at higher regional granularity, (2) considerations of local institutional capacity constraints and (3) independent evaluation mechanisms.

A lack of data is not a binding constraint in the development of rural electrification policy. Rather, disaggregate data collection across distinct attributes of supply is necessary for independent evaluation and effective regulatory control of these policies, as well as improving their design and targeting.

Combining a standardized set of survey questions together with utility reported data and recent advances in earth observation data processing is a promising pathway to improve the quality and frequency of data updates. This can reveal and thereby help mitigate sub-national differences in institutional capacity that have been shown to modify the success of central electrification policies.

Sustainable and Socially Resilient Minigrid Franchise Model for an Urban Informal Settlement in Kenya

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1 Motivations underlying the research

This article provides a case study of an environmentally sustainable and socially resilient minigrid distribution model to serve communities in an urban informal settlement in Kibera, Nairobi, Kenya. The process of designing resilient and sustainable urban solutions must account for the different needs, requirements, and barriers common to informal settlements, our understanding of which suffers from a severe lack of data. Therefore, we use an interdisciplinary approach, integrating a wide range of methods including: surveys, sensor-based monitoring, energy system simulation, policy analysis, and evaluation of a proposed business model. Conducted in collaboration with the Kibera Town Center (KTC), we collect unique primary electricity production and usage data to analyze informal settlement electricity demands. However, unlike previous literature in informal settlements that focuses on residential energy, this research focuses on critical, centralized community-scale energy that supports schools, water delivery, and livelihoods. Furthermore, under a policy change in Kenyaâ€™s Energy Act 2019, this minigrid now has the opportunity to expand and sell power to the local community under new business models. When scaled, our proposed innovative minigrid franchise business model can support microenterprises and return agency to slum dwellers.

Our research is guided by the following questions:

- What is the existing electricity landscape of the community center, local schools, and local shops?
- What is the optimal amount of solar photovoltaic (PV) capacity to serve KTC and the adjacent Olympic Primary and Secondary schools?

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- Which technical minigrid scenarios provide the lowest cost of electricity? Is it at a higher or lower cost than grid extension?
- How can a community minigrid franchise model - made possible through Kenyaâ€™s Energy Act 2019 and approached in collaboration with communities, non-governmental organizations (NGOs), and government stakeholders - showcase environmentally sustainable and socially resilient planning for urban informal settlements?
- How can results from this case study inform other resilient and sustainable infrastructure for informal settlements?

2. Research Performed

2.1 Minigrid Simulation

Using HOMER Pro, we first simulate the minigrid's techno-economic expansion from KTC to also serving the school and shop loads. Our simulation scenarios were designed with local stakeholder input so that the simulation results can inform real and policy-relevant decisions. The scenarios include: a business as usual scenario, adding school loads without increasing the system size, optimal solar expansion, constraining the system to 100% renewable energy, and adding shop loads.

2.2 Minigrid Franchise Business Model

Figure 7 in the full article depicts this research's key contribution of a Framework for a Minigrid Franchise Model at KTC, and the benefits to key stakeholders. In this model, the utility and government first grant the NGO with a license to generate and sell electricity under the Energy Act 2019. The NGO acts as a franchiser, relying on its established social capital. Microbusinesses are selected as franchisees that agree to connect and regulate payments for others that opt into the community minigrid. The NGO and other key community loads will be able to sustainably consume high-quality power to support basic community needs, empowerment services, and education. In doing so, they will reduce non-technical losses, increase grid resiliency, and support a growing local economy.

3. Main Conclusions and Policy Implications

This research details the extensive monitoring and evaluation efforts that can inform future resilient and sustainable urban planning for informal settlements. We manifest the benefits of investing in collaborations and ethically gathering electricity data, which can serve as a model for future city planners and basic needs providers.

We find that the community center, local schools, and individual shops surrounding the center respectively consume an average of 324 kWh, 274 kWh, and 2 kWh each daily. Through our minigrid simulation, we find that the levelized cost of energy (LCOE) will decrease by 60% with optimal minigrid expansion, thereby demonstrating expansion's economic feasibility. Net present value calculations indicate that KTC could save over $38,000 USD over the next 25 years by implementing the community minigrid instead of maintaining the status-quo system.

Through stakeholder mapping efforts we identify the franchise model's key drivers of success which include: the community's need for safe wires, better maintenance of the minigrid equipment, shifting a utility liability into a valuable community asset, and increasing opportunities for skilled employment. We also quantify significant potential emissions reductions which can improve both local health and global climate.

