Greening the Grid

VARIABLE RENEWABLE ENERGY GRID INTEGRATION STUDIES: A GUIDEBOOK FOR PRACTITIONERS

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VARIABLE RENEWABLE ENERGY GRID INTEGRATION STUDIES: A GUIDEBOOK FOR PRACTITIONERS

Authors

Jessica Katz and Ilya Chernyakhovskiy, *National Renewable Energy Laboratory (NREL)*

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List of Acronyms

BAU	business-as-usual
GHG	greenhouse gas
MWG	modeling working group
NREL	National Renewable Energy Laboratory
RE	renewable energy
TAC	technical advisory committee
TMY	typical meteorological year
TRC	technical review committee
USAID	United States Agency for International Development

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1 Introduction

Countries around the world are establishing ambitious goals to scale up the contribution of renewable energy (RE) toward meeting national energy demand. Because RE resources such as wind and solar generally increase variability and uncertainty associated with power system operations, reaching high penetrations of these resources on the grid requires an evolution in power system planning and operation. To plan for this evolution, power system stakeholders can undertake a grid integration study. A grid integration study is a comprehensive examination of the challenges and potential solutions associated with integrating significant variable RE generation in the electricity grid.

The purpose of this guidebook is to introduce power system policymakers, regulators, operators, and supporting organizations to RE grid integration studies.

1.1 How to Use This Guidebook

This guidebook provides a brief but comprehensive summary of the strategies, best practices, and terminology associated with conducting a high-quality grid integration study. Teams that are in initial stages of designing a grid integration study can use this guidebook to understand the key steps, modeling tools, data collection activities, and considerations that will enable a successful effort. Although this guidance is broadly applicable to most power systems, it emphasizes considerations relevant to developing economies, drawing on experiences from efforts by the United States Agency for International Development (USAID) to support analyses with its partner countries.

As the share of wind and solar in the global energy supply continues to rise, a growing body of research and experience is emerging related to the efficient integration of these variable RE resources into power systems. Recognizing both the wealth of existing resources and the difficulty in providing general guidance on analyses that are inherently system-specific, this guidebook does not detail all methodological steps and issues related to each topic. Instead, each section includes a toolkit with links to supplemental materials that provide more in-depth information and guidance. Each section also includes recommendations for topic-specific actions for the team leading a grid integration study. Finally, wherever possible, each section includes specific examples from actual grid integration studies.

The guidebook is organized as follows:

- Section 2 introduces grid integration studies for power system planning and outlines when a grid integration study may be valuable;
- Section 3 reviews key questions that grid integration studies address and key the analyses that help to address these questions: capacity expansion; production cost; and power flow analyses;
- Section 4 discusses five primary components of a grid integration study: stakeholder engagement; data collection; scenario development; power system modeling; and analysis and reporting. It concludes with insights on the costs of conducting a grid integration study; and
- Section 5 summarizes how a grid integration study can inform power system policies and planning .

The appendices include a variety of additional examples and resources. Several appendices provide templates for organizing and implementing various components of a grid integration study. Practitioners are encouraged to adapt these templates to their own efforts.

2 What Is a Grid Integration Study?

A grid integration study provides an analytical framework for evaluating a power system with high levels of variable RE. Studies can be undertaken by various regional, country, or local power sector organizations, including:

- Power sector regulatory commissions
- Energy ministries and other government entities tasked with electricity sector policy
- Power system and/or market operators
- Research organizations that support government decision-making.

A primary goal of a grid integration study is to address stakeholder concerns that a power system can operate reliably and cost-effectively under high-RE scenarios. While grid integration studies can include RE resources such as hydropower, biomass, and geothermal, they typically focus on the impacts and integration solutions associated with variable RE resources, particularly wind and solar. These resources pose distinct operational challenges for power systems due to their variability (i.e., their change in output over various timescales due to the underlying fluctuation in resource) and uncertainty (i.e., the inability to perfectly predict resource availability and generator output). Although all power systems are designed and operated to efficiently manage variability and uncertainty in electricity demand and resource availability, significant levels of variable RE amplify this inherent variability and uncertainty and may require changes to system operations and/or physical infrastructure.

Depending on the purpose and scope, a grid integration study can accomplish any combination of the following objectives:

1. Identifies future generation and transmission portfolios to achieve RE targets at least-cost while maintaining reliability objectives;
2. Simulates the operation of the power system under different future RE-penetration scenarios and at different timescales;
3. Identifies reliability constraints associated with different RE scenarios; and/or
4. Determines the relative cost of actions to integrate high levels of variable RE.

A grid integration study is not the same as a grid impact study or grid connection study. Grid impact and grid connection studies assess the technical feasibility of interconnecting a single wind or solar power plant. Grid integration studies, on the other hand, focus at the system level to analyze the technical and/or economic impacts of achieving higher shares of variable RE, usually from multiple generation sources, in the electricity mix. Although grid impact or grid connection studies represent an important component of the RE project development process, they are outside the scope of this guidebook.

2.1 When to Conduct a Grid Integration Study

A grid integration study is a valuable tool to inform energy sector planning; however, conducting a grid integration study is a significant undertaking that can require several months to multiple years to complete. The following considerations and questions can help identify whether the critical elements are in place to ensure that investing the necessary time and resources produces a relevant, high-quality product.

- **Potential to inform decision-making**—To what extent will a grid integration study address key questions and concerns that stakeholders have about integrating variable RE to the grid?

- **Data availability**—Perhaps most critically, are high-quality wind and solar resource data available, and are these data sufficient for the type of analyses being considered? Also, is detailed information about the power system (such as characteristics of existing and planned generators and transmission lines) readily available? (See Section 4.2 for more information about data requirements.)
- **Stakeholder convening mechanism**—Does a convening authority exist, and is there appetite among key energy sector stakeholders to actively engage in the grid integration study process (for example, by participating in a technical review committee [TRC])? (See Section 4.1 for more information about stakeholder engagement.)
- **Modeling staff capacity**—Are trained modelers available, and do they have the mandate and funding within their professional roles to conduct the analyses associated with a grid integration study?
- **Tool availability**—What software tools (commercially available or internally developed within public or research organizations) are available to answer the key questions of interest for a grid integration study? How much time and resources will be required to procure or develop tools that can answer the most important questions? (See Section 4.4 for more information about power system modeling tools.)

If one or more of these critical elements is missing, initial investments may be better focused on filling these gaps to lay the groundwork for a grid integration study.

Despite potential gaps in these critical elements, several actions can be taken to improve the ability of power systems to incorporate significant generation from variable RE resources. Several well-known practices can help to reduce costs and increase the power system's ability to reliably integrate variable RE without requiring a full grid integration study (Milligan et al. 2015; Smith et al. 2007). The following examples are well-vetted, "no-regrets" grid integration actions[1]:

- Implementing wind and solar power forecasting in power system operations
- Aggregating wind and solar power output over large geographical regions, for example, through balancing area coordination
- Moving to shorter intervals (such as sub-hourly) for scheduling, dispatch, and, where applicable, balancing markets
- Enabling wind and solar plants to provide ancillary services, for example, through updates to grid codes and/or power purchase agreements
- Implementing demand response programs.

There is no one-size-fits-all approach to grid integration—power systems differ in terms of their generation resource mix, market structure, and regulatory processes, among other factors. Nevertheless, each of the approaches outlined above can be adapted to fit the market structure, economic dynamics, and needs of a specific power system. Policymakers and system operators can explore and implement these actions in tandem with efforts to prepare for and conduct a grid integration study.

[1] More information and references related to each of these topics are available at http://greeningthegrid.org.

3 Types of Grid Integration Analyses

All grid integration studies are unique. Each study is tailored to address the concerns most relevant to a given power system. In general, a grid integration study involves modeling the power system using approaches that fall into one or more of three general categories: capacity expansion, production cost, and power flow. A best-in-class grid integration study uses all three types of analyses; however, many grid integration studies focus only on one or two methods. In subsequent chapters, this guidebook emphasizes production cost modeling (sometimes referred to as dispatch modeling) as a central component of a grid integration study. Production cost modeling enables an assessment of the costs and impacts of increased variability and uncertainty from weather-driven generation resources (such as wind and solar) in power system operations. Other analyses, including capacity expansion and power flow modeling, can address additional questions. All three types of analysis may also be used by power system planners and operators outside the context of RE integration.

The choice of which analysis or combination of analyses to implement depends on the policy-relevant questions that best address a country's priorities. For example, if planners are in the process of evaluating the optimal energy supply mix to meet long-term policy goals, a capacity expansion analysis that focuses on generation and transmission build-out may be most valuable, especially if it is complemented by production cost analysis to test the operational impacts of various expansion scenarios. On the other hand, if power system planners and operators are seeking to prioritize the near- and medium-term actions they can take to improve the flexibility of the power system, production cost analysis may provide the best framework. Power flow modeling can be the most relevant approach to address concerns from the system operator about the reliability implications that high variable RE scenarios might pose to the electricity grid.

Figure 1 illustrates the iterative relationship among capacity expansion, production cost, and power flow analyses, including how each type of analysis can inform the others. Regardless of the type of analysis, implementation of known effective solutions, data collection, and modeling expertise are prerequisites that enable an impactful integration study, as discussed Section 1.

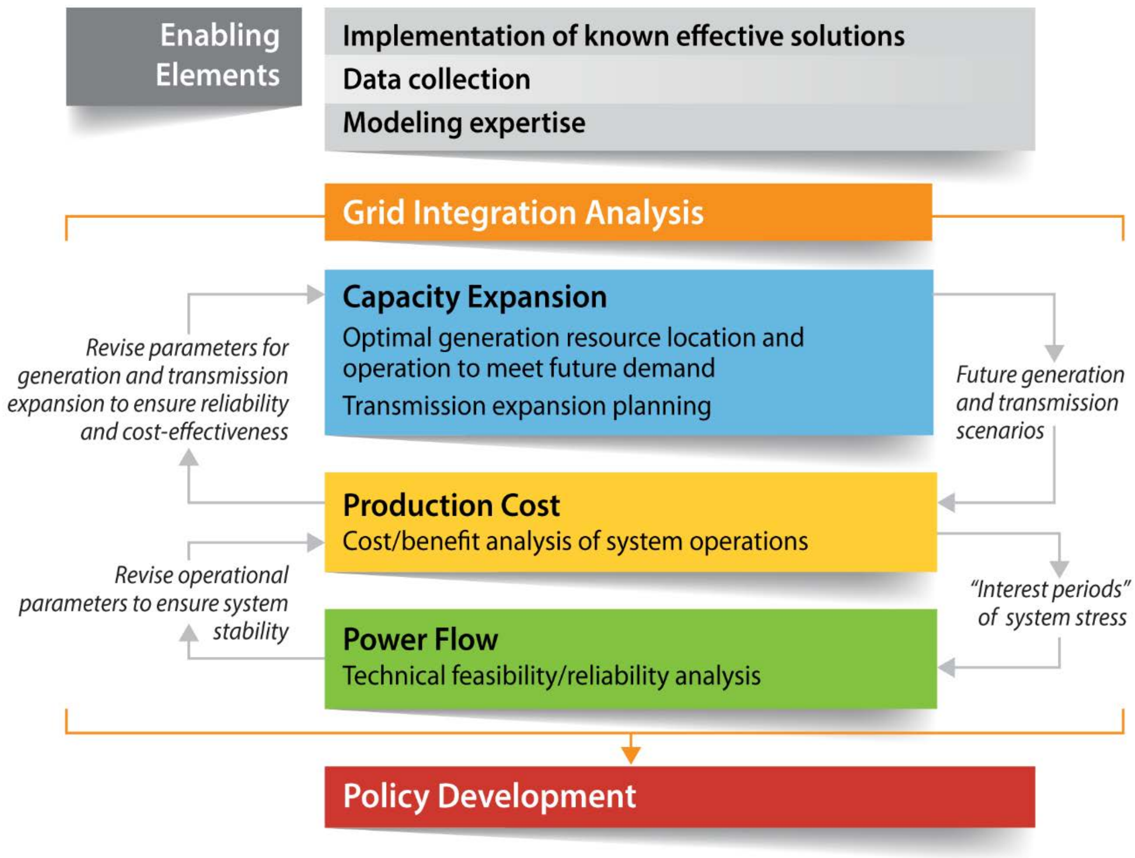

Figure 1. Types of and relationships among different analyses of a grid integration study

3.1 Capacity Expansion Analysis

Capacity expansion analysis identifies where, when, how much, and what types of generation and/or transmission resources can provide reliable electricity supply at least cost, taking into consideration factors such as new policies, technological advancement, fuel prices, and demand projections. In many power systems, capacity expansion analysis forms the basis of the development of a power sector master plan or integrated resource plan. Capacity expansion analysis is based on models that optimize the least-cost generation and transmission capacity mix. Grid integration studies use capacity expansion analyses to inform the type, amount, timing, and geographic placement of solar and wind generation capacity (as well as other generation and transmission resources) needed to achieve RE or other policy targets.

- *Modeling horizon*: medium- to long-term horizons (such as 20-50 years)
- *Temporal resolution:* Annual for each year within the modeling horizon, with representation of seasonal constraints and reduced-form intraday constraints
- *Key inputs*: high spatial resolution data on RE resource availability; annual electricity demand and projections; capital costs of generation technologies; fuel price projections; generation and transmission investment constraints; and operational constraints
- *Example applications*:
    - Identify cost-effective installed capacity and locations for variable RE and conventional generation
    - Evaluate the impacts of energy and climate policies on future systemwide costs, emissions, fuel consumption, and economic development indicators
    - Identify cost-effective transmission system upgrades and expansion—including trade-offs between transmission and generation expansion
    - Assess systemwide capital costs associated with one or more generation or transmission expansion plans
    - Inform production cost studies by identifying and prioritizing generation and transmission build-out scenarios—including installed variable RE capacity and siting
    - Examine the role of various technologies such as energy storage in integrating variable RE
    - Assess long-term, systemwide trends in the decarbonization of the power sector.

3.2 Production Cost Analysis

A production cost analysis assesses the impacts of one or more variable RE penetration scenarios on bulk power scheduling and economic dispatch. Production cost analyses focus on minimizing the operational cost of different future scenarios; the analyses do not evaluate capital costs of new generation or transmission assets.

- *Modeling horizon*: One future year (usually 10-20 years in the future)
- *Temporal resolution*: Hourly to sub-hourly (such as 30- minute or 15-minute) unit-commitment and/or dispatch intervals
- *Key inputs*: Time-synchronous demand and RE generation data; detailed system characteristics such as generator ramping and minimum generation capabilities, fuel and other operational costs, transmission system attributes, and emissions restrictions
- *Example applications*:
    - Evaluate the feasibility of high RE penetrations from an operational perspective by assessing RE curtailment levels, generator ramping, plant load factors, reserve requirements, reservoir and

- pumped storage management requirements, emissions, fuel consumption, transmission constraints, and operational costs associated with different RE scenarios and flexibility options
  - Test institutional and physical options for improving system flexibility to support high RE penetrations, and quantify the future operational costs associated with these options
  - Test the operational impacts of capacity expansion scenarios and provide feedback to help adjust capacity expansion analyses
  - Identify "periods of interest" (such as high RE/low load and/or low RE/high load) that may require further stability testing through power flow analyses.

