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THE BOTTOM LINE

The expansion of access to electricity remains an urgent international goal (IEA and others 2019). Recent progress in expanding access has depended on the use of planning models that fall into two broad categories: (i) power-flow models and (ii) newer GIS-based models. Tighter integration of the two categories, the authors believe, may facilitate better planning and so accelerate the expansion of access. If readers agree, the authors will develop a prototype and undertake a case study to explore whether the access solutions derived from the integrated model differ from the results of existing models already in use in World Bank projects.

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Planning Models for Electricity Access: Where Do we Go from Here?

What is the best way to expand access to electricity?

Closer integration of two schools of modeling may be the solution

Nearly 840 million across the globe still lack access to electricity, a majority of them in Sub-Saharan Africa (World Bank 2019). While there is no certainty that Sustainable Development Goal 7—universal access to modern energy by 2030—will be achieved, the access gap is slowly closing through innovation and diligent planning (Leke, Chironga, and Desvaux 2019). Progress is possible, as Kenya has demonstrated. Kenya's electricity access rate has nearly tripled in the past decade to nearly 75 percent (Njugunah 2018). Kenya has more than doubled its grid connections in a span of just four years. Off-grid expansion has also been rapid.

Most success stories are based on the application of one or more of four prevailing models for planning the expansion of access. This brief reflects on the state of the art of those models and discusses an analytical development that may make them more holistic and effective.

Access planning models fall into two broad categories: (i) old school models based on power flow, and (ii) their new school counterparts based on geographic information systems (GIS). At present, the latter do not use an integrated power-flow model. Here we discuss the pros and cons of the two categories and discuss the possibility of bringing them closer together to accelerate growth in access to electricity.

Currently, utilities and governments use both types of models to plan and design their access projects. The problem, however, is the limited coordination between models, which hinders holistic planning of electricity systems. Access could be advanced by combining the two types of models.

This brief is aimed at power system planners, as well as project managers and task team leaders in Sub-Saharan Africa and South Asia, who could benefit from deploying integrated electricity access planning in their projects. Our objective is to elicit opinions on the value proposition of an enhanced and integrated electricity access planning model. If the proposition commands interest, we will develop a prototype and undertake a case study to explore whether the access solutions derived from the integrated model differ from the results of existing models already in use in World Bank projects.

What distinguishes the two sets of access planning models?

They were devised at different times for different purposes

Most efforts to expand access to electricity are based on a power system planning model, a GIS-based planning model, or one of each. Although both groups of models aim to meet demand for access at the lowest cost, the two types are different.

Power system planning covers upstream generation and transmission planning along with incremental expansion of distribution systems. This conventional form of planning, widely used by utilities, entails load-flow analysis to determine network configuration, the length of distribution feeders, conductor specifications, and the resultant power flows and voltages.

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Power system planning models have several salient characteristics. They are bottom-up efforts—that is, the first step is usually to pull together demand estimates from the bottom up. They are well suited for incremental expansion of the network at granular levels of distribution. By contrast, they are not suitable for a higher-level study of a wider region with large off-grid areas. They align closely with the practical realities of the system—and they are well known to distribution system engineers.

GIS-based planning, a relatively recent innovation, constitutes a stand-alone tool for analyzing access at the distribution level. This form of planning is used by governments and the private sector, especially in the off-grid energy space. For example, NASA's night light imagery, originally developed for weather prediction, is being piloted for many innovative applications, including energy infrastructure planning (NASA 2017).

Stand-alone GIS models are more flexible than a power system planning model—they can proceed from the bottom up or from the top down. In the course of their development, they have become well aligned with off-grid systems and distributed energy resources (DER), especially renewables, which have been among the key drivers of the development of GIS models. They are often used for high-level studies, especially when other forms of data are limited. Their key shortcoming is that they do not embed power-flow constraints and hence are not a mainstream tool for utilities.