Environmentally sustainable and socially resilient planning for urban informal settlements hinges on enabling policies, such as Kenya's Energy Act 2019, combined with applied research and informed business models to leverage opportunities for equitable transitions toward sustainable urban development.

Residential Welfare-Loss from Electricity Supply Interruptions in South Africa: Cost-Benefit Analysis of Distributed Energy Resource Subsidy Programs

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1. Motivations underlying the research

Sub-Saharan Africa has one of the highest population growth projections among major global regions but one of the lowest electrification rates. Only 47% of households access electricity, while the population is expected to double to 2.2 billion within 30 years. Without improvements, this would leave over 1 billion people in the region without electricity. Those countries that do have well-developed electrical grids still often face a second major obstacle: grid reliability. South Africa provides grid electricity to over 90% of residents, but—like many of its regional neighbors—suffers chronic electricity shortages. While households have access, they must live around shortages, which occur regularly and can last for hours. The costs of adjusting can be substantial, especially for low-income households that depend on electricity. Reliable electricity maintains good air quality, helps improve literacy rates, increases free time for household members to devote to leisure and productive activities, and prevents emergency expenditures during a shortage, among many other benefits. With each hour of outage, these benefits slip away. Distributed energy resources, or DERs, (e.g., solar panels and batteries) offer households a solution by providing off-grid electricity resources to temporarily bridge the gap in electricity supply during a grid shortage. Off-grid electricity resources have already grown rapidly as a cost-effective solution to electricity access and reliability in the Sub-Saharan region, and more growth is needed to help keep supply at pace with future population growth. More research is needed to understand the benefits of off-grid technologies and how to deploy them to households in an affordable and scalable way.

2. Short account of research performed

The purpose of this paper is to use a market-based estimation of welfare-loss from electricity interruptions in order to determine whether distributed energy resources are a cost-effective solution for South African households. I use market data on electricity prices and consumption across 16,851 households to estimate residential welfare-loss from an electricity interruption and thereby how much households are willing to pay to avoid an outage. A two-part model uses regressors for household appliances and characteristics, electricity consumption, and price and income elasticities to determine welfare-loss from interruptions. I compare the willingness-to-pay to avoid an interruption to the cost of purchasing solar panels and batteries to determine the cost-effectiveness of investing in off-grid electricity across various scenarios. Solar panel products are varied by cost and electricity output. Government subsidy scenarios are also varied since investment costs often exceeds annual household income. Results are reported across income deciles to illuminate differences in off-grid benefits and costs between low-income and high-income households. This provides relevant insight on the interaction between income inequality and electricity in South Africa.

3. Main conclusions and policy implications

The results show that lower-income households are disproportionately affected by electricity interruptions in terms of relative welfare-loss. Welfare-loss in the lowest two income deciles equates to 6-14% of household income, but less than 0.5% for the top two income deciles. In the lowest income decile, welfare-loss as a portion of income is more than twice that of all other deciles, indicating that this group is disproportionately harmed by interruptions. The cost-benefit analysis shows that with at least a 40% government subsidy of investment costs, residential distributed energy resources are a cost-effective investment for households. To be cost-effective, the DERs must prevent more lifetime welfare-loss than

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their cost to acquire—both measured in time-adjusted US dollars. At the societal level, the aggregate benefit across all households in positive cost-benefit scenarios exceeds total spending for government subsidies in several cases. For instance, spending $1 Billion to subsidize low-output DERs for the lowest income decile households prevents $1.5 Billion in lifetime welfare-loss—a 50% return on investment. Positive social return-on-investment outcomes were also found for other income deciles. The main implication for policy-makers is that prioritizing subsidies for lower income deciles provides the most "bang for buck" in terms of net social and economic gains. Subsidizing DERs in this way would reduce welfare-loss inequality from electricity interruptions, while leading to a healthier population, a more stable electrical grid, and more productive households.

