Energy and Economic Growth
Applied Research Programme

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Thematic Note: Designing large-scale energy infrastructure for inclusive growth

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April, 2017

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Acknowledgements

The Applied Research Programme on Energy for Economic Growth (EEG) is led by Oxford Policy Management in partnership with the Center for Effective Global Action and the Energy Institute @ Haas at the University of California, Berkeley. The programme is funded by the UK Government, through UK Aid.

EEG will commission rigorous research exploring the links between energy, economic growth and poverty reduction in low-income countries. This evidence will be specifically geared to meet the needs of decision makers and enable the development of large-scale energy systems that support sustainable, inclusive growth in low income countries in South Asia and Sub-Saharan Africa.

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This programme is funded by UK Aid from the UK Government.

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List of abbreviations

AC	Alternating Current
AMR	Automated Meter Reading
DER	Distributed Energy Resources
DLR	Dynamic Line Rating
EEG	Applied Research Programme on Energy and Economic Growth
FACTS	Flexible Alternative Current Transmission Systems
GDP	Gross Domestic Product
GIS	Geographic Information Systems
HV	High Voltage
HVDC	High Voltage Direct Current
ICT	Information Communication Technology
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LIC	Low Income Country
LNG	Liquefied Natural Gas
LV	Low Voltage
MV	Medium Voltage
OECD	Organisation for Economic Co-operation and Development
OLTC	On Load Tap Changers
PAYG	Pay As You Go
PCS	Power Converter Systems
PV	Photovoltaic
SCADA	Supervisory Control and Data Acquisition
SVC	Static VAR Compensators
VAR	Volt-Ampere Reactive

1 Introduction

This Thematic Note is one of six produced in the first year of the Applied Research Programme on Energy and Economic Growth (EEG). Each summarises a set of EEG State-of-Knowledge Papers that explore current understanding around one aspect of a theme related to large-scale energy infrastructure and economic development. This Thematic Note summarises the State of Knowledge Papers produced under EEG's Theme 6 – Designing large-scale energy infrastructure for inclusive growth. It highlights the key findings and research gaps that were identified by State of Knowledge Paper authors through their literature review and their engagement with policymakers and industry practitioners at the EEG Policy Workshops and Research & Matchmaking Conference.

High-income countries have reaped large economic benefits from utilizing reliable power with a mix of fuels (and hydropower) that led to the cheapest electricity, largely ignoring environmental externalities. This resulted from rapid progress in grid technology, as well as from sufficient income for masses to be able to pay for the product, entrepreneurial approaches, industrial organization, varying combinations of public/private sector engagement and national leadership to create the enabling financing and regulations. High-income countries are now looking to efficiency, integration of renewables, and electrification of transport and heating. It took public financing, leadership, innovations and manufacturing at scale to get the costs of renewables lowered to a point where the question now is not the cost of generating electricity from renewables but instead the cost of bridging the temporal mismatch between supply and demand. Demand is being driven by daily usage patterns, weekday/weekend effects, weather-driven thermal comfort needs and the mix of commerce, industry and residential needs specific to a place. On the other hand, given the increasing importance of renewable energy sources, supply is increasingly driven by the availability and variability of natural resources.

Rapid advancements in technology and increasing concerns about carbon emissions have provided LICs with a choice in terms of developing its energy-mix. LICs could follow the path of least-cost generation-mix that the high-income countries followed, while simultaneously adopting low-cost measures like smart measurement and monitoring of usage. On the other hand, for countries or regions that are not connected to the grid, LICs could invest in off-grid renewable energy to enhance access, without investing in expanding grid connections. Off-grid technologies like solar lanterns, and solar home systems are important in providing access to electricity in areas where there is limited/no grid connectivity. These off-grid systems, however, are limited by the fact that daily energy use remains severely constrained and so does the peak power provision. These off-grid systems thus do not have the flexibility and the low cost of supply of grid connections. Power grids, however, are complex capital-intensive infrastructure requiring long-term planning, low-cost financing and co-ordination between multiple parallel executing entities. Even when built, operating them reliably and with financial sustainability can be challenging as well which had frequently led to inefficient allocation of resources and accumulated debt burden for the utilities.