3.3 Power Flow Analysis

Power flow analyses—including load flow simulations and dynamic stability analyses—test the stability of the transmission system under different RE penetration scenarios. For instance, these analyses can assess the ability of a power system to respond both under normal conditions and when a real-time disturbance such as an unplanned generator or transmission line outage occurs. Depending on their focus, power flow analyses model real and reactive power flow, fault tolerance, and frequency response over very short timeframes that correspond to periods of system stress. Evaluation of costs and economics is not usually a component of this type of reliability analysis.

- *Modeling horizon:* Several minutes, corresponding to periods of system stress
- *Temporal resolution:* Seconds to minutes
- *Key inputs:* RE generation profiles at discrete sites; details about generators' ability to respond to contingencies, transmission line impedances, transformer details, and tap settings
- *Example applications:*
  - Verify the technical feasibility of high RE penetrations in terms of reliability parameters, such as magnitude and duration of frequency deviation following a disturbance (including system recovery time), fault tolerance, voltage stability, network branch loading (congestion), short-circuit levels, and contingency response
  - Inform system operators about mitigation measures to keep system voltage and frequency within reliability parameters during normal- and high-stress periods
  - Serve as a reliability check for production cost scenarios
  - Determine whether different RE deployment scenarios meet grid code requirements.

Table 1 provides examples of questions addressed by different types of grid integration analyses.

Table 1. Examples of Questions Addressed by Capacity Expansion, Production Cost, and Power Flow Analyses

TYPE OF STUDY	EXAMPLE QUESTIONS ADDRESSED
Capacity Expansion	• Where, when, how much, and what types of infrastructure (generation and/or transmission) would achieve variable RE targets at least cost? • How will factors such as new policies, technological advancement, fuel prices, and electricity demand growth affect planning for generation and transmission infrastructure in the future? • What are the systemwide capital costs associated with different variable RE targets? • How will different variable RE penetration scenarios impact economic development indicators? • What are the expected air emissions reductions associated with various RE scenarios? • What types of generation and transmission infrastructure can protect the power sector against unexpected disruptions to the normal operations of a system?
Production Cost	• What are the impacts of variable RE penetration scenarios on bulk power scheduling and economic dispatch? • What are the expected variable RE curtailment levels, GHG emissions, generator ramps, plant load factors, reserve requirements, transmission constraints, and other generator-level impacts under different variable RE scenarios? • What are the relative systemwide operating impacts associated with different variable RE expansion scenarios (such as different levels of variable RE, siting of variable RE in best resource sites versus close to transmission lines)? • What are the cost-effective mechanisms to access flexibility (e.g., from institutional measures such as forecasting or new infrastructure such as transmission) under high variable RE penetration levels?
Power Flow	• How do high penetrations of wind and solar impact the transient stability and frequency response of the electric power system? • Do various RE scenarios meet the security or reliability criteria for the power system? • Can the power system sustain and recover from temporary and significant disturbances and with high levels of nonsynchronous generation? • Will various RE deployment scenarios meet grid code requirements? If not, what interventions may be necessary? • How does the power system respond to a real-time disturbance such as an unplanned generator and/or transmission line outages under various variable RE deployment scenarios? • What is the expected system recovery time (i.e., magnitude and duration of frequency deviation following a disturbance) under various variable RE deployment scenarios?

Box 1. Types of Grid Integration Studies: Quick References

Appendix A: Examples of grid integration studies and their results

This list summarizes several past efforts and demonstrates a diversity of approaches, objectives, and results of grid integration studies that assess the effects of scaling up variable RE on the power system.

Appendix B: Questions a production cost analysis can help address and implications for decision makers

This is a reference sheet presented to the technical review committee (TRC) at the outset of a USAID-sponsored grid integration study for the Philippines. Users of this guidebook can adapt this document to help clarify the scope of the production cost analysis and inform discussions with grid integration study stakeholders about scenario design.

4 Components of a Grid Integration Study

Conducting a grid integration study involves several iterative activities, as illustrated in Figure 2. Stakeholder engagement is a crucial component of the study across all phases.

The following sections of this guidebook describe each component of the grid integration study process in more detail, providing examples, templates, and references to more detailed documentation where available. In general, these sections refer primarily to production cost analyses; however, many elements are generally applicable to capacity expansion and power flow analyses.

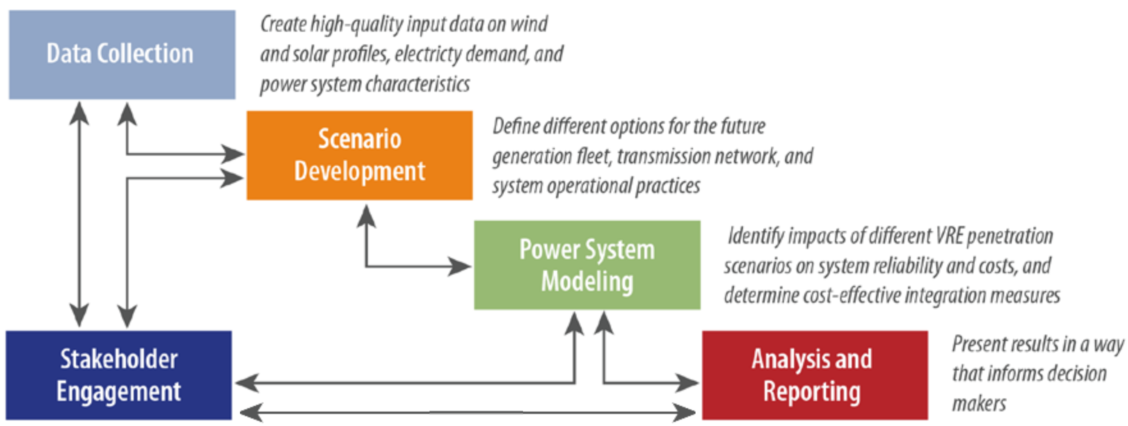

Figure 2. Components of a grid integration study (see Holttinen et. al. 2013 for a more detailed figure that includes decision points and recommended actions for each activity.)

4.1 Component 1: Stakeholder Engagement

A grid integration study that engages a broad array of stakeholders contributes to relevant, robust, and actionable planning that reflects industry and policymaker concerns. Stakeholder engagement helps to ensure study assumptions are grounded in reality and results have enough credibility to guide power sector transformation.

Stakeholders come from across the electric power sector. Since many stakeholders will be involved in developing and implementing grid integration measures, involving these groups in as many phases of a grid integration study as possible helps to ensure the results are relevant to these diverse perspectives.

Examples of important stakeholders in integration studies include:

- National or subnational government energy agencies
- Power system operators (such as regional transmission organizations, independent system operators, and/or vertically integrated utilities, among others)
- Electricity regulators
- Electricity market operators (where applicable)
- Utilities (if distinct from the system operator)
- Transmission providers and developers
- Wind and solar data providers

- Conventional and RE plant owners, operators, and developers
- Researchers and academia
- Public advocates.

4.1.1 *Mechanisms for Engaging Stakeholders*

Technical Review Committees. A TRC, also referred to as a technical advisory committee (TAC), facilitates productive engagement in a grid integration study. The members of a TRC provide rigorous peer review and expert input at multiple points throughout the execution of a grid integration study. A diverse TRC links industry and policy concerns and provides insights that deepen understanding of high-penetration RE issues and solutions.

While the members of a TRC may not necessarily be involved with the day-to-day modeling of the study, they provide direction to the core modeling team. Over the course of conducting a grid integration study, the TRC's roles include:

- Determining the study objectives, assumptions, scenarios, and sensitivities
- Reviewing the modeling team's methods, data sources, underlying assumptions, and other key inputs
- Interpreting (and, where appropriate, validating) modeling results
- Linking model outcomes with policy and regulatory concerns and processes
- Endorsing the technical rigor of the study.

A TRC is composed of decision makers from policymakers, power sector regulators, operators, variable RE and conventional plant owners, utilities, environmental and public advocates, technical experts, and other organizations with technical expertise or interest in power systems operation, markets (where applicable), and modeling. While private sector perspectives do play a contributing role in a TRC, to avoid conflicts of interest, the study team and broader TRC can ensure the methodology and results are objectively developed and based on objective analysis.

A TRC meets periodically—for example, every 2-5 months—throughout a grid integration study at key milestones or decision points (such as determining scenarios to be modeled, reviewing initial model output, and validating results).

Modeling Working Group. The modeling working group (MWG) is the technical team that conducts the detailed analytical and modeling activities of the grid integration study. The MWG's responsibilities include:

- Assembling and validating input data
- Developing power system models
- Simulating operations under a variety of scenarios and sensitivities
- Analyzing and verifying simulation results
- Compiling technical documentation to communicate findings.

The MWG is typically comprised of technical staff from the power system operator, policy institutions, and other organizations with expertise in power systems, electrical engineering, power flow modeling, and the mechanisms that drive electricity operations and, where applicable, electricity markets.

Box 2. Establishing a Stakeholder-Driven Process: Actions for the Study Leadership Team

- Determine which organizations should be represented in the TRC and MWG, and the desired number of representatives from each organization;
- Formally establish the TRC and MWG. For example, the Philippines Department of Energy issued a Department Circular establishing the scope of its grid integration study, as well as the representation and the core functions of the TRC and MWG (see Toolkit);
- Develop and circulate principles or terms of reference for the TRC and MWG (see Toolkit for examples);
- Determine the frequency, duration, and format of meetings for both the TRC and MWG. For example, the TRC may meet at key milestones of the study to review progress and validate the direction of the study. The MWG may meet more frequently (e.g., on a weekly or monthly basis);
- Organize and facilitate TRC and MWG meetings;
- Establish regular and transparent communication and documentation processes for both the TRC and MWG.

Box 3. Establishing a Stakeholder-Driven Process: Quick References

- **Example: Department Circular for Philippines Grid Integration Study**
  This Department Circular from the Philippine Department of Energy formalized the creation of the TRC (in the Philippines, this entity was called the TAC) and MWG for the purposes of conducting a solar and wind integration study. The Department Circular specifies the composition and responsibilities of each stakeholder group, including provisions for data sharing. This document can provide an example or template for other power systems in which a grid integration study and its supporting stakeholder engagement mechanisms must be established through an executive order.

- **Reference: Principles for Technical Review Committee (TRC) Involvement in Studies of Wind Integration into Electric Power Systems**—Utility Wind Integration Group and NREL, 2009
  This short document provides general principles for the functions, composition, responsibilities, and resource needs for a TRC. It can serve as a terms of reference template, independently or in addition to the materials below.

- **Appendix C: Example Terms of Reference: Modeling Working Group**
  This MWG Terms of Reference was developed for the grid integration study for the Philippines and can be adapted to other applications. It provides general guidance on the responsibilities, desired qualifications, and expectations for the MWG members.

- **Appendix D: Example Terms of Reference: Technical Review Committee**
  This TRC Terms of Reference was developed for the grid integration study for the Philippines and can be adapted to other applications. Like the MWG Terms of Reference, it provides guidance on the responsibilities, composition, expectations, and working principles for the TRC.

4.2 Component 2: Data Collection

Like stakeholder engagement, high-quality data are essential for a robust grid integration study. In many cases, data collection, especially to develop wind and solar resource profiles, can be time-intensive and may need to begin well in advance of the modeling activities associated with a grid integration study.

The Toolkit below provides references to more detailed descriptions and lists of input data for grid integration studies (with a focus on production cost analyses). Table 2 provides a general overview of the data needs for each type of grid integration analysis.

Table 2. General Data Needs for Capacity Expansion, Production Cost, and Power Flow Analyses

Type of Analysis/Data Category	Capacity Expansion	Production Cost	Power Flow
RE Resource Data	Average or typical meteorological year (TMY)[2] (monthly or more frequent time series)	Operational time-series for full modeling horizon (e.g., one year of daily, hourly, or sub-hourly solar and wind resource data that are time-synchronous with electricity demand data); archive forecast and forecast error (optional)	Operational time series for full modeling horizon (e.g., minute or sub-minute data that are time-synchronous with electricity demand data)
Electricity Demand	Projected annual, seasonal, and peak electricity demand	Historic demand time-series data that are time-synchronous with RE resource data and disaggregated by node or region (if available); projected changes to electricity demand magnitude and profile; archive forecast and forecast error (optional)	Historic demand time-series data that are time-synchronous with RE resource data and disaggregated by node or region (if available); projected changes to electricity demand
sGeneration	Aggregated fleet-level generator characteristics (conventional and RE)	Unit-level generator characteristics (conventional and RE)	Unit-level generator characteristics (conventional and RE), including dynamic characteristics for dynamic stability studies
Transmission Network Topology	Inter-region transmission flow capacity	Locations and electrical characteristics of substations, transformers, lines, and interfaces	Detailed electrical characteristics of all substations, lines and interfaces
Costs	Capital costs of generation and transmission resources; fuel price projections; emissions costs; operations and maintenance costs	Fuel prices; operations and maintenance costs; emissions costs	N/A
Complementary Spatial Data Layers	Land cover, protected areas, slope, and other characteristics that can be used to screen sites for potential solar and wind power plant development		

[2] TMY data typify conditions at a specific location over a long period of time, such as 30 years. TMY data sets are not averages; they are created by force-sampling values from the multiyear data set for each period (for instance, in a monthly TMY data set, January may be sampled from 2003, while March may be sampled from 2009). TMY data represent typical patterns (such as seasonality) over a long period and help smooth the impacts of unusual conditions, such as drought or El Niño.

System data on historic electricity generation, demand, and transmission grid characteristics are critical to developing an accurate reference case (see Section 4.3) that the modeling team can use to ensure the simulation produces realistic results relative to an actual year of operation. Projections of these data for the study time horizon inform the development of models for future years.

Data for grid integration studies come from a variety of sources. In some cases, system operators may already collect detailed information about generators and transmission network components for use in dispatch and power flow models. Additional data may be obtained from energy ministries, electricity regulators, and/or the private sector. Commercial vendors may also have access to proprietary data sources. In some cases, data-sharing or confidentiality agreements will need to be established to share data amongst the stakeholders involved in carrying out the grid integration study.

4.2.1 *The Importance of High-Quality RE Resource Data*

A grid integration study relies on wind and solar resource data that accurately represent variability of RE generation across both space and time. Wind and solar energy generation profiles are often based on resource measurement campaigns and/or modeling efforts. At a minimum, grid integration analyses of any type require one year of RE resource data for locations under consideration for wind or solar generation. High spatial-resolution data (e.g., 10-km grid cells for solar, 1-km grid cells for wind) that provide continuous coverage for the country or power system balancing area enable power system modelers to characterize the spatial variability of solar and wind resources and can, for example, enable a grid integration study to demonstrate the benefits of geographic diversity of solar and wind resources. Similarly, RE resource data with high temporal resolution capture the variability of solar and wind resources across various timescales. For production cost analyses, hourly RE resource data are useful for characterizing solar and/or wind availability within operational timeframes. Higher temporal resolution (i.e., sub-hourly) data better capture the variability of wind and solar generation and enable modeling of certain integration impacts and solutions, such as forecasting or changes to reserve requirements.

Production cost and power flow analyses should strive to utilize wind and solar data sets that are time-synchronous with load data (i.e., the time steps [year, day, hour, and so on]) align chronologically among the data sets. Since weather drives both demand and wind and solar generation, time-synchronous data enable power system modelers to understand trends related to the variability and magnitude of both load and variable RE availability.