Socio-technical Inertia: Understanding the Barriers to Distributed Generation in Pakistan

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1. Motivations underlying the research

Pakistan is the sixth most populous country in the world and its centralized energy sector remains confronted with multiple challenges—characterized by heavy reliance on fossil fuels, extensive inefficiencies in terms of corruption and excessive losses, and cyclical financial arrears (NEPRA 2020; Ichord Robert. F 2020). Pakistan also is the fourth largest electricity access deficit country, where 61 million people still have no access to electricity and the remainder have unreliable access to power supply (IEA et al. 2020; NEPRA 2020). Against this context, decentralized renewable energy configurations have the potential to unleash myriad benefits for the country— not only offering an alternative for end-users frustrated with dependencies on the failing centralized energy systems, but also an option for mitigating the causes of climate change. Distributed generation solar PV (DG solar) offers considerable benefits for a more versatile and efficient supply system.

In a bid to promote small scale distributed indigenous renewable energy resources, Pakistan launched net-metering regulations in 2015 (NEPRA 2015). These regulations allowed for on-site solar and wind generation. As per the regulations any category type consumers i.e., residential, industrial, commercial, and agricultural, having three-phase connection can avail net-metering facility for system sizes ranging between 1kW to 1MW (AEDB 2017). Once licenses are issued, the distributed generators are compensated at off-peak retail tariff; whereas cash compensations in case of positive net-balance are made after every three months (AEDB 2017; NEPRA 2015). Yet despite the launching of this facility and high electricity tariffs in Pakistan, adoption of DG solar has remained insignificant overtime in Pakistan. This study probes some of the reasons for this.

2. A short account of the research performed

In a bid to promote renewable energy, Pakistan issued net-metering regulations in 2015 that allowed for on-site solar and wind generation. However, five years on, overall growth in Distributed Generation (DG) remains insignificant. Here we investigate the reasons why, focusing on solar prosumage and exploring the key barriers and challenges in the existing socio-technical regime. The paper draws on document analysis; the views of key stakeholders including distributed solar PV adopters; end-users who have not yet adopted solar prosumage;

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the electricity distribution companies who are primary intermediaries responsible for implementing the regulations and connecting the end-users to the grid; commercial banks financing solar PV; and relevant authorities. We identify the obstacles to solar prosumage as including: difficulties in acquiring finance (especially in the case of smaller systems); under-facilitation of net-metering by electricity distribution companies, including an absence of Fee for Service models such as third-party investors; an awareness gap (especially on net-metering facility); and fragmented governance and regulations. We conclude that to succeed in the context of prevailing conditions, realistic implementation action plans based on the alignment of institutional coordination and cooperation, finance, and business model solutions, mandated and backed by significant national and regional policy level support, remain critical.

3. Main conclusions and policy implications of the work

In this study we investigated several barriers at multiple-levels relating to the transition to a sustainable DG system in Pakistan, drawing on questionnaire surveys and interviews with primary stakeholders in the socio-technical regime. In the next phase of the study, drawing on a neo-institutional framework of types of logic and mechanism – we characterize these obstacles to uptake of distributed PV in Pakistan, as well as observed inertia and resistance among key, incumbent actors as a problem of misaligned institutional logics.

The larger objective of the study is to inform debate of appropriate responses regarding how to support DG deployment and create an enabling environment that better suits the needs of prosumers. Based on these insights, we propose that the Pakistan government should place an increased emphasis on DG and set explicit targets for rooftop solar in its policies. Further, a proper mechanism needs to be designed, wherein the institutional barriers are addressed and DISCO relationships with distributed generators are subjected to scrutiny by an unbiased third party, which could be the regulator itself. The financial impediments both in terms of wide-scale adoption of 'SBP Financing Scheme for Renewable Energy', as well as difficulties in acquiring loans from banks, needs to be effectively addressed. In parallel, enabling regulations should be legislated to allow private sector engagement in driving rooftop solar and DG growth. The findings of the study thus imply a need for addressing the barriers in relation to 'solar PV financing', as well as 'enabling regulations for corporate solar PPA/leasing models', both of which are particularly important for DG dissemination.

Analytics on Pricing Signals in Peer-to-Peer Solar Microgrids in Bangladesh

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1. Motivations underlying the research

To be able to provide growing populations with access to affordable, reliable and clean energy in a manner that satisfies requirements based on all three dimensions, economic, environmental, and socially equitable, current business models need to be overhauled and be in synch with government policy and operations. In order to reach universal energy access by 2030, as defined in the Sustainable Development Goal (SDG) 7, we need integrated electrification pathways, where grid extension and distributed energy

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can work hand-in-hand. Grid expansion must not act as a counterweight to the wider adoption of clean distributed electrification solutions. Moreover, in the race toward achieving SDG 7, the world needs to build approximately 50 new microgrids per day. This stands in stark contrast to the present average rate of only one microgrid per day.