Evidence indicates that as countries grow, the consumption of electricity increases, and a relatively greater share of cleaner technologies is used. In the timeframe that loads grow, customer utility and country affordability would improve and technologies that leverages storage could emerge. The longer term drivers for the adoption of clean technologies would be educating the future workforce enabling health and ecosystem services, promoting greater use of ICT for knowledge dissemination.

This is based on the key assumption that economic growth would lead to a structural transformation of the economy from the primary and agricultural sectors towards the manufacturing and services sector. However, it is not clear if the LICs currently dependent on the primary and agricultural sectors would follow the same pattern of structural transformation. This would have important consequences for the energy systems adopted by these countries.

There is also a political economy dimension, as many LICs have taken a public-sector driven approach to power distribution. Many of the utilities in these LICs perform poorly, making losses year after year. The poor performance of the utilities could partly be driven by lack of institutional incentives, management, and potential tampering, or collusion. Additionally, political interference in tariff setting could also undermine operations. A vicious cycle of poor cost recovery and poor maintenance can also lead to poor reliability leading to further deteriorations in cost recovery.

This Concept Note is based on the following three State of Knowledge Papers:

1. Minuera. L., Mueller, S. & Dubbeling, T. (2016) Modular and Discrete: Opportunities for Alternative Power System Planning, Expansion and Operation in Developing Countries. Energy and Economic Growth Applied Research Programme.

2. Modi, V. & Rodriguez-Sanchez, S. (2016) Reducing Generation, Transmission & Distribution Inefficiencies and the Feasibility of Low-Voltage Supply in LICs. Energy and Economic Growth Applied Research Programme.

3. Modi, V. (2016) Low-Voltage System Designs for Energy Access. Energy and Economic Growth Applied Research Programme.

These papers are based on the following questions:

- To what degree is the inherent flexibility in the type and timing of electricity infrastructure exploited to support economic activities?

- What tools and technologies are available for renewables to challenge coal and other hydrocarbon based energy sources in energy mix and how would these be applied in LICs?

- Utilising modular or phased approaches for scaling up infrastructure.

- Reducing generation, transmission and distribution inefficiencies.

- Design options for lower voltage supplies.

2 Key insights from the State of Knowledge Papers

2.1 Paper 1: Modular and Discrete: Opportunities for Alternative Power System Planning, Expansion and Operation

The paper provides an overview of some of the technologies like DLR, HVDC, FACTS or power flow controllers, advanced inverters (or PCS) that support the deployment of DER, Volt-Watt control, volt-VAR control, OLTC, and SVC to provide reactive power at the grid level, that underpin a smart-grid While distributed technologies are facilitating a more flexible and decentralized transaction space, a robust network infrastructure, along with appropriate regulatory framework, remains a key enabler for this trend. Power system operation, and cross-border interconnection capacity allocation is increasingly driven by 'flow-based' optimizations, whereby the available grid capacity is calculated using the real-time status of critical grid components.

However, at the moment there are significant gaps in the literature as to the costs and benefits of smart transmission and distribution grid technologies in developing countries, signalling an important area for future research.

To date, there is no consistent assessment of the design requirements of ICT and smart grid technologies in a low-income country context. Specific standards for technologies that aim to enhance energy access in developing countries are critical – particularly considering the benefits of low maintenance equipment to ensure long usable lifetimes, and the difficulty of financing high capital cost technologies.

