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TECHNICAL BRIEF: GRID MODERNIZATION INVESTMENTS TO IMPROVE INTEGRATION OF VARIABLE RENEWABLE ENERGY

SCALING UP RENEWABLE ENERGY (SURE)

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BACKGROUND

As prices for clean energy and storage technologies continue to fall and nations explore ways to cut emissions, integrating higher shares of variable renewable energy (VRE) is becoming more urgent. Experts and policymakers around the world understand that this complex task requires a more flexible power system[1] and flexibility requires a modern grid. A "modern" grid is one that is larger, faster, and smarter.[2] A larger, faster, smarter grid enables VRE to be predictable, visible, and controllable, reducing integration costs (e.g., less need for generators providing reserves). Similarly, the flexibility needed to integrate more renewables can come from other generation sources (such as ramping hydro and thermal generation), demand-side management, and trade in balancing resources between zones and countries, all of which require a modern grid. Unmodernized grids are already a bottleneck in countries where the share of VRE is reaching a certain threshold.

Integrating renewables and modernizing grids both require improved policies and regulations, better power markets, and updated operational and commercial practices. They also require important investments in equipment, systems, and software. This technical brief examines the types and sequence of investments required to manage the flexibility needed for successful grid integration of renewables.

The world invests around $300 billion per year in electricity grids.[3] Roughly two-thirds of this is in distribution, and one-third in transmission. If we want to achieve Paris Agreement goals, most forecasters agree that we must make even larger investments in grids.[4] Investments in grid modernization and expansion should roughly double to around $600 to $700 billion per year until 2050, i.e., a total of more than $20 trillion in the next 30 years.

Grid modernization is needed not only to achieve greater flexibility for VRE integration but also to i) host emerging business models (such as EV charging and demand aggregation); ii) allow improved operations, workforce productivity, and cost efficiency; iii) underpin market integration; and iv) deliver the resiliency required to provide secure and good quality power to decarbonized and electrified economies in the context of extreme weather events caused by climate change.

Investments in modern grid assets occur continuously (e.g., natural replacement of malfunctioning devices), and in many cases without a clear strategy. This is detrimental, as it can lock in inefficient and dated technologies and miss leapfrogging opportunities. For instance, in the telecommunications arena, many countries have leapfrogged landline telephones to go straight to mobile phones. Grid modernization requires sound planning and strategy that answers the why, what, where, when, and who of grid modernization investments.

MAPPING GRID MODERNIZATION INVESTMENTS TO IMPROVE RENEWABLES INTEGRATION

Understanding the investments involved in grid modernization can be complex. The language easily becomes too technical, and there is a clear risk of obscuring the big picture by focusing on the details and costs, creating communication barriers between policymakers, investors, and technical experts that interfere with implementation.

We present a framework[5] in the figure below that simplifies understanding grid modernization by visually mapping the types and sequence of

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[1] Definition by the International Energy Agency: "power system flexibility encompasses all relevant characteristics of a power system that facilitate the reliable and cost-effective management of variability and uncertainty in both supply and demand." (IEA, 2018).

[2] While "larger, faster, smarter" is a useful working definition, there are some exceptions to this: in the context of providing electricity access in remote areas, small renewable energy–powered standalone systems or mini-grids may prove more cost-efficient than a "large" grid.

[3] Based on data from the IEA's "World Energy Investment 2022" and the Bloomberg New Energy Finance (BNEF) "New Energy Outlook 2019."

[4] Such as the IEA, International Renewable Energy Agency, BNEF, and others.