Bangladesh is home to the world's largest Solar Home System (SHS) market. Since 2003 local partner organizations have deployed over 4.3 million SHSs through a soft-financing program provided by the government's Infrastructure Development Company Limited (IDCOL). People living in energy poverty can be trapped in an (energy) poverty penalty that implies adverse effects for their development opportunities. This research's implementation partner, SOLshare, is a Bangladesh-based social enterprise that is leveraging existing distributed energy infrastructure to allow households and small firms to trade their surplus energy with SHS owners and non-owners through a local smart microgrid. The peer-to-peer trading network combined with mobile money-enabled pay-as-you-go billing provides customers with more reliable energy and allows them to generate a direct income from electricity sales. Solar microgrids enabling peer-to-peer energy exchange among off-grid households are poised to contribute to electrifying rural areas in the Global South.

The trading price currently does not vary dynamically, and the company takes a fee on each transaction by establishing a sell price that is relatively lower than the buy price. These local trading platforms offer a unique opportunity to study the gains from trade for both consumers and "prosumers" (i.e. customers with SHSs that consume and sell the electricity they generate). Measuring willingness to pay will facilitate the estimation of demand elasticities and consumer surplus, which can thereby inform pricing and guide the design of subsidies, as well as improved business models, a necessary requirement for a much larger uptake of microgrid deployment across the globe.

2. A short account of the research performed

To ensure these microgrids can be run sustainably, this paper seeks to provide some initial answers on how to improve on the prevailing static pricing approach. We are piloting variations in the buy and sell prices for electricity in several solar microgrids in rural Bangladesh to elicit price sensitivities. We analyze villagers' trading behavior in presence of varied prices by comparing absolute amounts of electricity bought and sold in the testing months in 2021 to data from the same time in the year in 2020.

3. Main conclusions and policy implications of the work

Understanding how reliable electricity can impact household and firm incomes in this setting can help inform policies that seek to maximize the returns to electrification. We find that making electricity much cheaper did not lead to observable shifts in customer behavior. Rendering feeding into the microgrid much more lucrative for prosumers, customers who sell electricity to as well as purchase it from the microgrid, produced inconclusive results. Anecdotal evidence of consumption smoothing in a microgrid with decreased buy-prices and of increased pick-up by customers with many appliances points to potential benefits from adjusting buy prices to daily and seasonal supply peaks and troughs. Failure of increased sell-prices to induce more prosumer energy feed-in may furthermore motivate new thinking on current passive trading regimes, which give preference to matching geographically close supply and demand and thus disadvantage individual prosumers. That a one-month buy-price reduction in two separate grids led to no clear changes in electricity purchase behavior among microgrid customers may cautiously be interpreted as an indication of microgrids meeting current village-level energy needs at prevailing prices, albeit with caveats. Those caveats, in turn, inform future research for better intervention design. Policymakers, especially in the Global South, might therefore want to consider (continuing) support for decentralized solar microgrids to boost rural electrification, despite relatively higher electricity tariffs for households. Moreover, microgrids, once established, can continue to play an important role for their participants even after national grids have reached their villages, as indicated by one of the microgrids in our sample. Given microgrids' cost-effectiveness, compared to national grid extensions, as well as their high reliability in providing energy throughout the year and the Covid-19 pandemic, they ought to play a bigger role in energy provision to remote and socially disadvantaged areas. In this context, well-designed subsidy schemes such as energy credits can help combat energy poverty and ensure citizens' energy needs are met. These positive indications notwithstanding, it is evident that for these local solutions to contribute to electrification meaningfully and sustainably in the mid to long term, a departure is required from setting microgrids' electricity buy and sell prices statically. Dynamic pricing must, however, be implemented so as to optimize trading to better reflect demand and supply shifts throughout the day and seasons. Peer-to-peer solar microgrids further empower prosumers while paying heed to both environmental and developmental concerns. The lessons from this experiment in Bangladesh also bear relevance for energy regulators in the Global South and can inform their design of incentive regulation of energy networks.

Prosumer Empowerment through Community Power Purchase Agreements: A Market Design for Swarm Grids

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1. Motivations Underlying the Research

Between 2010 and 2019, the population without access to electricity decreased from 1.2 billion to 759 million. Electricity access can be provided in two ways: either through top-down, centralized electrification via national grid extension or bottom-up, decentralized through decentralized renewable energy solutions (DREs), that is, standalone solar systems, mini grids, and swarm grids.