The rise of DER has gone hand in hand with the exponential increase in data in the energy system. Advances in data collection and management tools can provide more accurate information on the status of grid components in real time. Better data is one of the most valuable opportunities to improve grid planning and operations. Given untapped potential of data, Traditional system operators and planners will need to invest in the necessary tools and skills to collect and manage these data flows effectively. The paper also articulates the need to for GIS-driven information at a larger scale, including information on transmission and distribution infrastructure, solar and wind potentials, power plant locations, and location of demand centres. This would allow LICs to develop a balanced approach between expanding grid connections, decentralized off-grid technologies and interconnections.

Harmonising methodologies for the technological and economic evaluation of microgrids at a national level would also provide important insights. Institutions such as the IEC or ISO could be involved in a study to develop a 'standard design' for microgrids. The cost components could be sourced locally to develop a benchmark for the technology in the country, and understand what capacities need to be developed to reduce the cost of these projects. This would have great value for local policy-makers, who often need to rely on individual project developers or auctions to reveal costs of these options in contrast with grid-related expansion, where the costs are transparent and disclosed by a public utility. A key area of research here is developing standards and appropriate designs that provide for the level of interoperability required to expand networks in a bottom-up fashion, from low loads of solar home systems or small-scale micro- and mini-grids, to scaled-up local networks and eventual connection to large-scale regional or national grids. Such studies could serve as a benchmark to bring stakeholders together and develop an integrated and well-coordinated strategy among the various public bodies involved.

2.2 Paper 2: Reducing Generation, Transmission & Distribution Inefficiencies and the Feasibility of Low-Voltage Supply

Reducing generation, transmission and distribution inefficiencies along with appliance-side inefficiencies are recognized to be key ingredients in the future shape of the electricity sector. This paper emphasizes the fact that focusing on reducing technical losses alone may result in some important drivers of change being overlooked. In high income countries, where revenue collection systems have matured focus is increasingly on ensuring that appliance efficiency is in line with appliance-side role in demand response. In LICs, however, there are several, related issues that might shape technology choice.

These issues include technical and business architecture for metering; appliance finance and the potential involvement of utilities in financing efficient appliances; commercial losses of the utility; utility institutional and management structures; and transaction costs of payments and collections, amongst others. These aspects are inter-twined and need to be looked at holistically. Given these linkages between technical, business, commercial and social aspects, rigorous research has been difficult. However new designs and architecture that leverages ICTs, measurement technologies, data and knowledge on institutions and incentives, and understanding of the needs of a digitally-banked consumer in LICs can suggest novel approaches for addressing several linked issues simultaneously.

The paper highlights that unlocking investments for efficiency, access, growth and integration of renewables might be the key impediment. A switch from coal to gas may become viable only if a high initial investment cost gas pipeline (as opposed to LNG import, regasification and distribution) is built. Investing in renewables requires a high upfront cost, though with technological improvements these costs are rapidly decreasing. These investments are again linked back to the financial health of the entire sector which in turn is often characterized high aggregate losses, low ability to recover costs of generation, and a complex political economy surrounding tariffs and institutional issues. Given the limited availability of resources in LICs, most country planners are trying to prioritize investments, addressing issues regarding where to invest in grid connections, and assessing the alternatives for providing access to energy in areas that have no connectivity to the grid. Some of the solutions and emerging questions could contribute to the broader policy dialogue are summarized below

- Regional transmission lines could potentially both reduce losses and also reduce the overall cost of energy through interconnectors and electricity trade (e.g.: HVDC transmission lines between Kenya and Ethiopia)[1].

1 *Oguah, Samuel; Chattopadhyay, Debabrata; Bazilian, Morgan. 2015. Supporting Transmission and Distribution Projects : World Bank Investments since 2010. Live Wire, 2015/48. World Bank, Washington,*

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- In 2008, less than 4% of the global installed base of 1.5 billion electricity meters could be considered "smart". However, the smart meter market is exceptionally local, with different drivers, regulatory environments, favoured technologies, protocols and standards, value and supply chains, and especially, market timing[2], e.g.: China has a high penetration of smart meters (~67%) due to a decade of robust GDP growth, local technology development and rapid industrialization.
- Smart meters in the higher income countries are more for demand side management, "time-of-use" billing and peak power tariffs and necessitate high reliability of two-way communication networks. Can one imagine a lower cost, lean design for the LIC market that primarily enables prepayment given that it is possible to create good electricity audits through conventional meters if distribution transformers are metered?
- Are privatized utilities more likely to use technological improvements such as SCADA and GIS systems, improved metering, and registration and maintenance techniques, in order to meet the service quality requirements and the loss reduction targets imposed by regulators (ESMAP 2015)?