For many countries, developing high-quality wind and solar data sets is a crucial prerequisite to undertaking a grid integration study. Modeled solar and wind data sets can often be purchased from a vendor. Alternatively, a country or region can develop its own wind and/or solar data sets, for example, using actual measurements or numerical weather prediction models. Regardless of source, modeled wind and solar data should be validated and calibrated as much as possible with actual historic meteorological and/or wind and solar energy generation data.

Box 4. Example Wind and Solar Data Sets Used in Grid Integration Studies

- The USAID-funded grid integration study for India (Palchak et al. 2017) uses wind and solar profiles for 2014 (time synchronous with 2014 load data). Solar profiles are from the National Solar Radiation Database and have spatial and temporal resolutions of 10 km and 1 hour, respectively. Wind profiles are based on mesoscale modeling, which provides an annual time series at 5-minute time steps and 3-km spatial resolution. Both data sets were modified to 15-minute intervals to match load data. These data are available for download in the Renewable Energy Data Explorer.
- The 21st Century Power Partnership-funded grid integration study for Baja California Sur, Mexico uses 2013 solar data from the National Solar Radiation Database (1998-2014 update). This data comprises 30-minute solar and meteorological data with a 4-km resolution. This data is available for download here.
- The USAID-funded grid integration study for the Philippines (Barrows et al. 2018) uses an hourly solar resource data set for 2014 (time synchronous with load) modeled at 30-km spatial resolution. To provide a higher resolution, time-synchronous 2014 data set for wind, the study developed a "blended" data set using two underlying sources:
  - The Philippines Wind Atlas (available in the Renewable Energy Data Explorer), which is a TMY (force-sampled from 15 years of data) data set modeled at 1-km spatial and hourly temporal resolution
  - A 2014 wind data set modeled at 30-km spatial and hourly temporal resolution.
- The Western Wind and Solar Integration Study (Lew et al. 2013) and the Eastern Renewable Generation Integration Study (Bloom et al. 2016) for the United States employed a mesoscale Numerical Weather Prediction model to simulate wind conditions at a 10-minute resolution for the years 2004-2006. Solar data include one year (2006) of modeled 5-minute solar power profiles for approximately 6,000 simulated power plants. The two studies also developed and utilized forecast data sets (1-, 4-, 6-, and 24-hour ahead for wind and 24-hour ahead for solar). The wind and solar integration data sets are available for public download.

Box 5. Data Collection: Actions for the Study Leadership Team

- Develop a data requirements list for the grid integration study and map each data requirement to potential data sources
- Evaluate available wind and/or solar resource data to determine whether time-synchronous data sets are available for use in the study. If not, begin the process of developing or acquiring this data as soon as possible;
- Determine if a nondisclosure agreement is needed to share any of the data required for the study. If so, begin the nondisclosure agreement development and approval process as soon as possible, as finalizing such an agreement can be a lengthy process. The nondisclosure agreemnt should cover data sharing among all members of the MWG; and
- Work with the MWG to identify and establish a common secure file-sharing platform through which to exchange data.

Box 6. Establishing a Stakeholder-Driven Process: Toolkit

- **Reference:** ***Grid Integration Studies: Data Requirements Fact Sheet***
  This resource provides a high-level overview of the general categories of data that inform grid integration studies based on production cost analyses and can be used as a quick-read reference, for example, for members of the TRC.
- **Reference: International Energy Agency's Expert Group Report on Recommended Practices (16 Wind integration studies).**
  Section 2 of this comprehensive report provides detailed reference for power system modelers on input data needs for grid integration studies.
- **Reference: Meteorological data for RES-E integration studies: State of the art review**
  This report by the European Commission's Joint Research Centre provides an overview of how recent grid integration studies have applied meteorological models (including numerical weather prediction models) to represent solar and wind energy resources. It provides a reference containing general information and examples of software tools and data sets that are currently available, advantages and disadvantages of different types of meteorological models, and best practices.
- **Appendix E: [Template] Data List for Production Cost Analyses**
  This template is adapted from the data list developed for the grid integration study for the Philippines. It provides a comprehensive list of data inputs for conducting a production cost analysis and a framework for evaluating the availability and accessibility of data sources.

4.3 Component 3: Scenario Development

A scenario is one possible future electric generation system. Scenarios in a grid integration study provide the basis for exploring how different options for the future power generation fleet (including RE), transmission network, and/or operational practices impact least-cost power system development, operations, and other objectives, such as emissions reduction.

Defining a set of scenarios is one of the most important early activities in a grid integration study, and it represents a crucial area for input and guidance by the TRC so the scenarios reflect questions that are most interesting to power system stakeholders.

Scenarios define system conditions over a specific time horizon, usually referencing one or more future target years. Capacity expansion scenarios focus on the entire planning horizon (e.g., every year for the next 30 future years) while production cost and power flow scenarios typically focus on a single target year (e.g., 10-20 years in the future).

Grid integration studies typically consider the following types of scenarios:

- The reference scenario focuses on the current (or very recent) power system and is most useful for production cost and power flow modeling phases of a grid integration study. The purpose of the reference scenario is to build and test a model of the existing power system to ensure that it produces realistic results compared with an actual year of operation. The reference case is crucial to validating the model and assumptions underlying a grid integration study and helps build stakeholder confidence in the results of future-year scenarios.
- The base or business-as-usual (BAU) scenario applies assumptions that policies and operational practices will remain relatively unchanged from current or planned practices with respect to their treatment of variable RE. Power systems that have developed power development master plans, capacity expansion models, or integrated resource plans can use these existing projections as a starting point for defining the transmission and generation capacity additions and retirements to include in the BAU scenario of a grid integration study. Typically, the BAU scenario in a grid integration study includes minimal, if any, new wind or solar generation relative to the reference case.
- High-RE scenarios include higher levels of wind and/or solar generation relative to the BAU scenario for the target year. A typical analysis has three to four high-RE scenarios, which may vary, for example, by total RE penetration, location of wind and solar generation, and/or the ratio of solar to wind generation.

For each unique configuration of a high-RE scenario, grid integration studies can also include sensitivity analyses that analyze the impacts of different assumptions about operational practices (e.g., use of variable RE forecasting or flexible operation of conventional generators), policies and incentives, market designs, fuel price or availability, and/or the availability of technology and infrastructure (e.g., different conventional generation and transmission buildouts, utilization of active power controls on wind turbines, deployment of utility-scale storage, or early retirement of fossil-fueled generation).

Box 7. Example Scenarios From Grid Integration Studies

Exploring different levels of wind and solar in India (Palchak et al. 2017)
A national production cost analysis for India varies levels of solar versus wind, as well as overall RE capacity levels, in its high RE scenarios:

- Target year: 2022 (corresponding to India's RE policy goals)
- Reference scenario: 2014
- BAU scenario: no new RE compared to 2014
- Four high-RE scenarios:
  - Medium RE: 50 GW solar, 20 GW wind. This scenario is intended to show the interim impacts that could be expected before meeting the higher installation targets.
  - High solar: 100 GW solar, 60 GW wind
  - High wind: 60 GW solar, 100 GW wind
  - Very high RE: 150 GW solar, 100 GW wind.
- Sensitivity analyses:
  - National and regional coordination of scheduling and dispatch
  - More and less flexible operation of coal plants
  - More and less transmission capacity
  - Addition of storage capacity
  - Availability of hydro energy.

Analyzing different siting strategies in the Philippines (Barrows et al. 2018)
A production cost analysis for the Philippines (Luzon and Visayas regions) explores two different RE penetration targets and two approaches to siting wind and solar:

- Target year: 2030 (corresponding to the Philippines' Nationally Determined Contribution)
- Reference scenario: 2014
- BAU scenario: beyond any solar and wind power plants in the reference scenario, only committed new RE projects are included
- Four high-RE scenarios:
  - 30% RE penetration, with wind and solar sited in locations having the best resources
  - 30% RE penetration, with wind and solar sited in locations that minimize the need for new transmission
  - 50% RE penetration, with wind and solar sited in locations having the best resources
  - 50% RE penetration, with wind and solar sited in locations that minimize the need for new transmission.
- Sensitivity analyses:
  - More and less flexible operation of conventional generators
  - Additional transmission capacity
  - Alternative reserve provision schemes.

Box 7 (Continued)

Comparing RE development paths in the Eastern United States (Bloom et al. 2016)
A grid integration study encompassing both capacity expansion and production cost modeling for the Eastern Interconnection of the United States compares two different paths of development to meet a 30% wind and solar capacity target.

- Target year: 2026
- Reference scenario: 2010
- BAU scenario: No new RE compared to 2012
- Three high-RE scenarios:
    - Medium RE: solar and wind represent 2% and 9%, respectively, of total capacity. This scenario is intended to show the interim impacts that could be expected before meeting a 30% goal;
    - Each region within the interconnection meets a 30% capacity target (solar and wind represent 10% and 20%, respectively, of total capacity); and
    - The best resources across the entire interconnection are used to meet a 30% target (solar and wind represent 25% and 5%, respectively, of total capacity).

4.3.1 *Defining a BAU Scenario*

The BAU scenario in a grid integration study relies on a variety of assumptions regarding likely future market operations, technology, and economic conditions. At the least, grid integration studies may use current operating practices as a baseline from which changes can be evaluated. Where possible, BAU scenarios can be based on existing energy sector or power sector development plans and/or integrated resource plans to establish assumptions about demand, generation, and transmission in future years. Power sector development plans and integrated resource plans typically reflect a power system's official projections for the development of a country or region's energy mix, including new sources of generation, new transmission infrastructure, and projected changes in electricity demand. Using these existing plans as the basis for the BAU scenario in a grid integration study enables the study to draw on already vetted work and ensures high-RE scenarios provide relevant comparisons to the power system's most likely future.

The following guiding questions are examples of considerations that can help define a BAU scenario in a grid integration study:

- What will electricity demand be (e.g., in magnitude and profile) in the target year?
- What new transmission should the BAU scenario include?
- What conventional and nonvariable RE generation additions and retirements should the BAU scenario include?
- What variable RE plants (e.g., those that are 100% certain to be built) should the BAU scenario include?
- In the BAU scenario, should <u>new</u> conventional generation meeting load in the target year be equally or more flexible than that in the reference case? (i.e., will new natural gas plants use combined cycle or combustion turbine technologies?)

- What changes to operating practices, if any, should the BAU scenario include (such as forecasting improvements, new ancillary services, market changes, thermal turndown regulations, and others)?
- Are there any other likely changes to power system hardware and/or operations that the BAU scenario should reflect?
- Will reliability standards change in the BAU scenario relative to the reference scenario?
- What will the relative prices for different fuels in the generation mix be in the target year?

4.3.2 *Defining High-RE Scenarios*

High-RE scenarios are the primary focus of grid integration studies and can be tailored to explore a range of potential futures or goals. In capacity expansion analyses (in which solar and wind energy generator size and location are an output), different high-RE scenarios are driven by policy goals or other constraints, for example, RE installation or GHG emission reduction goals and different fuel price or technology cost assumptions. Ideally, capacity expansion analyses produce the high-RE scenarios that are then analysed for operational feasibility and reliability via production cost and/or power flow analyses.

For grid integration studies that do not include a capacity expansion analysis component, the MWG and TRC can define a set of high-RE scenarios to analyse based on the following considerations when designing high-RE scenarios:

- Clean energy target. Examples:
  - RE (including variable RE) penetration level (e.g., wind and solar serve 40% of annual electricity demand in the target year)
  - RE (including variable RE) capacity (e.g., wind and solar comprise 40% of total electricity generating capacity in the target year)
  - GHG mitigation (e.g., GHG emissions from the power sector in the target year are 20% lower than in the reference case).
- Mix of wind and/or solar technologies. Examples:
  - Equal mix (generation or capacity, depending on the type of RE target) of wind and solar
  - High wind/moderate solar
  - Wind only.
- Siting strategy for new variable RE. Examples:
  - Locations with the best wind or solar resources
  - Locations close in proximity to existing transmission
  - Proportion of rooftop versus utility-scale PV
  - Application of regional or provincial targets for wind and/or solar.
- Extreme operational or weather events (For reliability testing via power flow studies). Examples:
  - High variable RE generation and low load
  - Low variable RE generation and high load
  - High variable RE generation and high load.

4.3.3 *Defining Sensitivity Analyses*

A sensitivity in a grid integration study refers to an alternative set of assumptions about infrastructure or operational practices intended to mitigate variable RE integration issues. A sensitivity is applied to all or select scenarios, and the results are compared to the scenarios without sensitivities.

Sensitivity analyses provide a means of assessing how different institutional practices or physical infrastructure change the impacts of variable RE on the system. Thus, sensitivity analyses are a key element of a grid integration study because they provide a way to: (1) assess the robustness of findings from the grid integration study; and (2) identify and prioritize a variety of power system flexibility options that enable the system to more efficiently integrate variable RE under a high-RE scenario.

The list below provides examples of potential sensitivities to explore for high-RE scenarios, with an emphasis on those relevant in production cost analyses. The implementation of sensitivity analyses may require data inputs above and beyond those needed to analyse the core scenarios of a grid integration study.

- Changes to power system operations assumptions:
  - More flexible operation of conventional generation (e.g., lower minimum generation levels, faster starts and ramps)
  - Implementation or removal of must-run policies for variable RE and/or conventional generation
  - Different definitions of ancillary services (including reserves) and providers (for example, allowing solar and wind generators to participate in downward reserve provision
  - Increased coordination with neighboring balancing areas (e.g., through reserve sharing or coordinated unit commitment and/or economic dispatch)
  - Implementation or improvement of variable RE power forecasting
  - More frequent economic dispatch intervals
  - Implementation of demand response programs.
- Changes to market operation assumptions (if applicable):
  - Implementation of energy imbalance markets with neighboring power systems
  - Implementation of different ancillary service market products
  - More frequent interchange.
- Changes to infrastructure assumptions:
  - Addition of new transmission capacity to limit congestion and/or enable RE siting in highest resource density areas
  - Different assumptions about the capacity and type of conventional generation additions or retirements
  - Deployment of additional storage capacity.
- Changes to power system contextual assumptions:
  - Alternative demand scenarios (magnitude and profile)
  - Alternative fuel price (or other cost) trajectories

  Different climate scenarios (e.g., low versus high hydropower years).

Box 8. Scenario Development Actions for the Study Leadership Team

- Identify power sector development plans, integrated resource plans, demand forecasts, and other official projections of demand, generation additions and retirements, and transmission enhancements that can serve as a basis for the BAU and possibly other scenarios of a grid integration study
- Determine the number of high-RE scenarios and sensitivity analyses to include in the grid integration study. The study should include at least one high-RE scenario and may include several more, depending on study timeframe and budget;
- Solicit input from the TRC on the high-RE scenarios and sensitivities of greatest interest and value to stakeholders, as well as the core assumptions underlying the BAU scenario. The Toolkit below provides an example presentation template to facilitate discussion on scenario development among members of the TRC;
- Finalize the target year, reference case year, BAU scenario assumptions, high-RE scenarios, and key sensitivities working with the MWG to ensure sufficient data are available to model all scenarios and sensitivities
- Communicate the final set of scenarios to the TRC.