The IEA estimates that the number of people connected to DREs between 2010 and 2019 more than doubled, reaching 11 million people, while GOGLA et al. calculate that by 2019, 105 million people had access to off-grid solar systems (lanterns and solar home systems). To achieve the United Nation's Sustainable Development Goal 7 in a bottom-up dominated approach, Tilleard et al. estimate that in Africa alone, by 2030, more than 290 million people could be connected to mini grids (this translates to more than 4,000 mini grids). DREs represent the most economically viable option for servicing the part of the population that is too remote or for which the national grid extension is too expensive.

Advancing the top-down electrification process, countries of the Global South, with support of international aid and development funding, are accelerating their national grid expansion. As the national grid reaches their customers, the private sector (DRE companies) is put at danger of having to either relocate their assets or abandon them. At the same time, the DRE end-user, reached by the national grid, faces several challenges due to being exposed to a double infrastructure. The challenges can be of technical and financial nature caused by assets that are becoming abundant or need additional equipment to be suitable for national grid and DREs.

2. Research Performed

This paper investigates a technically and economically viable solution for the co-existence of the national grid–a centralized infrastructure–with the decentralized, renewable energy infrastructure in Global South countries, with a case study on Bangladesh. At the intersection of these two electrification pathways the question arises if the two approaches can be integrated to the benefit of society by maintaining existing assets. For this paper we assume the technical link to be a bidirectional inverter and a battery representing the point of common coupling (PCC) between national grid and currently off-grid systems. We then suggest to apply a cost recovery approach to calculate the economic value of a community power purchase agreement (C-PPA) that allows the community to enter into a trade agreement with the national grid to export at a specified rate. To verify and assess the feasibility we run an optimization model to simulate allocation of revenues and track trade activity for a case study using both, a mixed

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complementarity problem (MCP) and a linear problem (LP) formulation. In this analysis, we find that the C-PPA would bring economic benefits to end-users (consumers, prosumers) by decreasing network charges and increasing revenue from additional sales of electricity. Based on the indication of this being beneficial we suggest a framework where the private sector and national utilities work in a collaborative effort through a public-private partnership.

3. Main Conclusions and Policy Implications

The results demonstrate a series of co-benefits: (a) the prosumer is monetarily rewarded for the utilization of her assets and for electricity trading with no additional infrastructure investment; (b) if the state utility takes over the investment costs with the interconnection infrastructure and outsources the integrated grid operations and maintenance to the private sector, the otherwise high grid expansion costs can be saved and repurposed in other infrastructure investments; (c) the operations of the decentralized renewable energy company are no longer threatened by the grid expansion and it can become an Integrated Grid Operator.

State utilities need to define the grid interconnection requirements (i.e. delivery voltage, special requirements and conditions, point of supply, interconnection arrangement) so that the C-PPA can be accurately calculated. The private sector needs to be informed about the range of services it can provide to the national grid and the discussion to differentiate between a feed-in tariff and the C-PPA tariff need to be taken up. Finally, due to its better access to financing, the state utility should take over the cost of the DRE interconnection–in our case analysis, the cost of the PCC. Our estimations show that the cost of the PCC is lower than that of the grid extension and that its CAPEX can be recovered faster if the risk is taken over by the national utility. As the scenario analysis shows the OPEX of the newly interconnected infrastructure can be priced in the C-PPA.

As the C-PPA is a derivation of a standard PPA, energy regulators (such as energy ministries or renewable energy agencies) need to ensure that the contractual framework is defined and standardized. Moreover, regulators could also consider setting up utility concessions that can allow the IGOs to obtain the rights to provide services under the C-PPA, under public sector oversight or public-private partnership (PPP). These PPPs are a means to leverage private capital and must have a clear legal structure balancing between ensuring adequate financial returns and meeting the public objectives of the governing agency, particularly given that the fundamental economics of grid-based rural electrification remain difficult. Finally, tracking and making public the costs incurred with the national grid extension and individual consumer interconnection could enable researchers, international development organizations, and policymakers in further investigating the cost-benefit analysis of centralized vs. decentralized electrification, in quantifying the investment required to reach the remaining unelectrified population, and in supporting more targeted policy recommendations.