While the two types of model can and should be complementary, this is largely not the case, though there is some degree of complementarity in peripheral features such as visualization and geo-referenced data.

Utilities' approaches have not changed much since the 1970s. Planners in the seventies typically used a map, scattered data on population, and rules of thumb to decide whether to add a new substation to connect new customers (or to section load among existing substations), to decide on the length of feeders, or to undertake reactive compensation, among other tasks. This would be followed by a load-flow analysis to check the feasibility of the system and fine-tune the solution.

Distribution utilities in all countries that can afford load-flow tools and know how to use them still plan their systems using these tools, turning to GIS systems only to present the results. The National Rural Electric Cooperative Association (NRECA) in the United States is a good example. For NRECA, the WindMil load-flow model remains the central tool, with GIS aiding visualization. Innovations in GIS have made visualization more appealing and thus enhanced utilities' ability to translate intuitive understanding of the system into quantitative inputs on where and how the network should be expanded. As GIS tools become more sophisticated, they will be even more valuable as supplements to the load-flow models that drive electricity access planning.

However, as universal access to electricity has become a paramount goal for governments and development institutions, stand-alone GIS-based models that add intelligence and sophistication to existing GIS tools have come to be widely used. Commonly used on the national level, GIS models have long been adaptable to more granular levels where the requisite data are available. In recent years, in response to need, GIS models requiring less extensive data have evolved for use in contexts where access to data is limited, as is the case in many of the countries where electricity access projects are designed and implemented.

But although the ability to add multiple layers of population, income, and network data to a geospatial model greatly enhances the understanding of the system being modeled, stand-alone GIS-based systems are often used, unadvisedly, to make decisions on where and how access should be expanded in the absence of the larger picture of the power system that load-flow analysis can provide. In other words, power system modeling and stand-alone GIS-based modeling are not being used in a complementary manner to achieve holistic access planning. This lack of coordination, covered in a previous Live Wire (Chattopadhyay, Jordan, and Kitchlu 2014), is more relevant than ever.

How do existing planning models compare?

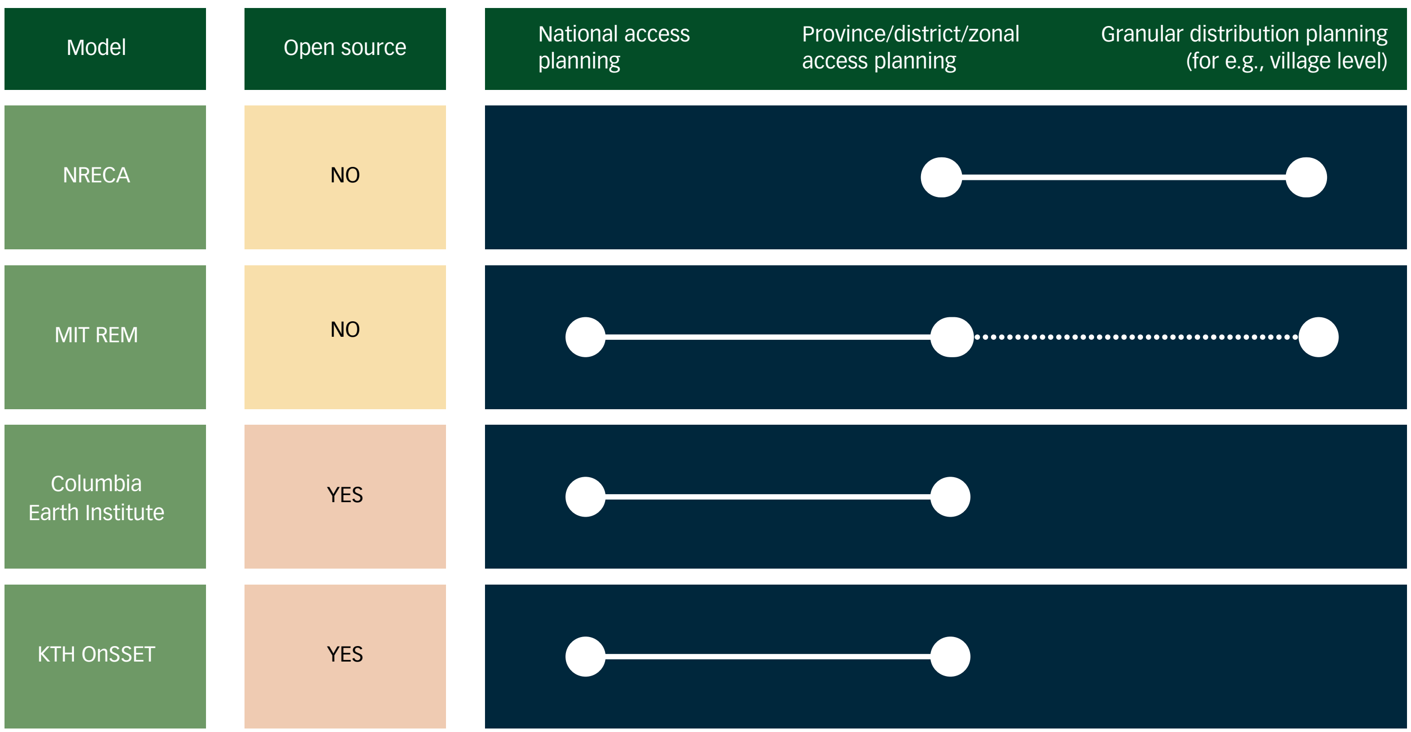
The models differ in their geographic focus, their data sources, and their proprietary status