Box 9. Scenario Development: Quick Reference

- **Reference: Example presentation for soliciting feedback from the members of the TRC on scenario definition**
  This presentation template was adapted based on a presentation to the TRC for the Philippine grid integration study. It provides examples of questions that can help a study team and TRC determine assumptions for the BAU and high-RE scenarios on which the grid integration study will focus. The presentation also includes examples of scenario selection from other integration studies.
- **Reference: International Energy Agency's Expert Group Report on Recommended Practices (16. Wind integration studies).**
  Section 3 of this comprehensive report provides a reference for additional detailed guidance on developing generation portfolio and transmission scenarios, including the treatment of reserve allocation considerations in scenario development for wind integration studies.

4.4 Component 4: Power System Modeling

A grid integration study is founded on power system modeling. The modeling process involves members of the MWG using the data inputs and scenario definitions developed in previous study phases to simulate system operations and identify the impacts of different scenarios on system reliability and costs. Much of the effort involved in conducting a grid integration study is related to building, testing, and validating a power system model.

4.4.1 *Choice of Model*

An important early action of the study leadership team is to choose the appropriate models for the grid integration study. The primary objectives of the study—coupled with data availability—drive the determination of the appropriate model. Different types of models focus on capacity expansion, production cost, and power flow analyses, as described below.

Capacity expansion models. Capacity expansion models optimize the least-cost generation and/or transmission mix subject to physical constraints. Capacity expansion models can analyze both operational and investment (including capital cost) considerations over a long-time horizon and inform understanding of how the power system might evolve over time. Unlike production cost models, capacity expansion models do not typically simulate system dispatch in detail, but instead use reduced-form dispatch models, for example, simulating a subset of representative days or weeks per year (Diakov et al. 2015).

Commercially available and open-source capacity expansion models can be adopted to a country or region-specific context; however, many traditional platforms are not designed to capture the unique temporal, stochastic, and spatial characteristics of wind and solar energy resources (Parsons et al. 2013) necessary for grid integration studies. For this reason, three options may exist for most grid integration study teams developing or procuring a capacity expansion model to analyze high-variable RE scenarios:

1. Applying country- or power system-specific data, policies, economic conditions, and operational practices to existing capacity expansion models that specifically account for the unique qualities of weather-dependent wind and solar generation resources.
2. Adapting existing country- or power system-specific capacity expansion models that contain relevant system characteristics to capture variable RE characteristics and concerns. Specific areas to critically examine in capacity expansion models to determine their ability to incorporate RE characteristics include:
    a. Ability to assess and incorporate the capacity value of RE resources into long-term planning decisions
    b. Ability to assess the impacts of intra-day variability RE generation, including estimating RE curtailment
    c. Ability to incorporate high-resolution representation of the geographic diversity of RE resources.
3. Building a new model that fully captures the unique characteristics of wind and solar energy resources, accounts for the details of the given power system, and answers the primary questions of the grid integration study. Custom-built capacity expansion models can be tailored to consider different priorities such as economic development, GHG emissions, and energy security.

Production cost models. Production cost models simulate the unit commitment and economic dispatch process, usually at a chronological hourly or sub-hourly timeseries for one year. The objective of production cost modeling is to optimize the scheduling and dispatch of generation to meet expected demand in the most cost-effective manner, within the context of constraints (e.g., RE resource and transmission availability, operational practices).

Unlike capacity expansion models, production cost models do not identify cost-effective locations for new generation and transmission. Rather, the system configuration—including the types, capacities, and locations of transmission and RE and conventional generation—are inputs to the model. Some existing grid integration studies have included both capacity expansion and production cost modeling in an attempt both to optimize the siting of new wind and solar and to analyze its operational impacts (see, for example, grid integration studies for the Eastern United States and South Africa: Bloom et al. 2016 and Chartan et al. 2018, respectively). Others have taken simplified approaches, such as siting RE in areas that are known to have high-quality resources or that are under consideration by the government or the private sector for development (see, for example, grid integration studies for India and the Philippines: Palchak et al. 2017 and Barrows et al. 2018, respectively).

Numerous production cost software platforms are available—including industry-accepted commercial software, open-source software, as well as models that are developed on a system- or project-specific basis. Like capacity expansion models, production cost models rely on detailed power system-specific data in order to accurately simulate system operations under a variety of conditions. For grid integration studies, choosing a model that can simulate dispatch at the sub-hourly level is ideal as this allows the model to better capture the variability of wind and solar resources and the impacts of different strategies, such as forecasting and changes to reserve requirements on managing this variability over short timescales; however, sub-hourly wind and solar data sets must also be available to enable modeling at fine temporal resolutions.

Power flow models. Power flow models, also known as load flow or stability analysis, enable detailed assessment of whether the grid can reliably cope with disturbances, such as rapid voltage changes and transmission bottlenecks. Power flow models simulate the electricity grid in normal steady-state operation and assess the system's capability to recover after a disturbance. Dynamic studies can determine if the grid is able to sustain both temporary disturbances and significant incidents.

Since power flow models focus at very small timescales (usually the few seconds during and following a disturbance such as a major transmission line or generator outage), these studies can utilize the results of operational analyses such as production cost modeling to identify periods of potential system stress (e.g., high wind/low load). In turn, results from power flow simulations provide feedback to refine the production cost and/or capacity expansion models. Load flow and dynamic simulations can expose weaknesses in the system that may need to be addressed by relaxing scenario assumptions, adding transmission or generation capacity, and/or adjusting grid operations.

Several industry-accepted, commercially available power flow models are available. Many power system operators already use these types of models to inform power system planning. To explore the impacts of variable RE, existing power system models can be adapted to incorporate site- and time-specific solar and/or wind generation data, as well as the capabilities of solar and wind generators to provide ancillary services, such as governor response.

4.4.2 *Related Analyses*

Depending on its scope, a grid integration study can incorporate additional analyses that complement and inform capacity expansion, production cost, and power flow modeling. These analyses may take place within or outside of the core models underlying the grid integration studies.

Demand projections. Projecting electricity demand is fundamental to analyzing future electricity systems. The results of a grid integration study (especially operational assessments such as production cost analyses) are very sensitive to uncertainties linked to projections of the magnitude and profile of future demand. These uncertainties include rate of demand growth; share of future demand across the industrial, commercial, and residential sectors; and demand shape, which is a function of weather and changes in end uses (e.g., air conditioning, electric vehicles, energy efficiency). Demand analysis is particularly important in the context of developing economies with shifting patterns of industrial, commercial, and domestic electricity consumption.

A variety of methods exist for demand projections, ranging from simple estimations (for example, based on projections of gross domestic product) to more sophisticated methods. These include top-down methods, which use economic and statistical models to analyze potential growth in demand, bottom-up methods, which use engineering or end-use models to estimate growth in demand, and hybrid methods, which have some combination of top-down and bottom-up approaches. A key consideration for grid integration studies is to ensure that the time steps of the demand projection (e.g., hourly, 15-minute) match the time steps of solar and wind generation profiles that are used to model power system operations.

Capacity adequacy assessments. Capacity value, also known as capacity credit, refers to the contribution of a power plant to reliably meet demand and represents the amount of additional load that can be served with the integration of new generation resources, including wind and solar. Modeling capacity adequacy is particularly important when evaluating a high-RE resource mix. Due to variability and uncertainty, RE resources typically have a lower capacity value than conventional generators. For example, an analysis of a 60% RE supply scenario in the European Union estimates that the development of 700 GW of wind and solar capacity would contribute enough capacity value to enable a reduction of about 100 GW in conventional generation capacity (Burtin and Silva 2015).

Several methods exist for calculating the capacity value of wind and solar, including detailed reliability-based metrics such as effective load carrying capacity. In the context of grid integration studies, capacity adequacy assessments can evaluate future RE scenarios, for example, by testing the outputs of capacity expansion models to ensure adequacy criteria are met. Capacity adequacy assessments can also serve as a prescreening tool for production cost modeling to identify whether future scenarios need to be revised to increase generating capacity (or decrease demand) prior to detailed operational modeling.

Capacity value calculations require high temporal and spatial resolution RE resource data for multiple historic years. If high-resolution wind or solar resource data sets are not available, commercially available modeled data sets (lower resolution and lower cost) may be used for the purposes of prescreening (Parsons et al. 2013).

Flexibility assessment (as a screening tool). Flexibility is the ability of the electricity grid to respond to changes in generation and/or demand. In a power system with high levels of variable RE, additional flexibility may be needed to mitigate changes in output due to wind and solar variability. A flexibility assessment evaluates the system operator's ability to balance supply and demand with variable RE generation. Flexibility assessments are carried out for operation and planning horizons. Assessments with an operation horizon focus on the flexibility provision and constraints of a particular system (current or future), while assessments with a planning horizon evaluate different generation portfolios and operational or market designs to determine future flexibility needs and options. Flexibility assessments in the operation horizon are implicitly conducted in a production cost model (Holtinnen et al. 2013).

Flexibility assessments can also take place as a separate screening activity outside of the primary modeling that supports a grid integration study. Using flexibility assessment, for example, as a prescreen to production cost modeling can help determine whether a particular system configuration will be able to respond to rapid changes in net load (Parsons et al. 2013). Metrics such as the Insufficient Ramping Resource Expectation metric (which calculates the expected number of instances when the power system cannot respond to changes in net load) can provide insights in lieu of, or in addition to, more detailed production cost modeling.

Box 10. Power System Modeling: Actions for the Study Leadership Team

- Determine which models (capacity expansion, production cost, and power flow) are currently in use to support planning in the system of interest. Evaluate whether and how these models can be adapted to answer the questions of greatest interest for the grid integration study;
- If new commercially available software is needed, procure software licenses as needed for the members of the MWG. For some organizations, software procurement can be a lengthy process, so initializing licensing as soon as possible will help keep the project schedule on track; and
- Organize training for members of the MWG on the model chosen for the study. Many commercial software vendors offer training packages for their products.

Box 11. Power System Modeling: Toolkit

- **Appendix A: Examples of grid integration studies and their outcomes**
  The grid integration study summaries in this appendix specify the models used in each effort.

- **Reference: Planning for the Renewable Future: Long-term Modelling and Tools to Expand Variable Renewable Power in Emerging Economies**
  This technical report by the International Renewable Energy Agency outlines an integrated approach to power system planning for high levels of variable RE (IRENA 2017). Part 2 catalogues a variety of approaches modeling can take to improve the representation of variable RE in capacity expansion planning models. The report references long-term planning modeling tools in use in a variety of countries; Appendices 3 and 4 summarize these efforts and tools.
- **Reference: International Energy Agency's Expert Group Report on Recommended Practices (16. Wind integration studies)**
  This report includes more detailed technical guidance on conducting power system modeling for integration studies. For example, Chapter 4 focuses on capacity value assessments, Chapter 5 focuses on production cost simulations and flexibility assessments, and Chapter 6 focuses on transmission grid simulations (including power flow and dynamic stability analysis).
- **Reference: Electricity Capacity Expansion Modeling, Analysis, and Visualization: A Summary of Selected High-Renewable Modeling Experiences**
  This technical report summarizes lessons learned from capacity expansion modeling studies conducted by the United States Department of Energy's National Renewable Energy Laboratory (Blair et al. 2015). The report's topics include analysis questions for capacity expansion models, critical inputs to capacity expansion models, representation of grid operation physics and rules, and visualization of the model results. The report contextualizes these topics for China, but its insights are applicable for other power systems as well.
- **Reference: Using Wind and Solar to Reliably Meet Electricity Demand Fact Sheet**
  This document reviews of considerations related to the calculation of capacity value for wind and solar energy.

4.5 Component 5: Analysis and Reporting

The final component of conducting a grid integration study is analyzing and presenting results in a way that provides meaningful, actionable information to decision makers.

4.5.1 *Analysis of Results*

The outputs of capacity expansion, production cost, and power flow models provide important feedback regarding initial scenario assumptions and model parameters, which may require updates if the initial results are unrealistic or infeasible. For example, if the results show excess congestion in power lines or significant loss of load, study assumptions and/or input data can be updated to explore additional sources of flexibility, alternative siting for variable RE generation, and/or additional transmission capacity.

Each study scenario will produce a wealth of results to analyze, compare, and report. Results of interest from a **production cost modeling** scenario for high variable RE, for example, could include the following metrics:

- Generation from each generator at each timestep, which can be aggregated to daily, monthly, or annual values
- Fuel consumption
- Air emissions
- Net load (demand minus generation from solar and wind power plants)
- Curtailment of wind and solar energy
- Operational costs, including fuel costs, operations and maintenance, emissions, and transmission congestion
- Reserve requirements, provision, and shortage
- Utilization of thermal generators, such as, number of starts and stops, plant load factors (capacity factors), time spent at minimum generation, and frequency and magnitude of ramping and/or cycling
- Transmission congestion and losses
- Outage rates
- Periods of unserved load or dump energy
- Energy transfers and power flows, including interregional flows
- Periods of interest, including hours when nonsynchronous generation exceeds a certain proportion of total generation.

4.5.2 *Reporting Results*

The output of a grid integration study is typically a technical report summarizing the assumptions, methodology, results of the study and implications for power sector decision makers. Other reporting products can include:

- Executive summaries for decision makers (grid integration reports are often detailed summaries of the work and decision makers may need a summary of key takeaways)
- Summary presentations
- Visualizations (e.g., videos, data viewers)

- Infographics
- Fact sheets and project overviews
- Journal articles
- Underlying data sets (if cleared to be disseminated by the data providers)
- Press releases.

Figure 3 provides an example of an infographic from a national grid integration study for India (Palchak et al. 2017). This infographic provides a visual comparison of the results of several sensitivity analyses that the modeling team conducted for a scenario in that included 100 GW of solar and 60 GW of wind (corresponding to India's national RE target). Specifically, the image shows how different approaches to coordinated scheduling and dispatch, different levels of coal plant flexibility, and a combination of these factors impact production costs and RE curtailment relative to the core scenario. The results indicate that scheduling and dispatch coordinated at the national level (versus current state-level dispatch) results in the highest production cost savings, while a combination of nationally coordinated scheduling and dispatch and lower minimum generation levels for coal result in the lowest variable RE curtailment.