Cost Efficiency Evaluation of Thermal Power Plants in Bangladesh Using a Two-Stage DEA Model

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1. Motivations underlying the research

Electricity production in Bangladesh is based primarily on fossil fuels, which leads to one of the highest levels of subsidies in the world. These subsidies arise from the supply of subsidized fuels to the

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plants, but also to support plants which operate at a loss from selling electricity at a tariff lower than the cost of production. The cost of production depends on the fuel cost, the fixed costs and the variable O&M costs. The loss occurs more frequently in peaking power plants, which do not operate at high plant factors, but must be given capacity payments in order to compensate the plant owners for their capital investments. This inefficiency became particularly evident during the Covid 19 pandemic, where subsidy payments to the power sector broke all records, while electricity demand plummeted. Capacity payments for idle plants take up a third of the budget allocated to the entire power and energy sector.

Bangladesh is planning to implement an energy transition plan, by cutting down inefficiency in the power sector, while increasing the share of renewable energy in electricity production. However, the cost of renewable electricity is not perceived to be competitive with the average cost of fossil fuel electricity, and this point is highlighted by the traditional fossil fuel industry to downplay the potential of renewable electricity solutions. In this research we aim to highlight how the average cost of fossil fuel electricity does not represent the wide variation in the profitability of individual fossil fuel plants, and that many such plants have generation costs that far exceed the current cost of solar PV even combined with storage.

We take the annual generation and cost data of the thermal power plant fleet of Bangladesh, including 30 baseload plants and 91 peaking plants, for the financial year 2019-2020. Using a two stage approach of Data Envelopment Analysis and Tobit regression, the study aims to investigate and compare the pattern of cost efficiencies among the thermal power plants of Bangladesh, and identify the main causes of loss, which make subsidization necessary. It takes into account the three main cost components of plants, and analyzes which costs are responsible for the cost inefficincies.

2. A short account of the research performed

In the input oriented data envelopment analysis model, the input variables are fuel cost, variable O&M costs, fixed costs and installed capacity, and the output is electricity generation. In addition to the BCC and CCR efficiencies, a slack analysis is also conducted. In the Tobit regression analysis, the effects of uncontrollable variables such as the age of the plant in years, the technology of the plant, the fuel used, the location in the country, the installed capacity, and the type of ownership are analyzed. Base load plants and peaking plants are analyzed separately.

The analysis of base load plants reveals that most of the plants are operating at increasing returns to scale. Few of them have fuel cost, variable cost and fixed cost slacks, but none have installed capacity slacks. The biggest predictor of cost inefficiency among these plants is the type of fuel used. Higher capacity plants have greater efficiency, but ownership or technology has no impact on efficiency. The cost of fuel often determines the merit order of plants. The cost of fuel leads to inefficiency in high speed diesel based plants, which then have low plant factors and high capacity payments. Low supply of coal can lead to the poor performance of even coal plants, which then have low plant factors.

Among peaking plants, the overall efficiency levels are low, and many have fuel cost and fixed cost slacks. Plants operate on an economic merit order, where low cost fuel plants are used before the high cost fuel plants. Therefore, heavy fuel oil and diesel plants have higher cost fuels, and lower priority in dispact and lower plant factors. Capacity slacks occur mostly among privately owned plants, but of all fuels. Fixed cost slacks occur in low plant factor plants. Fuel type again is the greatest predictor of inefficiency. Even though gas is a low cost fuel, the shortage in the supply of gas leads to low plant factors in large gas plants.

3. Main conclusions and policy implications of the work

The findings point to the importance of the choice of fuels, which affect not only the cost of operations of power plants, but the frequency and priority of use, and therefore their long run operational efficiency. The high cost of fuels in many thermal power plants of Bangladesh can make modern renewable electricity competitive in comparison. Our analysis points to the possibility of replacing the most inefficient plants from among especially the peaking groups, with cheaper renewable energy technologies, as these plants become due for retirement. Some of the expensive liquid fuel based plants which run during the daytime may be replaced with solar plants, combined with limited storage. As a small number of liquid fuel plants are disproportionately responsible for a large portion of subsidy payments, replacing them will also reduce the subsidy burden to the electricity sector.