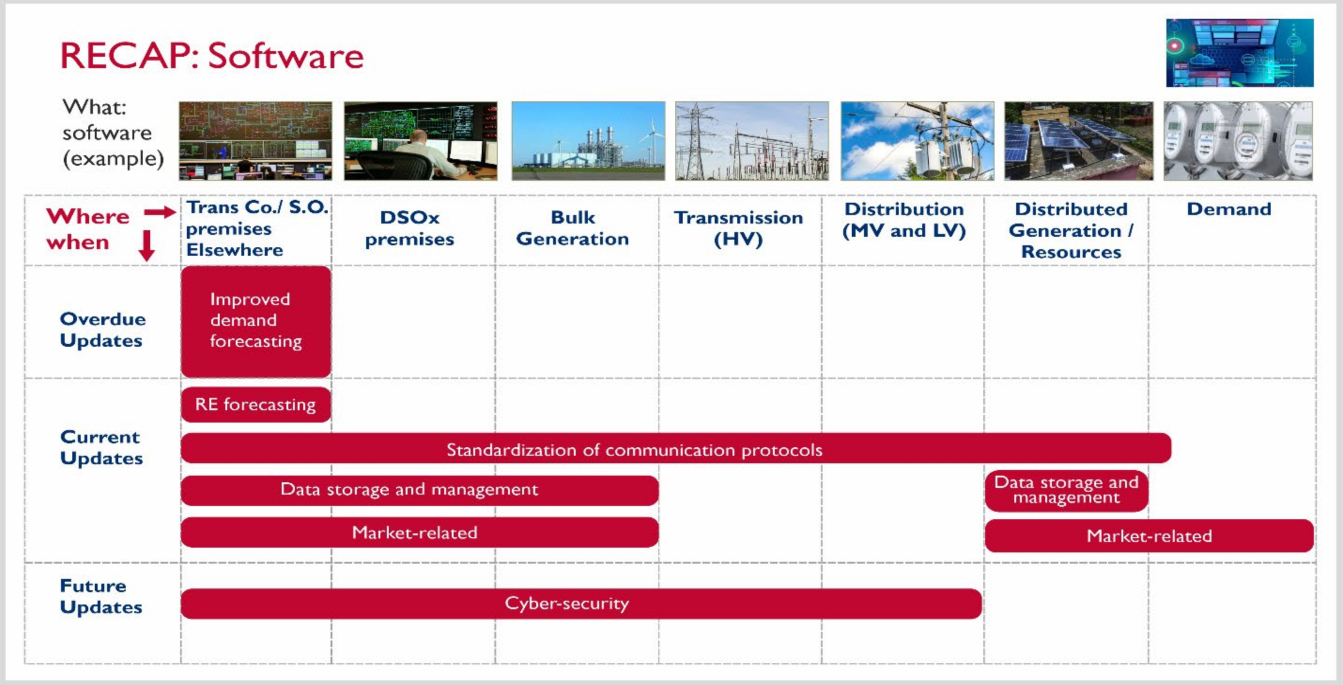
[5] Inspired by similar frameworks being developed around the globe, such as the NIST Framework and Roadmap for Smart Grid Interoperability Standards in the United States or the Smart Grid Architecture Model (SGAM) in Europe.

investments required. We then apply this framework to three country examples: Colombia, Kazakhstan, and India.[6] These three examples feature different flexibility needs and stages of grid modernization. Our goal is to identify key components and common traits across countries. Ultimately, this framework could serve as a blueprint for where to start building understanding, support, and buy-in from policymakers and investors on grid modernization investments.

Our framework maps investments in three dimensions: "what, where, and when." A fourth dimension could be "why," i.e., the driver behind each investment. Drivers could be flexibility for VRE integration, loss reduction, increased reliability, enhanced climate resilience, or improved energy security. This brief focuses only on the investments required to address the first driver—flexibility for VRE integration—though there may be overlaps and synergies with the other drivers.

Key investments (the "what") include energy hardware (the thick cables and heavy equipment through which energy flows); hardware for measuring/communications/controls/IT/data management (i.e., thin cables and small electronic devices through which low-energy electronic signals flow); and software for data management, applications, and analysis. The location of an investment (the "where") refers to where within the power system the investment is made (e.g., consumers, grids, distributed generators, bulk generation assets, or control centers). The "when" of an investment addresses the sequence in which each investment must be made. "Overdue updates" refers to existing assets that should have been replaced or reinforced in the past; "current updates" means new assets that are the early backbone of a modern grid and can probably be tackled immediately; and "future updates" implies new assets that are advanced elements of a modern grid and can likely wait. The sequence of investments tends to vary across countries. Below is a sample application of the framework, showing software investments that are common to all three countries.

The figure below shows how improved demand forecasting software, mostly implemented on the premises of transmission companies and system operators, is one of the first investments in grid modernization. Current investments include RE forecasting, standardized communication protocols, applications for data storage and management, and market-related software. Cybersecurity is the key software element planned for the near future.



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[6] The detailed application of the framework to the three countries is not shown in this technical brief due to space constraints. This brief presents only the conclusions of said exercise (which deliver the key policy messages) and shows a visual example (for illustrative purposes and the reader's understanding).

KEY GRID MODERNIZATION INVESTMENTS TO ENHANCE FLEXIBILITY AND ENABLE VRE INTEGRATION

Countries modernize their grids for a variety of reasons (the "why" discussed earlier). Colombia, Philippines, and Ukraine, for example, modernized their grids as part of setting up wholesale or ancillary services markets (e.g., modern grids are required to measure and settle trading in ramping services). These countries have an advantage when it comes to grid modernization for renewable energy integration because the process has begun already.