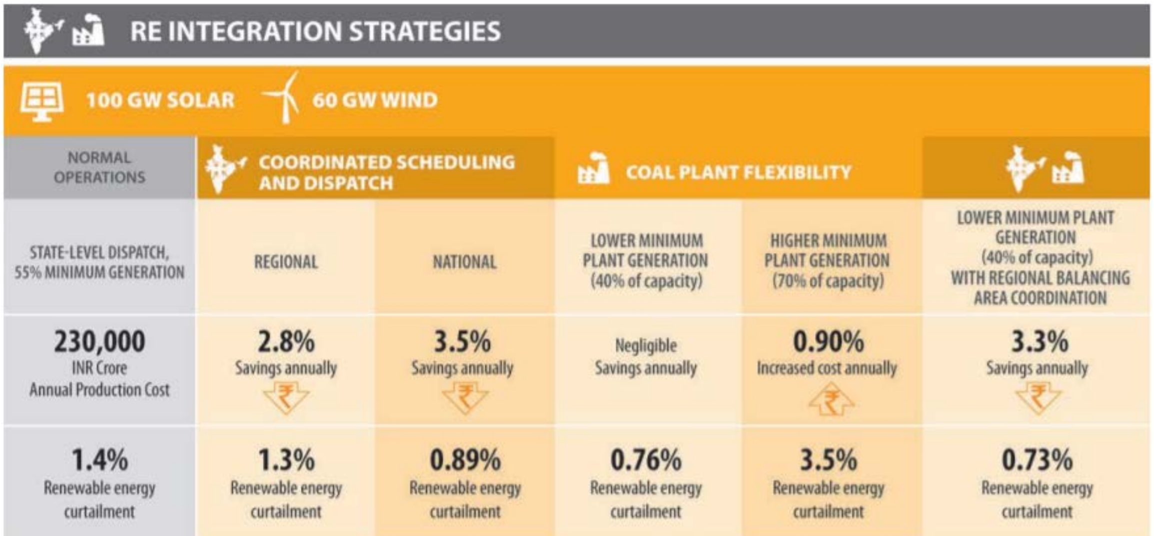

Figure 3. Figure for India's grid integration study summarizing the impact of RE integration strategies on production costs and RE curtailment

Source: Palchak et al. 2017

Regardless of how results are presented, reporting products should clearly define assumptions and present the results of sensitivity analyses to clearly communicate the study limitations. Clearly defined, transparent methods and limitations enable the international expert community to provide input and feedback on ongoing integration analysis efforts. Understanding the data, assumptions, and methods that led to the results is also critical when comparing results from different studies and previous work.

At a minimum, grid integration study reports should clearly define the following assumptions:

- Primary analysis questions and type of study (e.g., capacity expansion, production cost, and/or power flow)
- RE (or GHG mitigation) target, including assumptions about the contribution of variable RE resources to meeting this target
- Study horizon (target year) and temporal resolution
- Geographic scope
- Modeling methods and simulation tool, and their primary limitations in assessing the system under study
- Modeling participants and stakeholder review process
- Characteristics and size of the power system (i.e., peak load, generation mix, and transmission network capacity and topology)
- Definition of scenarios (e.g., reference scenario, BAU scenario, high-RE scenarios, and sensitivity analyses)
- Assumptions regarding current and future generation fleet, transmission system, system flexibility, interconnection, operational practices
- Data sources, including methods for estimating RE generation profiles
- Assumptions regarding future fuel prices, electricity demand, and policies (e.g., emission pricing).

Beyond assumptions, study outputs will include information about the findings of the study. Depending on the focus of the study, findings could include high-level observations about how a power system with high levels of wind and solar behaves (including the impacts on thermal generators), discussion of how different scenarios contribute to power system goals (e.g., RE or GHG targets, reliability, costs), and the results of sensitivity analyses—including potential actions that can help to efficiently integrate variable RE, for example, by lowering costs or reducing curtailment.

Box 12. The Challenge of Defining and Assessing Integration Costs

Adapted from Palchak et al. 2017

Stakeholders are typically interested in quantifying RE integration costs or conducting cost-benefit assessments more broadly; however, integration cost—the cost imposed on the power system to integrate a resource—is a deceptively challenging concept to define and calculate. Some of the costs that have been attributed to wind and solar resources include:

- Reserves to accommodate the variability and uncertainty of wind and solar
- Thermal generator cycling costs that result from more frequent changes in dispatch to complement variable output from wind and solar (cycling can lead to greater operations and maintenance costs and reduced plant efficiencies)
- Transmission expansion to serve locations with strong solar and wind resources
- Stranded investments in conventional generators that are displaced by wind and solar.

These costs are not unique to RE. Reserves are an extension of existing practices to balance the system. Cycling costs and stranded investments, and in some cases, new transmission, occur anytime a new resource is added to the system. Moreover, these costs are not directly calculable or observable—the costs of maintaining a reliable power system reflect the complex interactions among resources and loads, making it difficult if not impossible to untangle costs and allocate them to individual cost-causers—generation or load (the end users). Thus, great care must be taken when analyzing and communicating costs in a grid integration study.

Analytically, the best practice for calculating the costs associated with integrating wind and solar is to model system operating costs of a wind and/or solar and alternative resource scenario and compare the costs. Yet, because wind and solar generation has zero operating costs, the scenario with wind and solar will always have lower operating costs than a no- or low-RE case. The difference in operating costs with the alternative resource scenario will be dominated by fuel costs from energy that must be provided by conventional resources. Thus, the calculation of added reserves and thermal cycling costs will be reflected as a reduction in savings in operating costs, not an increase in operating costs.

Despite the computational challenges of quantifying integration costs, the preponderance of experience suggests that up to moderate penetrations of variable RE, integration of wind and solar carries costs that are small compared to total system benefits. For example, in quantifying the costs and benefits of high RE penetration, the second phase of the Western Wind and Solar Integration Study compared an estimated United States dollars ($) 35 to $157 million cycling cost to accommodate RE variability with a $7 billion benefit associated with avoided fuel costs for conventional base load generators (Lew et al. 2013).

The resources in the Toolkit of this guidebook section provide additional discussion and analysis.

To create an actionable study, the framing of the results of the technical analysis should reflect concerns or questions that decision-makers have about grid integration of RE. The Toolkit below includes links to additional reporting guidance and a variety of examples of reporting products from existing grid integration studies.

Box 13. Analysis and Reporting: Actions for the Study Leadership Team

- Work with the MWG and TAC to determine the priority metrics to analyze (e.g., variable RE curtailment, hours of transmission congestion, or number of starts and stops and time at minimum stable levels for thermal generators)
- Agree on how to define, assess, and communicate grid integration costs to stakeholders
- Develop an outline of the final grid integration study report and vet with the MWG and TAC as needed
- Determine which communication products to develop, and budget appropriately for products such as visualization and scenario analysis tools
- Determine the review and clearance process from the study sponsors and MWG agencies. Seek guidance and review as needed from the international grid integration expert community to provide input and feedback on draft results
- Develop a plan for results dissemination and outreach to ensure that all key stakeholders are aware of the study results.

Box 14. Analysis and Reporting: Quick References

- **Appendix A**: **Examples of grid integration studies and their outcomes**
  This appendix links to several examples of grid integration study analysis and reports, please refer to the documentation. The Executive Summary and Table of Contents of these existing studies may provide useful ideas and templates for structuring and communicating results of a new grid integration study.
- **References:**
  For additional guidance and discussion of calculating integration costs of variable RE, please refer to the following reports:
  - **Wind Integration Cost and Cost-Causation** (Milligan et al. 2013)
  - **Integration Costs: Are They Unique to Wind and Solar Energy?** (Milligan et al. 2012)
- **Reference: International Energy Agency's Expert Group Report on Recommended Practices (16. Wind integration studies).**
  Chapter 7 of this report includes more detailed technical guidance on how to analyze grid integration model outputs and present the results. This chapter includes discussion of issues around analyzing integration costs, as well as other impacts on transmission congestion, thermal units, and balancing. A particularly useful reference in this chapter is the "Summary of Issues" table, which provides a checklist of different issues to be considered and reported in grid integration studies.
- **Reference: Electricity Capacity Expansion Modeling, Analysis, and Visualization: A Summary of Selected High-Renewable Modeling Experiences**
  "Issue Four" of this technical report provides several examples of effective visualization of model results from existing capacity expansion studies. Additionally, Appendix A to the report summarizes "Top Ten Lessons on Scenarios and Modeling for Policymakers," which provides insights on managing expectations and communicating the limitations of grid integration studies (these lessons originally appeared in Mai et al. 2013).
- **Examples** of visualization products from international grid integration studies:
  - Renewable Energy Futures scenario viewer: http://www.nrel.gov/analysis/re_futures/data_viewer/.
  - Renewable Energy Futures visualizations of electric sector transformation, hourly operations, and power flow in the 2050 target year (Mai et al. 2012).
  - India grid integration study visualization: https://maps.nrel.gov/IndiaGTG

4.6 Cost of Conducting a Grid Integration Study

Conducting a grid integration study is a significant undertaking that can take several months to multiple years to complete. The time frame, as well as the cost of the study, depend on the scope of the study, extent of stakeholder engagement, data availability, and level of capacity building needed to develop modeling expertise. In the United States, the cost of a three-year study to model the large, complex Western Interconnection system approached USD $2 million (not including the in-kind stakeholder contributions to the TRC or the cost of wind and solar data sets); however, the Western Interconnection is a very large system, and the costs for a smaller system or a less detailed study may be proportionally less.

As described in Parsons et al. (2013), the major costs associated with a grid integration study include data development and labor to run models, analyze data, communicate results, and conduct stakeholder engagement. Based on grid integration study experiences at NREL, Table 3 shows a rough breakdown of costs for a production cost analysis.

TABLE 3. ROUGH BREAKDOWN OF COSTS FOR A PRODUCTION COST ANALYSIS (SOURCE: PARSONS ET AL. 2013)	
TASK	PERCENTAGE OF TOTAL COST
Utility data acquisition, development and validation	15%
Capacity expansion and RE scenario development	7.5%
Acquisition and development of wind and solar resource data	7.5%
Software, computing hardware, and running models	20%
Data analysis	20%
Communications, stakeholder interaction, and presentations	30%

Box 15. Scoping a Grid Integration Study: Toolkit

- **Appendix F:** **[Template/Example] Concept Note and Statement of Work: Renewable Energy Grid Integration Study (Production Cost Modeling Study)**
  This appendix includes a generic version of the concept note and statement of work for the grid integration study (a production cost analysis) for the Philippines. Implementers can adapt it as needed to fit the context of their power system and grid integration study focus. In the case of the Philippines, the NREL was the implementing organization and the Philippine Department of Energy and USAID were the conveners and chairs of the Technical Advisory Committee. The study effort included a significant capacity building component, which is reflected in the language of the template concept note.

5 From Study to Roadmap—Using the Results of a Grid Integration Study

The ultimate goal of a grid integration study is to address stakeholder concerns that a power system can operate reliably and cost-effectively under high-RE scenarios and give decision makers the information and confidence they need to set and meet ambitious variable RE and climate change mitigation targets. With the results in hand, decision makers can be more precise and effective in developing national, regional, and local-level implementation roadmaps that prioritize the most cost-effective actions to meet their grid integration goals, and identify the implementation steps, costs, timeframe, and actors responsible for implementation. At the same time, a grid integration study adds transparency to the policymaking process by clearly communicating the study objectives, assumptions, data sources, analytical methods, results, and limitations to all relevant power system stakeholders and the broader public.

In addition to identifying highest-value integration actions, a grid integration study will likely raise additional questions that may warrant further analysis. Subsequent analyses can build on the framework developed for an initial study to analyze additional timescales, scenarios, and geographic regions or to focus on broader energy systems analysis that considers the combined impacts of variable RE on the transmission, distribution, natural gas, and transportation systems. With rigorous technical oversight and robust stakeholder engagement, a grid integration study can serve as a powerful long-term tool to guide decision makers in planning and implementing well-informed RE policies.

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Appendix A: Examples of Grid Integration Studies

This section summarizes several grid integration studies. This list is not comprehensive of all grid integration studies conducted to date, but rather seeks to highlight a diversity of power systems, approaches, objectives, and results of grid integration studies that assess the effects of scaling up variable RE on the power system.

1. **Greening the Grid: Solar and Wind Grid Integration Study for the Luzon-Visayas System of the Philippines**
   Philippine Department of Energy and United States Agency for International Development (Barrows et al. 2018)

- Power system: Integrated Luzon and Visayas grids of the Philippines
- Types of analysis: production cost
- Model used: PLEXOS®
- Primary study objectives:
  - Overall: Evaluate how the power system performs with different amounts of wind and solar
  - Inform policy, operations, market design, and technologies that can support the Philippines in preparing for the integration of new technologies, especially as costs of solar and wind technologies decrease.
- RE penetration scenarios: Base case with 15% annual RE (including solar and wind as well as other RE resources) based on existing plans, two 30% RE scenarios, and two 50% RE scenarios. The 30% and 50% RE scenarios vary solar and wind siting based on using the best variable RE resources versus minimizing transmission impacts of new variable RE. All scenarios focus on the year 2030.
- Key findings:
  - RE targets of 30% and 50% are achievable in the power system as planned for 2030. Achieving these high RE targets will likely involve changes to how the power system is operated;
  - System flexibility will contribute to cost-effective integration of variable RE;
  - Achieving high levels of solar and wind integration will require coordinated planning of generation and transmission development;
  - Strategic, economic curtailments of solar and wind energy can enhance system flexibility; and
  - Reserve provision may become an issue regardless of RE penetration. Additional qualified reserve-providing facilities, including from solar and wind generators, and/or enhanced sharing of ancillary services between the Luzon and Visayas interconnections will likely be needed.

2. **Greening the Grid: Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid, Vol. 1—National Study**
   Ministry of Power of the Government of India and United States Agency for International Development (Palchak et al. 2017)

- Power system: India
- Types of analysis: production cost
- Model used: PLEXOS®
- Primary study objectives:
  - Overall: Explore the operational impacts of the Government of India's target of 175 GW of installed RE capacity by 2022, including 60 GW of wind and 100 GW of solar

- Identify potential grid reliability concerns and actions that may be favorable for large-scale RE integration in India
  - Assess how the cost of operating the Indian system with high RE can be reduced through alternative operating procedures or technologies
  - Identify characteristics of thermal plant flexibility that would help reduce RE curtailment.
- RE penetration scenarios: One BAU scenario with 5-GW solar and 23-GW wind capacity; one medium-RE scenario with 20-GW solar and 50-GW wind capacity; and three high-RE scenarios with solar capacity ranging from 60-150 GW and wind capacity ranging from 50-100 GW. All scenarios study the year 2022.
- Key findings:
  - Power system balancing with 100 GW of solar and 60 GW of wind in India's power system is achievable at 15-minute operational timescales with minimal RE curtailment;
  - Changes to operational practice can reduce the cost of operating the Indian power system and reduce RE curtailment, but they not essential for large-scale RE integration; and
  - Reducing minimum generation requirements of large thermal plants provides most significant contribution towards to reducing RE curtailment.

3. **Eastern Renewable Generation Integration Study**
   National Renewable Energy Laboratory (Bloom et al. 2016)

- Power system: Eastern Interconnection of the United States and the Quebec Interconnection of Canada
- Types of analysis: capacity expansion, production cost
- Models used: ReEDS, PLEXOS®
- Primary study objectives:
  - Overall: Investigate the operational impact of up to 30% annual penetration of variable RE in the generation mix, with instantaneous penetration over 50%
  - Assess the impacts of various RE scenarios on traditional power sources such as coal, natural gas, and hydroelectric power
  - Assess how regional power flows are affected by high shares of variable RE in the generation mix
  - Use advanced modeling and computing technologies to increase the spatial and temporal resolution of production cost simulations.
- RE penetration scenarios: Four generation portfolio scenarios with wind annual penetration targets ranging from 3% to 25% and solar annual penetration targets ranging from 3% to 10%. Two high-variable generation scenarios, each with 30% combined wind and solar generation, also varying interregional transmission infrastructure buildout.
- Key findings:
  - The power system can balance annual penetrations of 30% variable wind and solar generation at a five-minute dispatch interval;
  - The operation of thermal and hydro power generation changes as wind and solar PV increase;
  - System operations at sunrise and sunset could follow different patterns; and
  - Transmission flows will likely change more rapidly and more frequently with higher penetrations of wind and PV.