2.3 Paper 3: Low-Voltage System Designs for Energy Access

This paper explores the potential for innovative designs for last-mile distribution and/or stand-alone systems for electricity access in low income settings. The last decade has seen innovations and scaling of off-grid technologies such as solar/battery home systems and minigrids. While still expensive per kWh compared to grid tariffs, they offer the possibility of a lower capex, faster execution times, and institutional flexibility particularly if planning for the first few kWhs/month of service. Their viability for immediate first access to lighting and small DC loads is becoming clear, but that of providing pathways to larger consumption and economic growth is less clear.

The innovations in last mile distribution are primarily in the LV space, which is continuously evolving. This sub-400V space is where the conventional last-mile distribution in LICs takes place. In high income countries, there may be a single transformer for a single customer given that the load served for the customer maybe 25 kVA. (In Europe, three-phase 230/400V is common whereas in USA, a three-wire system is common with a standard phase-neutral voltage of 120 V). In LICs where loads are relatively smaller, and sometimes even as low as 0.5 kVA, a single distribution transformer or DT may serve multiple customers using what is termed as low-voltage or LV distribution. In conventional grids in existence today, all low-voltage distribution is AC just like the MV and the HV network wires that carry the current to the DT and to the LV network.

Most stand-alone mini-grids today utilize the same AC distribution voltages as the LV network of the grid. However, there are some designs emerging with DC voltages. Off-grid systems as discussed earlier can be either AC or DC. The choices have the following trade-offs.

- Higher voltages are better suited for longer distances in general, but generally require using an AC system, which also has the benefit of an appliance supply chain.

DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/22112 License: CC BY 3.0 IGO.

2 Pike Research. Smart Electric Meters, Advanced Metering Infrastructure, and Meter Communications: Global Market Analysis and Forecasts. 2012

- Increasingly many devices, especially in LIC residential setting are DC (and more are becoming available even for motor loads such as refrigeration and fans). This offers the possibility that one can completely avoid conversion losses from AC to DC and DC back to AC, if one has a purely DC distribution network at least beyond the DT or within the customer premises especially when a backup system for critical loads is dependent upon solar generation with batteries.
- Also if one considers access through solar home systems then, one can have entirely sub-48V DC wiring, which has safety benefits as well.
- The trade-off between a minigrid and off-grid systems are worth exploring further. They are both technical and commercial, offering different business models.
- Off-grid systems do not require distribution wire at all and thus save considerably on the cost of materials as well as installation costs. They however do not allow sharing of storage or sharing of capacity.
- Minigrids on the other hand, through shared storage and inverters can allow higher levels of peak use since individual customer peaks are not all at the same time.
- Moreover a minigrid installation is larger allowing some economies of scale. More importantly it allows ring-fencing of the generation and storage equipment allowing a pure service based model where the customer does not need to own or house generation and storage.
- Minigrids can financially justify higher investment in automation and battery management systems.
- Through load management, minigrids can also enable provision of critical loads for everyone, and this permits operation with high utilization and high customer satisfaction.
- Minigrids however have significant disadvantages compared to off-grid systems. They require high soft costs in assessment, design, land acquisition, installation and operation. These disadvantages can outweigh their viability if operated purely on commercial terms without any public support.