Our objective is to elicit opinions on the value proposition of an enhanced and integrated electricity access planning model.

This section discusses existing models used in electricity access planning (figure 1). Planning occurs at all levels, from the national level down to collections of villages. The figure specifies the geographic scope of the models shown. Selection of a model is also governed by the availability of data. It is important to remember that the selection of a model is shaped both by the objective of the study (i.e., its geographic scope) and the availability of data. The models are summarized below.

NRECA methodology. After georeferencing the existing electrical system, the NRECA model evaluates the technical performance of each distribution feeder using Milsoft's WindMil, a commercial power-flow software package, or NRECA modules devoted to load flow, voltage profile, and technical losses. A commercial evaluation is also performed. Similarly, technical and commercial analyses are conducted for line extension based on load, number of customers, and prospective increases in energy consumption. The NRECA methodology, which is well suited to detailed distribution planning at granular levels, reflects utilities' focus on traditional power system modeling.

Figure 1. Comparison of access planning models—from the country level to groups of villages



Note: Solid line indicates that the entire geographical spectrum between the circles is covered. Dotted line for MIT REM model indicates that the distribution network planning component is not fully integrated into the model. See discussion of Reference Network Model in text.

As universal access to electricity has become paramount for governments and development institutions, stand-alone GIS-based models that add intelligence and sophistication to existing GIS tools have come to be widely used.

MIT's Reference Electrification Model (REM). In the REM model, GIS is used to ascertain unknown attributes of households (e.g., size) in particular clusters, as well as the geographical characteristics of those clusters. Household census data, satellite image processing, and crowdsourced pinpointing of users are some of the methods used to obtain information. Based on this information, the REM model compares various energy technologies and layouts to identify an optimal power system design for the area.

The model compiles customers' load profiles, which can be estimated using their average income level and service tier. It can be used by planners (including distribution companies, policymakers, regulators) to estimate electrification costs and appropriate electrification modes (network extension, isolated mini-grids, and stand-alone systems) at a regional level. Additionally, engineers and designers intending to electrify specific areas can use it to make design decisions that appropriately balance level of service and costs. The REM model thus includes both power system planning and GIS and can be used iteratively with the Reference Network Model (RNM), a distribution network planning model that is not (yet) fully integrated in REM.