Relative Cost-Effectiveness of Electricity and Transportation Policies as a Means to Reduce CO_2 Emissions in the United States: A Multi-Model Assessment

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1. Motivations underlying the research

Given the absence of comprehensive federal climate policy in the form of economy-wide emissions pricing, climate policy in the United States is effectively defined by a collection of energy policies and measures at the federal, state and local levels. Two common energy policy instruments are tax incentives and technology standards. Although such instruments have been shown to be less cost-effective as a means to reduce CO_2 emissions than other policies, such as economy-wide carbon pricing, it can be challenging to compare the costs of CO_2 emissions reductions associated with such policies across sectors. This difficulty arises because of the wide range in estimates and inconsistencies in how such estimates are constructed for any given policy.

This study fills the gap identified above by comparing the cost-effectiveness of several US energy policies across the electricity and transportation sectors in terms of CO_2 reduction using a common framework and approach. Specifically, it considers wind and solar tax credits, a renewable portfolio standard, a renewable fuel standard, and an electric vehicle tax credit. It relies on three well-known, publicly available US energy system models (NEMS[f], ReEDS, GCAM-USA) incorporating up-to-date information about technology cost and performance to compare policy costs and examine robustness to the choice of model. The use of more recent cost and performance information relative to prior studies is particularly relevant in light of rapid technology advancement in some sectors.

2. A short account of the research performed

The models used in this study (EM-NEMS, ReEDS, GCAM-USA) are extensively documented, publicly available US energy system models that have been used in numerous climate and energy policy analyses. In the case of wind and solar tax incentives, the extension case extends the existing tax credits at their historical maximum value through 2050 (the production tax credit of 2.3 cents per kWh for onshore wind and the investment tax credit of 30% for solar). Similarly the EV tax credit extension extends the full applicable subsidy based on battery size up to $7,500 per vehicle to all new electric vehicle purchases (although this subsidy does not apply to HEVs without plugs). In the expanded RFS case, total biofuel volumes are increased to approximately 34 billion gallons in 2050, with most of the increase assumed to come from advanced biofuels. The expanded RPS case envisions a domestic policy environment in which at least some US states increase stringency beyond what they have already enacted. To avoid having to make judgments about which states enact which particular changes, the expanded RPS case is implemented by layering a single national RPS with unrestricted interstate trading on top of existing state RPSs. The national RPS increases the share of renewable sources in national

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f NEMS refers to the National Energy Modeling System developed and maintained by the US Energy Information Administration (EIA): https://www.eia.gov/outlooks/aeo/nems/documentation/. In what follows, we will use the term EM-NEMS to refer to the version of the model used in this study to distinguish it from EIA's version.

electricity generation from about 40% in the Reference Case to roughly 50% in the expanded case by 2050. In addition to the four cases discussed above, several economy-wide carbon tax cases were evaluated. Specifically, four cases were run with carbon taxes starting at $5, $10, $20 and $40 per ton CO_2 in 2022 and rising at 5% per year in real terms. These trajectories were selected in order to understand how cost varies with stringency and to provide several points that would enable construction of the economic "efficient frontier".

3. Main conclusions and policy implications of the work

Results from this study confirm that the sectoral policies evaluated are less cost-effective as a means to reduce CO_2 than an economy-wide carbon tax and that the transportation policies evaluated are less cost-effective than the electricity policies. In addition, it is notable that the sectoral instruments considered, to the extent that they extend or modestly expand existing polices with national scope, do not achieve annual CO_2 reductions greater than ~200 $MtCO_2$ per year on average over the projection period. This suggests that more expansive policy would be required to achieve CO_2 reductions consistent with stated national policy goals. Our results also provide several insights about existing sectoral policies that are relevant as refinements and modifications to such policies are considered. First, we find that the current wind and solar tax credits strongly favor wind over solar, because the solar ITC applies to capital costs, which have decreased significantly in recent years. Second, despite known inefficiencies, renewable energy policies in the electricity sector are less costly than earlier estimates due to recent and expected future technology advancement. Third, in transport, we find that expanding advanced biofuel targets in the RFS by the amounts assumed here would be more cost-effective than extending the EV tax credit under plausible assumptions. Fourth, we find a significant rebound in fuel economy under the EV tax credit extension, such that there is a smaller increase in fuel economy of conventional vehicles when the LDV fleet electrifies. This effect tends to further increase the cost of the EV tax credit extension, all else equal. Finally, we find that the change in policy cost over time varies by policy and model, although the cost ordering among polices does not change when different timeframes are considered.

Relative Cost-Effectiveness of Electricity and Transportation Policies as a Means to Reduce CO_2 Emissions in the United States: A Multi-Model Assessment

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