Transmission and distribution grids require specific capabilities to measure and manage sources of flexibility, but there is no single "correct" architecture and implementation is country dependent. However, all modern grids are composed of three building blocks. See image below.

THE KEY BUILDING BLOCKS

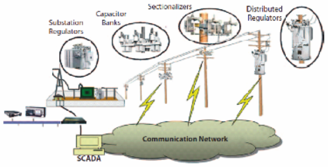
Intelligent electronic devices (IED):
to remotely visualize and control


a. Electromechanical devices
b. Intelligent electronic device

Source: Cooper Power Systems 2013 product catalogue.

Practical Guidance for Defining a Smart Grid Modernization Strategy (Revised Edition)

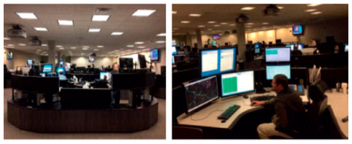
Two-way communication network:
to link IEDs and control centers



Source: McGranaghan and Uluski 2010.

Modern control centers:
with data and software tools to manage information and process it faster and better than humans

Figure 3.3b Modern Computer-Based Control Center and Operator Console Design



Source: Alabama Power 2014.

The first building block is intelligent electronic devices (IEDs) that replace old "electromechanical" equipment and allow remote visualization and control of many parts of the power system (i.e., "remote," "visualize," and "control" are the keywords of a modern grid). The second building block is a modern control center, which is where the people in charge of managing the grid go to work every day. These modern control centers rely on screens and computers instead of printed documents and telephones. This is where all the data from the intelligent electronic devices is received and processed, using computer software that processes information faster and better than humans and sends instructions back to the remote controls. The third building block is the two-way communication network that carries signals back and forth between the intelligent electronic devices and the control center.

The specific implementation of these building blocks in a grid modernization program varies depending on each country's power system. After our analysis, some common features emerge from the cases of Colombia, Kazakhstan, and India, which can be seen as key grid modernization investments required to enhance flexibility. They include:

- First, in many countries, existing generation can provide flexibility without much hardware modification. Grid modernization measures that tap into existing flexibility include ramp control and certification; automated generation control (AGC)[7] and related communication and control systems; and commercial accounting and settlement systems (e.g., systems to meter,

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[7] AGC rapidly and automatically adjusts the power output of multiple generators in response to changes in frequency which are, in turn, a symptom of unbalanced supply and demand that can threaten power system stability.

account, and pay for the ramping services provided).
- Remote visibility and control of flexible generation is another key area of investment. Much of what has been implemented globally is based on supervisory control and data acquisition (SCADA) systems,[8] but some believe SCADA needs upgrading to manage increasing flexibility. VRE integration and more distributed power systems may require something faster that covers distributed energy resources and that allows for bidirectional energy flows. These are sometimes called distributed resource management systems, or DERMS.[9]
- Another common investment refers to advanced sensors that allow system operators to gain visibility on grid health and on the impacts of RE generation on power quality (e.g., phasor measurement units, or PMUs[10]).
- Forecasting systems for RE and demand are also widely used. Better forecasting allows system operators to understand the amount and types of flexibility required and to make adjustments that are more accurate and timely.
- A communications backbone is also key. It must be fast, able to handle high volumes of data, and available for multiple types of communications needs.
- Finally, investments in data storage, data management and analysis, and cybersecurity are also common.

All countries that add large amounts of VRE face the challenge of managing the variability of these generation sources. In most situations, the grid needs to be modernized in ways that enhance the ability to access and manage flexible resources, including generation, demand, and trade between zones and neighboring countries. Careful planning and a stepwise implementation program, such as the one mapped here, are the keys to success.

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[8] SCADA systems have been around for years. SCADA allows remote visualization and centralized control of what is happening throughout the high-voltage network and collection and processing of the data. SCADA is a great set of "eyes and arms" (being behind the information shown on screens), but its "brain" is limited and requires human intervention.

[9] DERMS is a platform that helps distribution system operators (DSO) manage their grids.

[10] PMUs are advanced sensors that measure voltage and the physical characteristics of electric currents, such as angles, and present the data as phase vectors, or "phasors." Current SCADA systems observe grid conditions every few seconds. Thus, they are slow and incapable of providing information about the dynamic state of the power system. In addition, SCADA data are not consistently time-synchronized and shared widely across the network. Therefore, SCADA does not provide operators with real-time and wide-area visibility. The emergence of PMUs provides a significant improvement in reliability by offering unprecedented time-synchronized and high-resolution information over a wide area, in real time. Many advanced smart grid applications can take advantage of the measurement capabilities of PMUs.