Columbia Earth Institute methodology. The model's inputs include electricity demand, costs, and geographic characteristics. Its spatial nature enables the presentation of existing electricity network and population distributions, which form the basis for future expansion decisions. While it does not build in load-flow analyses, the model acknowledges that these are required for holistic access planning, especially at granular levels.

KTH OnSSET. The KTH model also focuses largely on GIS planning. Its overall aim is to link GIS and energy planning by (i) utilizing the open source GIS datasets that have recently become available to estimate the technical and economic potential of local energy resources, and (ii) developing and applying a geospatial electrification toolkit that yields the mix of technologies needed to secure universal electricity access at the least cost. This model is well aligned with efforts to exploit DERs, but it does not include much power system planning and has limited value for access planning at granular levels.

Could power system planning and GIS-based planning be better integrated? If so, how?

Fusing the two paradigms promises substantial benefits, and doing so is feasible

The foregoing review of power system planning models and sophisticated stand-alone GIS-based models suggests the following questions:

- Is there a need to bring the two paradigms closer?
- If so, do analytical frameworks exist to accomplish the task?

Well-integrated planning models can help cover the whole planning spectrum—from the national level down to granular distribution at the village level. GIS electrification plans made at the distribution level should not be used in isolation; instead, power system models should be used to synchronize generation and transmission planning with expansion at the distribution level. Planning engineers have retained their faith in power-flow models such as Siemens's PSS®E (Power System Simulation for Engineering) that have a solid engineering foundation. Integration of models is critical to ensure that investment plans are realistic and accurately reflect the costs that utilities face in practice.

Well-integrated models also ensure that the network is efficient, secure, and resilient.

Achieving *efficiency* with respect to technical characteristics (e.g., low levels of loss) and cost may require that aspects of the existing network be carefully redesigned as an integral part of the expansion process. A common deficiency of distribution network expansion in developing countries is that the medium- and low-voltage network is repeatedly extended without regard to the possibility that some existing feeders should be upgraded before they are extended. There is almost no consideration of such questions in a typical stand-alone GIS-based model. Also, GIS-based models do not take into account central generation capacity or the implications for the grid of increasing that capacity.

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A *secure* network has sufficient capacity and redundancy to absorb contingencies. This issue, too, is typically ignored by stand-alone GIS-based models.

Finally, a *resilient* network is one designed to withstand natural disasters.

Because grid expansion at the distribution level must be coordinated with generation and transmission planning, the two models are complementary—one model centered on load flow and used to expand the grid incrementally; and a GIS-based model at the other end that closely aligns with DERs. The complementarity is particularly relevant in light of planners' concerns to maximize system reliability and resilience when expanding existing networks, as opposed to emphasizing off-grid means to expand access in isolation from attention to the grid. Of course, both grid and off-grid expansion are important to close the electricity access gap, but an integrated model offers the best means of determining where and how each should be expanded.

Having established the merits of bringing the two paradigms closer, we now consider how this can best be done.

Sophisticated stand-alone GIS tools are still largely used by universities and have not yet been fully embraced by utilities' planning groups, except in capacity building exercises undertaken by donor agencies. Practicing engineers and consulting firms continue to rely on traditional load flow–based tools for power system analysis. But now we know that a well-integrated model can advance access planning across the geographical spectrum (from the national to the village level). The residual problems are (i) that licenses for models such as NRECA and REM can be expensive and (ii) that the RNM distribution network planning model is not fully integrated into MIT's REM model. Until these obstacles are surmounted, one or more of the following tactics can be employed to take advantage of the benefits of combining the two planning paradigms. One can:

- Embed one of the variants of load-flow models (three-phase AC load flow, single-phase AC load flow, DC load flow) into a GIS-based model. Even the simplest version would substantially improve the current state of the GIS models and hence improve their compatibility with pure load-flow models.
- Increase the emphasis on network reliability and security considerations, to push planners toward a better balance of DER and grid-supply options.
- Promote better coordination between distribution and upstream generation/transmission models.