4. **Technical and Economic Analysis of the European Electricity System with 60% RES**
   EDF, Research and Development Division (Burtin and Silva 2015)

- Power system: European Union
- Types of analysis: Capacity expansion, production cost, power flow
- Models used: In-house models developed for this study
- Primary study objectives:
    - Overall*:* Examine the technical and economic feasibility of integrating a high share of variable RE into the interconnected European electricity grid
    - Identify the system flexibility needs to handle variability introduced by wind and solar PV generation
    - Assess how the security and dynamic stability of the European power system will be affected by increased variability and uncertainty in power generation
    - Evaluate the need for transmission network reinforcements and determine how much cross-border interconnection capacity will be required to benefit from the geographic diversity of variable RE generation across Europe
    - Determine whether wind and solar PV generation will be profitable in European electricity markets.
- RE penetration scenario: Analyzes a European-wide generation portfolio with 60% RE share by 2030. In this scenario, wind and solar PV meet 40% of electricity demand, and dispatchable RE resources (e.g., hydro, biomass) meet the other 20%.
- Key findings:
    - New mechanisms for flexibility (complementary with existing flexibility) will be needed to cope with the variability of variable RE generation;
    - Thermal generation will continue to be needed to provide security of supply under a 60% RE penetration scenario (of which 40% is from variable RE sources);
    - Network upgrades at both the distribution and transmission scales (including additional cross-border transmission network capacity) may be required to take advantage of the smoothing effect associated with aggregating variability of supply and demand over large geographic footprints. However, variability associated with wind and solar generation will be significant even at the European continent level under the 60% RE scenario;
    - Demand response mechanisms can play a role in balancing electricity supply and demand but will not be capable of solely managing the variability associated with wind and solar PV;
    - The study did not find a strong business case for wide-scale development of storage over the next 15 years to manage variable RE integration; and
    - The pace at which variable RE is deployed needs to be optimized to avoid high costs of storage and high curtailment, and to manage the impacts of high variable RE penetration on the dynamic stability of the system.

5. **Minnesota Renewable Energy Integration and Transmission Study**
Minnesota Department of Commerce (General Electric Energy 2014)

- Power system: Minnesota
- Types of analysis: Production cost, power flow
- Models used: PLEXOS®; PSS®E, Positive Sequence Load Flow
- Primary study objectives:
    - Overall: Evaluate the reliability and associated cost impacts of a 40% RE Standard in Minnesota by 2030, and higher proportions thereafter

- Assess the costs associated with the reliability impacts of increased levels of variable RE generation
    - Develop a conceptual transmission plan to access regional geographic diversity and improve system flexibility
    - Identify options to manage the reliability impacts of variable RE generation
    - Produce meaningful results through a technically rigorous and transparent study.
- RE penetration scenarios: Analyzes generation portfolios from 28 - 50% variable RE (wind and solar) penetration in 2028, with a particular focus on a 40% RE penetration scenario.
- Key findings:
    - The power system can reliably accommodate variable RE generation to supply 40% of Minnesota's annual electricity retail sales;
    - Assuming current generation interconnection requirements and wind turbine standards are met, there are no fundamental systemwide dynamic stability or voltage regulation issues associated with 40% RE; and
    - Additional analysis is needed to ensure power system reliability under 50% RE penetration scenario, however, production cost analysis indicates this target is operationally achievable for all hours of the year, assuming that sufficient transmission upgrades and expansions are undertaken.

6. **Hawaii Solar Integration Study**
   U.S. Department of Energy, Hawaii Natural Energy Institute, and Hawaii Electric Company (Eber and Corbus 2013)

- Power system: Hawaii (specifically, the islands of Maui and Oahu)
- Types of analysis: Production cost, power flow
- Model used: Multi-Area Production Simulation (MAPS), PSLF
- Primary study objectives:
    - Overall: Examine the technical impacts of high penetrations of solar and wind on the operations of the electricity grids on two Hawaiian Islands.
- RE penetration scenarios:
    - Oahu: BAU scenario of 160-MW solar and wind; four high-RE scenarios ranging from 460-860 MW of installed solar and wind capacity. Each scenario varies the magnitude and distribution of central solar PV power plants versus distributed solar PV systems; and
    - Maui: BAU scenario of 87 MW solar and wind capacity; one high-RE scenario with 117 MW of RE (an additional 15 MW of centralized PV and 15 MW of distributed PV above the BAU scenario).
- Key findings:
    - Adding large amounts of new solar power to the Maui and Oahu grids will increase operational and reliability challenges;
    - Operational and reliability challenges are manageable with the implementation of a variety of mitigation measures, including changes to utility equipment and operating practices as well as variable RE equipment;
    - Asking for certain capabilities (e.g., inertial and frequency response, voltage and frequency ridethrough, and ancillary services) from variable RE generators enable RE to serve a grid support function to help mitigate integration issues; and
    - Changing operating practices of conventional generators (e.g., by reducing minimum power levels of conventional units, relaxing the operating schedule for certain baseload units, providing

reserves from demand response or battery energy storage, and upgrading conventional units) mitigate integration challenges and reduce RE curtailment.

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7. **Renewable Energy Futures Study**
   National Renewable Energy Laboratory (Mai et al. 2012)

- Power system: Continental electricity grid of the United States
- Types of analysis: Capacity expansion, production cost
- Models used: Regional Energy Deployment System (ReEDS) model, GridView
- Primary study objectives:
  - Overall: Examine the extent to which RE technologies can meet the electricity demand of the continental United States through 2050
  - Identify the characteristics of a U.S. electricity grid that can accommodate high levels of variable RE generation
  - Identify the benefits of aggregating diverse RE resources over larger geographic areas
  - Describe the challenges and implications of realizing high levels of RE penetration.
- RE penetration scenarios: RE penetration levels (including wind, solar, geothermal, biomass, and hydropower) in 2050 ranging from 30% to 90%, with a focus on 80%.
- Key findings:
  - RE generation from technologies commercially available today can supply 80% of total U.S. electricity generation in 2050;
  - Increased electric system flexibility will be necessary to enable high levels of generation and can come from a portfolio of supply- and demand-side options;
  - RE generation can result in deep reductions in electric sector GHG emissions and water use; and
  - Improvement in cost and performance of RE technologies will be important to reducing incremental costs.

8. **All Island Grid Study**
   Department of Enterprise, Trade and Investment and Department of Communications, Energy and Natural Resources, Republic of Ireland (2008)

- Power system: Ireland
- Types of analysis: Capacity expansion, production cost, power flow
- Models used: WILMAR Planning Tool, EnergyPLAN; Security Constrained Optimal Power Flow (SCOPF); in-house tools for voltage security analysis.
- Primary study objectives:
  - Overall: Assess the technical feasibility and relative costs and benefits associated with six generation portfolios, each comprising different shares of renewable and conventional energy, for a single year (2020)
  - Identify least-cost generation portfolios, taking into consideration different cost scenarios for fuel, carbon, renewable and conventional energy generation, and network reinforcements
  - Evaluate hourly dispatch, operational costs, fuel consumption, reserves provision, electricity imports and exports and carbon dioxide emissions for each generation portfolio
  - Analyze the extent and cost of additional transmission network development required to accommodate RE during high-stress times for each generation portfolio
  - Compare the costs and benefits of each generation portfolio based on the analyses above.

- RE penetration scenarios: Analyzes generation portfolios ranging from 16-42% RE (as a percent of annual demand) in 2020.
- Key findings:
  - The differences in costs between the highest- and lowest-cost portfolios are low;
  - 25% of total carbon dioxide emissions from the electricity sector could be avoided by moving from the most conservative to the most aggressive RE scenario;
  - Further development of the transmission network is required to implement the portfolios analyzed; and
  - Maintaining adequate system security will involve developing market mechanisms, for example, to facilitate flexible cycling from conventional plants.

9. **Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements**
   Electric Reliability Council of Texas (General Electric International 2008)

- Power system: Texas
- Types of analysis: production cost
- Model used: MAPS
- Primary study objectives:
  - Overall: Evaluate the effects of increasing wind power generation on the levels of ancillary services required in the Texas power system
  - Recommend improvements to the methodology that the system operator uses to determine the amount of ancillary series required
  - Estimate the impact of increasing wind generation on the costs of procuring ancillary services
  - Identify potential changes to operating practices that may be needed to manage severe weather conditions.
- RE penetration scenarios: Analyzes five scenarios with wind capacity ranging from 0 MW to 15,000 MW in Texas, using 2008 as the study year. Each scenario assigns wind capacity to each of Texas's Competitive Renewable Energy Zones.
- Key findings:
  - The operational impacts of wind generation increase as target wind generating capacity grows; at 5,000 MW generating capacity, wind generation has limited impact on the system, while at 15,000 MW of generating capacity, operational issues will become significant; however, these issues can be addressed without radical alteration of operations;
  - The system operator's existing methodology (at the time of the study) is adequate to procure sufficient regulating reserves. Including wind generation forecasts can help reduce reserve requirement; and
  - Infrequent periods occur when the unit commitment and dispatch of thermal generating units may need to be altered to provide ancillary services, especially in the highest wind energy penetration scenarios.

10. **Western Wind and Solar Integration Study (WWSIS) Phase 1**
    National Renewable Energy Laboratory (General Electric Energy 2010)

- Power system: WestConnect group of utilities in the Western United States (responsible for meeting much of the electricity demand in Arizona, Colorado, Nevada, New Mexico, and Wyoming).
- Type of integration study: Primarily production cost (some elements of capacity expansion)

- Model used: MAPS
- Primary study objectives:
  - Overall: Investigate the operational impact of up to 35% penetration of wind, solar PV, and concentrated solar energy on the power system
  - Assess how geographic diversity can help to mitigate variability from variable RE
  - Compare the deployment of RE resources that are near existing transmission and load centers to higher-quality resources delivered by long-distance transmission
  - Evaluate the benefits of operational practices such as wind and solar forecasting and balancing area cooperation
  - Assess the effects of variability in RE generation on reserve requirements.
- RE penetration scenarios: Analyzes various locations for wind and solar resources, and various levels of energy penetration for wind and solar, ranging from 11% to 35%.
- Key findings:
  - There are significant benefits and no significant adverse impacts of scenarios up to 20% RE penetration (assuming balancing area cooperation);
  - Given imperfect RE forecasting, RE penetrations above 20% require extra spinning reserves and/or demand response programs to provide additional system flexibility;
  - A 30% RE penetration scenario reduces fuel and emissions costs by 40% and CO_2 emissions by 25-45% across the Western Interconnection; and
  - It is operationally feasible to accommodate 30% wind and 5% solar power penetration for the WestConnect power system but doing so would require changes to operational practices and extensive balancing area cooperation.

11. **Western Wind and Solar Integration Study (WWSIS) Phase 2**
    National Renewable Energy Laboratory (Lew et al. 2013)

- Power system: WestConnect group of utilities in the Western United States (responsible for meeting much of the electricity demand in Arizona, Colorado, Nevada, New Mexico, and Wyoming).
- Types of analysis: Primarily production cost (some elements of capacity expansion)
- Model used: PLEXOS®
- Primary study objectives:
  - Overall: Evaluate the impact of wind and solar integration on the conventional generation fleet
  - Quantify the additional cycling costs borne by fossil-fuel generators due to added variability in the power system
  - Assess whether wear and tear of fossil-fuel generators significantly reduces the benefits of wind and solar integration
  - Calculate the emissions impacts of increased cycling of fossil-fuel generators.
- RE penetration scenarios: Analyzes various generation portfolios ranging from 20%-33% wind and solar penetration in 2020, including high wind and high solar scenarios.
- Key findings:
  - Under high penetrations of wind and solar, wear and tear costs for fossil-fueled generators due to increased cycling represent a small percentage of the annual fuel costs reduced by wind and solar generation;
  - Additional emissions from increased cycling of fossil-fueled generators are a small percentage of emissions avoided by wind and solar generation; and

- The systemwide impacts of wind versus solar generation on production costs are remarkably similar.

12. **Western Wind and Solar Integration Study (WWSIS) Phase 3**
    National Renewable Energy Laboratory (Miller et al. 2014)

- Power system: WestConnect group of utilities in the Western United States (responsible for meeting much of the electricity demand in Arizona, Colorado, Nevada, New Mexico, and Wyoming).
- Types of analysis: Power flow
- Model used: WECC composite load model (CMPLDWG)
- Primary study objectives:
  - Examine the large-scale transient stability and frequency response of the Western Interconnection with high penetrations of wind and solar generation
  - Identify means to mitigate any adverse impacts of wind and solar on the system performance during times of disturbance.
- RE penetration scenarios: Analyzes four primary scenarios to represent different extreme system conditions, including different combinations of light and heavy load, and base case and high renewables. Wind and solar penetration levels range from 4%-53% across all study scenarios.
- Key findings:
  - There are no fundamental reasons why the Western Interconnections cannot meet transient stability and frequency response objectives with high penetrations of wind and solar;
  - Traditional system reinforcements as well as nonstandard measures (such as synchronous condenser conversions) can result in acceptable transient stability performance under a 90% reduction in coal plant commitment;
  - Local stability, voltage, and thermal problems need to be addressed with traditional system reinforcements to maintain systemwide frequency response with high levels of wind and solar generation;
  - Frequency response controls on wind, solar PV, CSP plants, and energy storage are effective at improving frequency response. Refinement of these controls can improve performance; and
  - Further analysis is needed to determine additional operational limits and to quantify the impact of distributed generation.

Appendix B: Questions a Grid Integration Study Based on Production Cost Modeling Can Help Address

Table B- 1. Questions a Grid Integration Study Based on Production Cost Modeling Can Help Address

Questions a Production Cost Analysis Helps Answer	Implications for the TRC
What is required to achieve a specific RE target (% penetration or capacity target)?	A production cost analysis can highlight how the power system could be operated to achieve a high RE target. Modeling multiple targets would allow the study to evaluate how the system might need to change over time. Modeling a single target also has value—the study would be able to evaluate and compare multiple pathways to meeting that target. Decision for TRC: What RE targets should the study use?
What are the impacts of different RE policies on the operation of the grid? For example, impact of: • Polices that support wind vs. solar • Policies that support RE development in a particular location	If differences between wind and solar are important to investigate, a production cost analysis should include at least two scenarios that have different wind to solar ratios (e.g., high wind and high solar scenarios). If RE development locations, transmission siting, or transmission congestion are important to evaluate, then the study should include at least two scenarios that evaluate different approaches to site selection (best RE resource sites vs. sites close to load centers).
What is the reduction in GHG emissions associated with the RE target? **Example implication for policy:** higher wind growth may lead to equal RE deployment (in GW) as high solar growth but result in lower total emissions.	Most commercially available production cost models can calculate carbon dioxide (CO_2) emissions for each scenario. The TRC does not need to request this, but the choice in scenarios will affect what is compared.
What policy actions are needed to achieve the RE target?	Production cost models do not address this question directly, however, for a given RE target, some scenarios (e.g., based on wind to solar ratio or site selection) might suggest a preferred deployment path.