An important question highlighted in the paper is the need for a careful quantitative analysis of the public financing and public good that results from mini-grids as opposed to off-grid systems. The answer will depend upon the consumption levels, load profiles, load growth prospects, productive loads, geographic clustering and density of loads as well as load diversity. These dependencies need to be explicitly understood.

Some other questions raised by paper 3 are:

- Do mini-grids allow for emergence of entrepreneurial or small/medium industrial activity? Is there a threshold size or capacity that is needed? What kind of electricity service and the service delivery infrastructure is needed to nurture the non-residential customer? How can one prioritize such infrastructure?
- Can the flexible supply and business model of mini-grids allow for signalling growth and prioritization for the grid? Or would be simply institutionally and financially easier to roll out grid in an entire region?
- Insufficient information on existing and new customers (including off-grid demand) makes it impossible to estimate future demand. Demand projection is critical to selection

of transmission and distribution components, and the optimization of grid extension with off-grid solutions.

- Does one benefit from linking the need to build new infrastructure (schools, clinics, government offices, housing and roads) with electrical distribution?

3 Priority Research Questions

3.1 Questions emerging from the Research & Matchmaking Workshop

Much of the discussion at the Research & Matchmaking Worksohp touched upon the questions raised in the State-of-Knowledge Papers outlined above. For completeness, some of the questions and points raised were as follows:

- To what degree will regional trade/interconnects help with cost of generation?
- There was a sentiment expressed that sometimes external donors are pushing technologies that are too expensive or not market ready.
- There is a need for improved short-term forecasting of wind, and clear rules on who should pay for supply and demand imbalance.
- There is a need to understand the trade-offs countries make when they choose to use coal for generation versus the larger climate change imperatives.
- Does publicly funded grid extension provision make sense where industrial, mining or other large income generating loads can be served?
- Do fixed monthly fees/taxes for an electricity connection adversely impact the poor?
- Does promotion/adoption of high value low-cost cooking devices help alleviate time poverty?

3.2 Priority Research Questions

Given the key insights from the State of Knowledge Papers and the Research & Matchmaking Conference, we propose the following questions as research priorities to promote better understanding of the barriers to and the opportunities for innovative design for large scale energy infrastructure for more inclusive growth.

1. Robust tools for cost/benefit dynamics of different technologies for electrification.

   The research project should distinguish between cost differences that arise from:

   - Geography, settlement patterns, topography, etc. (which may require remote sensing, imagery, deep learning, and ideally digital census for identifying geo-located demographics).
   - Material cost differences due to transport/customs, scale, ad-hoc imports
   - Standards/sizing for reticulation and metering.

   It should also identify value or benefit that arise from:
   - Demand per residential connection, and commercial/industrial/public consumption over and above the residential sector.

   Ideally, the research would lead to norms for future demand projections that are generalizable. Projected demand differentiation could be based on:

   - Income and/or per kWh tariff

- Tariff structure, any flat monthly fees, and/or tariff stages
- Reliability and curtailment
- Additional productive demands (present or expected).
- Settlement size, reflecting additional non-residential demand
- Promotion of appliances, local scarcity of biomass derived cooking fuel, thermal comfort needs and electricity subsidy delivery mechanism.

2. Should a spatial approach be taken to bring the electricity grid to areas of likely high demand density?

   Prioritization methodologies could potentially conserve financial resources, lower political interference, allow longer term sector-wide approaches, but perhaps trade-off immediate benefits of grid connection at the household level for the wider population and leave no room for emergent unanticipated productive demand. The proposed research project would build upon what is learnt from the cost/benefit analysis suggested above, so that good indicators can be developed to provide planning-grade estimates that can feed into a spatial planning framework.

   Sub-questions:
   - What are the different "indicators" that can predict demand and demand growth beyond the residential sector (for example, demand from industry, mining, irrigable land, cold storage, aggregated settlements, government and social services, and tourism)?