The first option could entail a significant investment in model development. Integrating load-flow equations into a GIS-based model may pose significant data and computational issues. Simpler and more expedient options may include better coordination between (i) GIS-based and load-flow models (following the example of MIT's REM model and, to a lesser extent, the NRECA model) or (ii) distribution planning and upstream models.

Choices will have to be made among these multiple possibilities. The key objective of this brief is to seek opinions on relative priorities. If readers can provide evidence that access programs have been affected by lack of supply at the transmission substation level, this will argue for a better coordination between generation and transmission master planning. If evidence surfaces of persistent problems with underestimation of investment needs following use of GIS-based models, the priority will be to enhance the technical rigor of the models. Some of the open questions we hope to resolve are:

- The value proposition (cost, effectiveness) of an integrated model for utilities in developing countries
- The feasibility of upgrading existing models (integrating RNM into REM) to improve their usefulness in securing holistic outcomes
- Computational feasibility and the maximum network size a given model can handle
- Accessibility and financial feasibility of integrated models for governments and utility planners.

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Live Wire 2014/9. "Tracking Access to Electricity," by Sudeshna Ghosh Banerjee and Elisa Portale.

Live Wire 2014/16. "Capturing the Multi-Dimensionality of Energy Access," by Mikul Bhatia and Nicolina Angelou.

Live Wire 2014/20. "Scaling Up Access to Electricity: The Case of Lighting Africa," by Daniel Murphy and Arsh Sharma.

Live Wire 2014/35. "Planning for Electricity Access," by Debabrata Chattopadhyay, Rahul Kitchlu, and Rhonda L. Jordan.

Live Wire 2015/51. "Scaling Up Access to Electricity: Emerging Best Practices for Mini-Grid Regulation," by Chris Greacen, Stephanie Nsom, and Dana Rysankova.

What are the next steps to better integrate power system planning and GIS-based planning?

Several opportunities are within our grasp

The access planning exercises and least-cost electrification studies conducted by the World Bank have generally been expensive. The collection of primary data has accounted for a large share of this expense. However, the advantages of building the Bank's in-house capacity for cheaper and better modeling can be significant. The past five years have seen some encouraging developments, including the global access planning tool developed by the World Bank's Geospatial Operation Support Team (World Bank 2018), the Global Electrification Platform helmed by ESMAP, and significant country-level work done by regional teams with the participation of Bank staff and consultants.

Moving forward, some key recommendations for World Bank teams are:

- Explore practical ways to integrate load-flow modeling and GIS-based modeling and make the resulting model accessible and economical for governments and utility planners in client countries. One practical way of arriving at this outcome would be to reassess the priorities of the Bank's task team leaders and power system experts.
- Collaborate with universities to develop integrated models that leverage innovations, new data, and new tools and that can be applied to the full geographic spectrum, from national planning to granular distribution planning at the village level.
- Offer workshops and training programs to build technical planning capacities within the World Bank, governments, utilities, universities, and the private sector.

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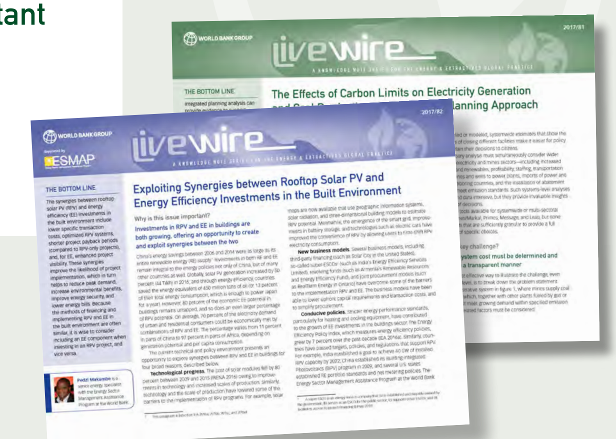

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