Questions a Production Cost Analysis Helps Answer	Implications for the TRC
	Model results usually will show hourly or sub-hourly system operations needed to balance the generation and load. If there are reliability problems identified by the model, the modeling team will evaluate those problems and suggest changes that could mitigate the problems. There are many options available for mitigating reliability issues. Those which can be easily modeled include: • Lowering the minimum stable levels of thermal plants • Changing assumptions about hydro and thermal generation flexibility • Adding transmission • Changing reserve requirements • Adding additional generation or storage assets.
What are the relative costs of integration strategies (from among the options modeled)?	A production cost analysis will be able to show the relative value of several strategies (likely those described in the bullets above). In other words, the results can point to which strategies policy makers or system operators might want to implement. Note, a production cost model cannot evaluate the political feasibility of implementing these strategies, nor will it be able to provide an absolute value associated with each option (e.g., it would not be able to say with certainty that 5 MW of storage will integrate 3 MW of wind). The value of each option depends on the underlying system. What the study can show is relative values (i.e., reduction in operating costs from adopting one integration strategy versus another).
What are the fuel requirements (for gas, coal plants) to meet RE targets?	A production cost model can calculate fuel consumption for each scenario.
What new transmission is required to meet the RE targets?	Each scenario will likely have a different set of transmission requirements, which can be used to inform energy planning (Example conclusions: new transmission capacity in certain areas of the grid would help meet a 30% RE target by reducing RE curtailments).
What are the costs of operating a power system with a specific RE target (% penetration or capacity target)?	A production cost model can calculate total production costs, which can be compared across scenarios. The model can also quantify MW changes in investments under each scenario (i.e.,

Questions a Production Cost Analysis Helps Answer	Implications for the TRC
	compare MW installed capacity of different types of generation and transmission).
How does RE curtailment compare across different scenarios?	A production cost model can calculate the amount of curtailed RE (in MWh). This output is not a fixed quantity per scenario—changes to how the system is operated, additions of flexible generation or storage, and so on, can reduce curtailment. The study team can set a limit on what amount of curtailment is acceptable in the study. If curtailment exceeds that amount, then the study team will look for mitigation strategies to reduce curtailment. Curtailment that is too high will reduce the investment-quality of the resource; curtailment that is too low might imply an overbuilt transmission system.
What types of balancing resources are needed to meet the RE targets?	Modeling for each scenario can indicate the type, location, and time resources are needed, and can also indicate any shortfalls.
What is the optimal generation dispatch for every hour of the year?	A production cost model can produce this based on minimizing production costs subject to physical, market, or other operational constraints. The study report will likely include this information at aggregated levels (e.g., monthly generation summaries).
What are the periods of stress that would warrant follow-up load flow studies?	A production cost model enables the study team to identify periods of potential reliability concerns regarding grid stability. The dispatch information (what is online and dispatched during this period) can feed into load flow cases for evaluation in follow-on efforts.

Appendix C: Example Terms of Reference for a Modeling Working Group

An MWG is the set of technical members who will conduct the modeling activities of the grid integration study. The MWG is critical to the grid integration study process. Members of an MWG help to ensure the data and analysis methods used over the course of the study satisfy industry standards and contribute to accurate, trustworthy results. To accomplish this, MWG members should satisfy the following guidelines.

What Does the MWG Do?

- Assembles and validates data from a variety of sources
- Constructs power system models
- Simulates operations under a variety of modeling assumptions
- Analyzes and verifies simulation results
- Compiles technical documents to disseminate findings and methodologies.

Modeling Team Requirements

The MWG team is comprised of technical staff from power system operators, energy agencies, and other organizations with expertise in power systems or electrical engineering, power flow modeling, and the mechanisms that drive electricity markets.

Desired qualifications of team members include:

1. Electrical or power systems engineering
2. Modeling experience in power flow studies
3. Knowledge of power systems operation, including unit commitment and economic dispatch
4. Understanding of electricity market mechanisms.

Time commitment: Team members are expected to devote at least 10 h/week/person, which may vary depending on the stage of the project.

Meetings, Trainings, and Workshops

1. Basic training on analysis methods and/or software needed to conduct analysis (Timing: First month of the study period)
2. Workshop on validating and executing the analysis and simulation software (Timing: 2-3 months into the study period)
3. Regularly scheduled virtual team meetings, either weekly or bi-weekly.

Appendix D: Example Terms of Reference for a TRC

A TRC is an instrumental component of a rigorous, industry-grounded RE grid integration study. The purpose of the TRC is to ensure the direction of the study is relevant to industry and that the results are technically accurate. Because the TRC will reflect expertise from across the power system, the TRC will ensure that the study reflects industry practices and concerns, thereby raising the credibility of the study results. The TRC provides peer review and input at all stages of the study, from selection of data inputs through implications of results. The TRC can also serve to disseminate the study results and key messages.

What does the TRC do?

- Assist the sponsors in developing study parameters, including objectives, scenarios, and sensitivities[3]
- Reviews the modeling team's methods, data sources, assumptions, and other key issues, and offers suggestions when appropriate to strengthen the study
- Helps interpret modeling results
- Links model outcomes with policy and regulatory processes
- Endorses technical rigor of the study.

Who should be on the TRC?

The TRC members should collectively provide the breadth of technical expertise relevant to the study. The TRC is a technical body whose members should have deep industry knowledge. TRC members should be prepared to engage in the details of the study, such as reviewing data, and to actively participate in meetings. Likely members include technical staff representing grid operators, planners, renewable developers, regulators, utilities, independent power producers, and others with technical expertise in renewable integration and power systems operations, markets, and/or modeling. International experts can also participate in the TRC to ensure that the studies follow peer-reviewed methodologies for grid integration studies and reflect broadly supported best practices for grid integration.

Private sector perspectives are important for the TRC because project developers may have unique insights into market opportunities and emerging technologies. The project team and TRC will ensure that the methodology and results are objectively developed and not skewed to support interests of individual TRC members.

The size of the TRC is typically 30 members. Each organization typically nominates 1-2 individuals to participate in the TRCs; multiple individuals from a single organization are desirable if more than one individual is needed to represent that organization's breadth of activity. Having a large TRC is crucial to ensuring that technical and economic perspectives are represented from all relevant parts of the electric power industry, and that the technical considerations evaluated in the study are not too narrow. The level of interest and engagement will likely vary among group members, particularly as related to different aspects of the study. The TRC facilitator will manage the meetings to maintain progress in discussions.

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[3] *Scenario:* A scenario is one possible future electric generation system. A typical analysis has 3-4 scenarios, which may vary by total renewable generation penetration, locations of wind and solar generation, and/or the ratio of solar to wind generation. *Sensitivities*: A sensitivity is generally an alternative operational practice or the availability of a mitigation option. For example, changing the flexibility of load or hydro resources; changing the size of a balancing area. A sensitivity is applied to all scenarios and the results are reported relative to scenarios without sensitivity options.

Time Commitment

Time commitments are periodic, roughly once every 3-4 months. Each TRC meeting typically lasts one day and requires approximately one day's worth of advanced reading and material review. Some TRC meetings may benefit from more preparation (e.g., reviewing the draft final report) while others may require less preparation in advance (e.g., brainstorming scenarios and sensitivities to be analyzed). There may also be phone calls on particular topics when TRC input is needed in advance of the next meeting. In general, members of a TRC can expect to spend approximately seven days of time over a one-year period.

Members should attend meetings in person or send a delegate. Members are also encouraged to provide more frequent input and reviews as desired. Ongoing critical review and discussion contribute the success of a grid integration study.

Key Principles for a TRC

A successful TRC strives to:

- Engender collegial discussions of methods and results among TRC members, the study team, project sponsors and other interested parties. The aim of these discussions is to improve accuracy, clarity, and understanding of the work, and reach consensus on issues that arise;
- Avoid public disclosure of meeting discussions and preliminary results. In general, findings should not be released until accepted and generally agreed upon by project sponsors, the study team, and the TRC. When advisable, possible, and agreed to by all project participants, interim progress reports can be provided to a broader stakeholder group; and
- Ensure that findings are based entirely on facts and accurate engineering and science. Project sponsors need to embrace this aim so that the results and findings are objectively developed and not skewed to support any desired outcome.

The study results, with documentation of key assumptions and methodologies, will be made available to the public. Where possible, data, as well as pre- and post-processing tools, will be shared publicly. The project sponsors and modeling teams will describe the project as having the benefit of expert review by a TRC member only if the individual or organization has clearly expressed its acceptance of and agreement with the results of the study.

Appendix E: [Template] Data Requirements for Production Cost Modeling

This template provides a detailed list of data inputs for RE grid integration studies based on production cost modeling. While data specific to the study system will contribute to the highest-quality study, many of the inputs in this list can be generalized and possibly simplified in the absence of system specific data (e.g., thermal plant operation parameters such as ramp rates, heat rates, start times, and so on, can be assigned by plant or fuel type based on regional or international averages). Most studies use one or more years of historic data to develop a modeling reference case. If the power system is expected to change in a future target year (e.g., due to generation and transmission capacity expansion or retirements), the data characterizing projections for the target year should be provided wherever possible.

In some cases, power system agencies may already have detailed models of their power system. For example, the system operator may use power flow software to model present or future year stability issues. In these cases, existing models can serve as a starting point for data collection for production cost analyses, as these models include many of the same data required for production cost analysis.

<u>Data Collection for Grid Integration Studies Based on Production Cost Analysis</u>

- **Best option: Begin with an existing production cost model for the power system in a recent year and the target year (if available)**
  Existing models will include most of the data required, and missing pieces can be collected based on the detailed list below.

- **Second best option (collect all of the data below):**
  1. **Begin with an existing power flow model for a recent year and the target year, if available.**
     This model will include most of the data listed under "Transmission network data" below.
  2. **Latitude and longitude of each bus (node) location**
  3. **Load data (see list below)**
  4. **Generator data (see list below)**

- **Third option: collect all of the detailed data elements below.**

In addition to the existing and planned infrastructure data listed below, information describing RE resource availability (include land availability) and quality (wind speed, solar irradiance) are required to develop a high-RE generation expansion plan.

Table E- 1. Data Needs for Production Cost Modeling

DATA DESCRIPTION	DATA SOURCE	SYSTEM-SPECIFIC DATA AVAILABLE?	CONFIDENTIAL/ PROPRIETARY?	NEEDS PROCESSING?
Buses (Nodes):				
Node ID (numeric)—unique identification number of each node				
Node Name (text)—unique name of each node				
Zone (text)—zonal assignment of each node				
Voltage (numeric, kV)—nominal voltage level in kV				
Load Participation Factor (numeric)—fraction of load assigned to each node. This is a way of disaggregating a system or zonal load profile to individual load profiles for each node.				
Latitude (numeric, degrees)—latitude of node location				
Longitude (numeric, degrees)—longitude of node location				
Transmission Lines (Including Transformers):				
Line Name (text)—unique line name of each transmission line				
Node From (text: Buses.Node Name)—source connection of transmission line				
Node To (text: Buses.Node Name)—sink connection of transmission line				
Max Flow (numeric, MW)—maximum real power flow rating in the forward direction				
Min Flow (numeric, MW)—minimum real power flow rating in the forward direction (negative value for backward direction flow)				
Resistance (numeric, p.u.)—the per-unit line resistance				
Reactance (numeric, p.u.)—the per-unit line reactance (zero value for DC lines)				
Transmission Line Forced Outage Rate—numeric percentage (%), and all voltage levels to be included				
Interface Details (Connections Between Other Interconnections):				
Node Name (text: Buses.Node Name)—node at which the interface is connected				

Max Export (numeric, MW)—maximum export as defined from the node to the external system				
Max Import (numeric, MW)—maximum import as defined from the external system to the node				
Flow Profile (numeric, hourly, MW)—historical hourly flow schedule (if it exists)				
Max Flow Ramp (numeric, MW/min)—maximum ramp rate of dispatchable flow				
Thermal Generating Plants:				
Generator Name (text)—unique name of generating unit				
Node Name (text: Buses.Node Name)—connection node of generator				
Online Date (numeric, date)—beginning date of generator interconnection				
Max Capacity (numeric, MW)—name plate generating unit capacity				
Min Stable Level (numeric, MW)—minimum generator output				
Ramp Rate (numeric, MW/min)—maximum ramp rate				
Fuel Type (text)—primary generator fuel type				
VO&M Cost (numeric, $/MWh)—variable operations and maintenance cost				
Start Cost (numeric, $) - cost to startup generating unit				
Start Time (numeric, hrs)—time to start up generating unit				
Forced Outage Rate (numeric)—annual % of periods down for contingencies				
Mean Time to Repair (numeric, hrs)—mean time to repair after forced outage				
Planned Outage Rate (numeric)—annual % of periods down for planned outages				
Mean Maintenance Time (numeric, hrs)—mean down time for planned outages				
Heat Rate (piecewise linear curve, numeric, BTU/kWh)—thermal plant efficiency (can be a scalar or a piecewise curve)				
Fuel Cost (numeric, $/MMBTU)—delivered fuel cost of primary generator fuel				

Renewable Generating Plants:				
Generator Name (text)—unique name of generating unit				
Node Name (text)—connection node of generator				
Online Date (numeric, date)—beginning date of generator interconnection				
Max Capacity (numeric, MW)—name plate generating unit capacity				
Power Output (numeric, MW)—annual hourly profile of historic output				
VO&M Cost (numeric, $/MWh)—variable operations and maintenance cost				
Forced Outage Rate (numeric)—annual % of periods down for contingencies				
Mean Time to Repair (numeric, hrs)—mean time to repair after forced outage				
Planned Outage Rate (numeric)—annual % of periods down for planned outages				
Mean Maintenance Time (numeric, hrs)—mean down time for planned outages				
Wind and/or solar power profiles (numeric, MW)—hourly or subhourly (time-synchronous with load) wind and solar power output, based on underlying resource data				
Forecasted wind and solar output (numeric, MW)—Forecasted power output for a given time period and resolution to match the chronological settings of the model (e.g., day-ahead hourly forecasts), and associated error				
Hydro Generation:				
Generator Name (text)—unique name of generating unit				
Node Name (text: Buses.Node Name)—connection node of generator				
Online Date (numeric, date)—beginning date of generator interconnection				
Max Capacity (numeric, MW)—name plate generating unit capacity				
Min Stable Level (numeric, MW)—minimum generator output				
Ramp Rate (numeric, MW/min)—maximum ramp rate				
Power Output (numeric, MW)—annual hourly profile of historic output				

VO&M Cost (numeric, $/MWh)—variable operations and maintenance cost				
Energy limits (numeric, MWh/period)—yearly/monthly/weekly energy limits				
Forced Outage Rate (numeric)—annual % of periods down for contingencies				
Mean Time to Repair (numeric, hrs)—mean time to repair after forced outage				
Planned Outage Rate (numeric)—annual % of periods down for planned outages				
Mean Maintenance Time (numeric, hrs)—mean down time for planned outages				
Storage/Demand Response Systems:				
Generator Name (text)—unique name of generating unit				
Node Name (text: Buses.Node Name)—connection node of generator				
Online Date (numeric, date)—beginning date of generator interconnection				
Max Capacity (numeric, MW)—name plate generating unit capacity				
VO&M Cost (numeric, $/MWh)—variable operations and maintenance cost				
Energy Capacity (numeric, MW-h)—maximum energy storage capacity				
Min Stable Level (numeric, MW)—minimum generator output				
Round Trip Efficiency (numeric)—Efficiency of storage system				
Ramp Rate (numeric, MW/min)—maximum ramp rate				
Forced Outage Rate (numeric)—annual % of periods down for contingencies				
Mean Time to Repair (numeric, hrs)—mean time to repair after forced outage				
Planned Outage Rate (numeric)—annual % of periods down for planned outages				
Mean Maintenance Time (numeric, hrs)—mean down time for planned outages				
Demand:				
Load profile (numeric)—hourly or subhourly (preferably time-synchronous with wind and solar power profiles load for system/zone/node)				

Appendix F: [Template/Example] Concept Note and Statement of Work for a Renewable Energy Grid Integration Study (Production Cost Modeling Analysis)

Background:

[IMPLEMENTING ORGANIZATION/AGENCY(S)] seeks to support [COUNTRY/REGION] efforts to pursue long-term, transformative development and to accelerate sustainable, climate-resilient economic growth while slowing the increase of greenhouse gas emissions.