   - What are the pros and cons of an approach to promoting productive uses of energy based on special economic zones/industrial parks or areas identified for irrigated agriculture with other complementary investments in infrastructure such as roads. Certain productive demands have threshold effects in that they only materialize at low electric supply costs. Agriculture demand may require investment in water supply, seed, and fertilizer. Should higher-reliability access be provided in the special zones to encourage service-based economic activities? Similarly, what are the pros and cons of an approach that prioritizes grid connectivity for social infrastructure.

3. Temporal/transition dynamics of technology choice and financing implications.

   Ideally a dynamic approach allows incremental strengthening of the standards as demands become larger (not on an annual basis but certainly decadal basis), since the cost of capital is high and one can benefit from signals emerging out of demand evolution based on observed data. This approach could also allow one to ensure a timely move from off-grid to minigrid, and minigrid to grid. Political-economy considerations driving grid and tariff setting may make this mute, but the private sector is taking the approach of meeting demand at the point of profitable cost of supply. Newer solar/storage models are creating innovative models for privately financed businesses and governments could leverage those investments. Technologies are also emerging that allow unreliable grids to switch to local sources/storage when interruptions occur.

   Sub-questions

- With battery technology improving, solar PV costs declining and potentially deep efficiency gains in appliances forthcoming, should developing countries take a different path in the short term? Is there a role for aggregating appliance specs/orders across countries to drive BOTH cost and performance?

- Can utilities be empowered to be more "data rich" in their decision making to allow more efficient resource utilization at the local-level? What kind of data is required? What is possible today with information technology?

- Off-grid systems currently being considered could be made compatible with future arrival of the grid. It is conceivable that a single-phase 230V AC distribution mini-grid eventually becomes one leg of a larger 3-phase grid when the grid arrives. Can mini-grid deployments create an initial roll-out compatible with the future, and with prepaid smart meters that would be just as valuable to the electricity audits and transparent operations of the utility managing the national grid?

- What are the different ways to address the financing gaps for meeting electricity access targets? Are there capital/operating subsidies to the private sector, akin to providing subsidies to transport firms to serve some areas?

- Can real-time data and/or transformer/feeder AMR assist with both demand estimation and meter reading audits?

4. Addressing commercial losses.

   Can PAYG/prepaid metering – or even simple but pervasive, validated metering (with appropriate software on the commercial side for audits that allow feeder, transformer and/or meter-reader level aggregations) – improve the incentives and institutional challenges faced by utilities. Can these measures lead to higher revenue recovery? Note that an altered operating model that has lower transaction cost and is more accountable, fraud-proof, responsive and technically, as well as financially, tight would reduce commercial losses and allow investments to start flowing to what should otherwise be a profit-making enterprise. Certainly, research shows consumers are willing to pay and are creditworthy.

   Sub-questions

- Are there best practices and low cost approaches emerging, and how are these best implemented?

- Are utilities ready for a "digital utility" approach? Does an evolution from prepaid minigrids actually help conventional utilities?

5. Are there elements, or a suite of elements, that constitute best practices for technological leapfrogging to a smarter grid future in low-income settings?

   Sub-questions:

- Do some of these measures provide better mechanisms to integrate renewables, demand side measures and flexibility?

- Are there implementations in pervasive sensing that can be more immediately deployed at low additional costs with control, real-time ISO market operations, edge of grid volt-var measures, and appliance power/voltage standards that come down the line? Is there a cost-effective sequencing of these measures?

- How can appliance finance promote appliance efficiency as well as demand growth?

- Lack of adequate co-ordination between generation, transmission and distribution might imply a possibility of shortfall of supply. In the short term, when supply proves inadequate the utility usually ends up buying power at an exorbitant rate, and/or commissioning expensive emergency diesel-powered generation. The use of backup generators on the consumer side as a hedge against unreliable supply is estimated to cost African economies between 1 and 5 percent of GDP each year. How can technology address these issues? Is it possible to move towards a digitally metered approach that allows one to schedule and curtail power, while still providing a minimum level of supply?