This work plan seeks to provide resources and guidance to support [COUNTRY/REGION] in addressing key challenges in integrating more variable renewable energy into the grid. A grid integration study for [COUNTRY/REGION] is a key element in strengthening the capacity of policymakers and system planners/operators to address the constraints for integrating more variable renewable energy (VRE) into the grid.

[OTHER RELEVANT BACKGROUND INFORMATION]

Purpose:

Support key power system stakeholders in [COUNTRY/REGION] in evaluating the impacts of integrating significant levels of VRE to the grid and assess actions that can cost-effectively improve the integration of these VRE sources into the grid. This goal will be achieved through a grid integration study,[4] which will identify potential grid reliability concerns with the scaling of VRE, and identify options to improve system flexibility and balance the power system at all hours throughout the year. This study will likewise inform [COUNTRY/REGION GOVERNMENT] in setting new VRE installation targets and in identifying system operations changes.

[IMPLEMENTING ORGANIZATION(S)] will work jointly with [STUDY CHAIR(S) OR COMMISSIONER] to: (1) develop and validate a production cost model, (2) identify the potential for VRE capacity expansion, (3) run several VRE scenarios, and (4) evaluate the cost impacts of integrating VRE (e.g., changes to dispatch rules, improvements in forecasting). The production cost modeling activities will draw from and complement existing modeling capabilities at [COUNTRY/REGION SYSTEM OPERATOR] and elsewhere (e.g., transmission load flow analyses), and will seek to build internal capacity to continue this work. The development of high-resolution production cost modeling data sets required for this study will enable future studies to address optimal capacity (transmission/generation) expansion, detailed load flow analysis, and additional production cost model scenario simulations. Below is a summary of the expected output and benefits/actions.

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[4] Definitions: *Grid integration study:* Analysis of a set of scenarios and sensitivities that seek to inform the stakeholders on a particular question. For example, what is the impact of increased thermal generator cycling with the addition of renewable generation?
Scenario: A scenario is one possible future electric generation system. A typical grid integration study has 3-4 scenarios that parameterize the focus. For example, scenarios for understanding cycling impacts might vary by total renewable generation penetration or the ratio of solar to wind generation.
Sensitivities: A sensitivity is generally an alternative operational practice or the availability of a mitigation option, for example, changing the flexibility of load or hydro resources. A sensitivity is applied to all scenarios and the results are reported relative to the base case (and to scenarios without sensitivity options).

Table F- 1. Expected Outputs and Benefits

Expected Output	Benefits/Actions Enabled
Hourly system performance and economics, including renewable and traditional generation and interchange magnitude and direction.	• Systemwide market production values of various VRE expansion scenarios (e.g., VRE in best resource sites, RE in sites close to transmission lines) • Balancing needs • Investments needed in flexible generation and transmission infrastructure • Mechanism to access balancing resources (e.g., market changes, regulatory actions) • System operating costs, average cost of generation, impact on retail price • Transmission utilization • Estimation of GHG emissions avoided • Impacts on existing resources.

Study Focus:

The focus of the grid integration study will be the [GEOGRAPHIC AREA OR INTERCONNECTION(S) TO BE STUDIED].

Scope of Work:

Task 1. Engage Technical Review Committee

A critical program design element is the inclusion of a technical review committee (TRC) to be co-chaired by [STUDY CHAIR(S) and/or IMPLEMENTING ORGANIZATION]. The purpose of the TRC is to provide guidance on scenarios, methods, assumptions, and interpretation of results. The TRC may include stakeholders from across the power sector, such as: wind and solar data providers, system operators, distribution utilities, RE plant owners/operators/developers, conventional plant owners/operators/developers, transmission companies, regulators, and public advocates. The committee will be relatively balanced and reflect a cross-section of the power system industry and also include representation from experts with prior experience in conducting grid integration studies. The TRC is a critical component to ensure that the analysis is credible and actionable.

Table F- 2. Task 1 Activities

Activity	Lead Organization	Supporting Organizations	Suggested Time Frame
i. Organization of TRC	[STUDY CHAIR(S)]—to send a letter to other agencies and organizations requesting nominations of TRC members	[IMPLEMENTING ORGANIZATION(S)]—to draft terms of reference and invitation letters for the TRC members	1–3 months following study kick-off
ii. TRC meeting #1: Review overall study methodology; review draft reference case model; define high-RE scenarios and sensitivities to model	[IMPLEMENTING ORGANIZATION(S)]—to organize and conduct meeting and provide TRC members with advance reading	*TRC members*—to review advance reading materials and participate in the meeting	3–6 months following Activity 1a
iii. TRC meeting #2: Review draft results	[IMPLEMENTING ORGANIZATION(S)]–-to organize and conduct meeting and provide TRC members with advance reading	*TRC members*—to review advance reading materials and participate in the meeting	4–6 months following Activity 1b
iv. TRC meeting #3: Review final results and provide endorsement	[IMPLEMENTING ORGANIZATION(S)]—to organize and conduct meeting; [STUDY CHAIR(S) and IMPLEMENTING ORGANIZATION(S)]—to formally request and consolidate comments and field concurrence on grid integration study outputs	*TRC members*—to review and provide comments and concurrence on grid integration study outputs; to participate in the meeting	2–4 months following Activity 1c

Task 2: Develop Unit Commitment and Dispatch Model

This study will require robust data sets of wind, solar, and water resources and existing and future transmission, generation and load infrastructure. Data sets must be time synchronous to accurately represent the relationships between electricity generation and consumption. Once collected, data will provide inputs to a production cost model. The study will utilize the [PRODUCTION COST MODELING AND SIMULATION SOFTWARE].

2a. Establish the MWG

Target Participants: [IMPLEMENTING ORGANIZATION(s)] team and total of 3-5 modelers from energy agencies, system and market operators, regulators, and/or other key technical agencies that support electricity sector development.

Table F- 3. Task 2a Activities

Activity	Lead Organization	Supporting Organizations	Suggested Time Frame
i. Identify MWG participants	[STUDY CHAIR(S)]—to send a letter to other agencies requesting nominations of MWG members; and, if needed, to nominate MWG participants from [STUDY CHAIR(S) ORGANIZATION]	[IMPLEMENTING ORGANIZATION(S)]—to draft terms of reference and invitation letters for the MWG members [MWG ORGANIZATIONS]—to nominate MWG members from their organizations	1 month following study kickoff
ii. Secure letters of commitment	[STUDY CHAIR(S)]—to field letters of commitment from MWG members	*MWG members*—to provide letters of commitment	1 month following Activity 2a
iii. Provide description of responsibilities/work plan	[IMPLEMENTING ORGANIZATION(S)]—to draft work plan for MWG	*MWG members*—to review terms of reference and work plan	1 month following Activity 2a
iv. Provide basic software training	[IMPLEMENTING ORGANIZATION(S)]—to organize training	[IMPLEMENTING ORGANIZATIONS]—to procure training from [SOFTWARE VENDOR] [SOFTWARE VENDOR]—to conduct training [STUDY CHAIR(S)]—to work with [IMPLEMENTING ORGANIZATION(S)] to determine training dates and logistics *MWG members*—to participate in training	1-3 months following Activity 2c

2b. Develop Data Sets

Table F- 4. Task 2b Activities

Activity	Lead Organization	Supporting Organizations	Suggested Time Frame
i. Data gathering	[IMPLEMENTING ORGANIZATION(S)]—to work with [STUDY CHAIR(S)] to identify point(s) of contact; to provide data requirements; to request data from point/s of contact; to implement nondisclosure agreements if needed; and to identify alternatives if data is not available	[STUDY CHAIR(S)] *and other MWG members*—to work with [IMPLEMENTING ORGANIZATION(S)] to assemble and validate the data requested	3-6 months following Activity 2c
ii. Procurement of [MODELING SOFTWARE]	[IMPLEMENTING ORGANIZATION(S) or MWG MEMBERS]—to procure [MODELING SOFTWARE] licenses for use by MWG members		1–3 months following Activity 2c
iii. Input system data (load, generator characteristics, transmission) into [MODELING SOFTWARE]	[IMPLEMENTING ORGANIZATION(S)]—to consolidate and input system data into [MODELING SOFTWARE]	*MWG members*—to review data and validate data input in the [MODELING SOFTWARE] model as requested	1-2 months following Activity 2d
iv. Wind and solar profile development	[IMPLEMENTING ORGANIZATION(S)]—to procure or create wind and solar profiles and input them into [MODELING SOFTWARE]	*MWG members*—to review wind and solar inputs as requested	3 months following study kickoff

2c. Develop Scenarios

Table F- 5. Task 2c Activities

Activity	Lead Organization	Supporting Organizations	Suggested Time Frame
i. Develop and validate a reference case	*MWG (with final responsibility to* [IMPLEMENTING ORGANIZATION(S)]—to construct and validate a reference case system model in [MODELING SOFTWARE]	*TRC members*—to assist the MWG in developing reference case parameters; to review MWG's methods, data sources, assumptions, and other key issues, and offers suggestions when appropriate to strengthen the study	1-3 months following 2g
ii. Develop capacity expansion scenarios (including retiring and prescribed RE and conventional generators and transmission)	*MWG (with final responsibility to* [IMPLEMENTING ORGANIZATION(S)]*)*—to construct and validate capacity expansion scenarios in [MODELING SOFTWARE]	*TRC members*—to assist the MWG in developing capacity expansion parameters (objectives, scenarios, and sensitivities); to review MWG's methods, data sources, assumptions, and other key issues, and offers suggestions when appropriate to strengthen the study	1-3 months following Activity 2i
iii. Develop alternative RE scenarios and implement in models	*MWG (with final responsibility to* [IMPLEMENTING ORGANIZATION(S)]*)*—to construct and validate RE scenarios in [MODELING SOFTWARE]	*TRC members*—to assist the MWG in developing RE scenario parameters (objectives, scenarios, and sensitivities); to review MWG's methods, data sources, assumptions, and other key issues, and offers suggestions when appropriate to strengthen the study	2–4 months following Activity 2i

2d: Conduct Sensitivity Analyses

Table F- 6. Task 2d Activities

Activity	Lead Organization	Supporting Organizations	Suggested Time Frame
i. Develop and run sensitivity analyses in the model	*MWG (with final responsibility to* [IMPLEMENTING ORGANIZATION(S)])—to develop, run, and validate sensitivity analyses in [MODELING SOFTWARE]	*TRC members*—to assist the MWG in developing RE sensitivities; to review MWG's methods, data sources, assumptions, and other key issues, and offers suggestions when appropriate to strengthen the study	1-3 months following Activity 2k
ii. Validate outputs	*TRC members*—to review and validate results of sensitivity analysis; to help interpret modeling results	[IMPLEMENTING ORGANIZATION(S)])—to provide results of sensitivity analysis and field comments from the TRC	1 month following Activity 2l

Task 3: Analyze and Communicate Results

Table F- 7. Task 3 Activities

Activity	Lead Organization	Supporting Organizations	Suggested Time Frame
i. Analyze and synthesize modeling results	MWG (with final responsibility to [IMPLEMENTING ORGANIZATION(S)])—to analyze, synthesize, and verify modeling results		Throughout, beginning with Activity 2i
ii. Prepare a high-level summary	[IMPLEMENTING ORGANIZATION(S)]—to draft high-level results summary and field comments; to finalize and disseminate final document	*MWG members*—to review high-level summary and provide inputs as requested	1–4 months following Activity 2m
iii. Integration study report finalization	MWG (with final responsibility to [IMPLEMENTING ORGANIZATION(S)])—to incorporate TRC comments, finalize technical documents, and disseminate findings and methodologies	[STUDY CHAIR(S)]—to provide concurrence on final report; to work with [IMPLEMENTING ORGANIZATION(S)] to disseminate final report *TRC members*—to provide concurrence on final report; to link model outcomes with policy and regulatory processes	1-4 months following Activity 2m
iv. Journal article drafting and submission	[IMPLEMENTING ORGANIZATION(S)]—to draft and submit journal article	*MWG and TRC*—to contribute and review as needed	1-3 months following Activity 3c

Task 4. RE Roadmap and Target Setting/Revision

Table F- 8. Task 4 Activities

Activity	Lead Organization	Supporting Organizations	Suggested Time Frame
i. Integration Action Roadmap—conduct initial workshop to allow stakeholders to prioritize actions	[IMPLEMENTING ORGANIZATION(S)]—to organize and conduct workshop (possibly in conjunction with final integration study workshop); to provide TRC members with advance reading	*TRC members*—to review advance reading materials and participate in the workshop	1-2 months following Activity 3c
ii. Action Roadmap and Implementation Plan—detailed roadmapping to achieve specific actions	[IMPLEMENTING ORGANIZATION(S)]—to draft Action Roadmap and Implementation Plan and circulate to TRC members for review	*TRC members*—review and provide feedback and concurrence on Action Roadmap and Implementation Plan	2-4 months following Activity 4a
iii. RE Target Setting, National RE Plan and Power System Planning support to DOE	[IMPLEMENTING ORGANIZATION(S)]—to provide assistance as requested by the [STUDY CHAIR(S)]	[STUDY CHAIR(S)]—to request assistance as needed from [IMPLEMENTING ORGANIZATIONS]	As needed following Activity 4b

Table F- 9. Time Frame

	1-3 months	3-6 months	6-9 months	9-12 months	12-15 months	15-18 months
Engage TRC						
Develop model	Establish MWG Wind and solar profile development	Software training and procurement Data gathering Reference case model development Wind and solar profile development	Reference case model execution Capacity expansion scenario execution High RE scenario execution	High RE scenario execution Sensitivity analysis Validation	Validation	
Communicate Results					Report writing	
RE Roadmap						Roadmap

Data needs for production cost modeling:

[*Please refer to Appendix E]*

The specific location, security, and format of the data will be established in agreement with [STUDY CHAIRS].

Computer system requirements for [MODELING SOFTWARE]:

[MODELING SOFTWARE] is a commercial software package produced and distributed by [SOFTWARE VENDOR]. Software downloads and licensing, and additional software information are available from [SOFTWARE VENDOR]. The basic computer configuration required to execute production cost model simulations using [MODELING SOFTWARE] are as follows: [MODELING SOFTWARE REQUIREMENTS]

Written by Jessica Katz and Ilya Chernyakhovskiy, National Renewable Energy Laboratory

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Jeremy Foster
U.S. Agency for International Development
Email: jfoster@usaid.gov

Sarah Lawson
U.S. Agency for International Development
Email: slawson@usaid.gov

Ilya Chernyakhovskiy
National Renewable Energy Laboratory
Email: ilya.chernyakhovskiy@nrel.gov

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