# [**Variable Renewable Energy Grid Integration Studies: A Guidebook for Practitioners**](https://www.nrel.gov/docs/fy20osti/72143.pdf)

# **Guidebook Draft Summary**

# **<Page 1> Introduction**

## Introduction

Countries worldwide are increasing their use of renewable energy (RE) to meet energy demands, but this requires changes in power system planning and operation due to the variability and uncertainty of renewable energy resources like wind and solar. To prepare for this transition, power system stakeholders can conduct a grid integration study, which examines challenges and potential solutions for integrating significant variable renewable energy (VRE) generation into the electricity grid. This guidebook aims to introduce policymakers, regulators, operators, and supporting organizations to VRE grid integration studies.

## What Is Variable Renewable Energy?

Variable renewable energy (VRE): electricity generation technologies whose primary energy source varies over time and cannot easily be stored. VRE sources include solar, wind, ocean, and some hydropower generation technologies.

*Source*: <https://www.nrel.gov/docs/fy15osti/63033.pdf>

## How to Use this Guidebook

This guidebook offers a concise and thorough overview of the strategies, best practices, and terminology involved in conducting a high-quality VRE grid integration study, with a focus on considerations relevant to developing economies. As wind and solar power become increasingly prevalent globally, it is important to understand the key steps, modeling tools, and data collection activities necessary for successful integration of these VRE resources into power systems. While the guidebook does not provide exhaustive guidance on system-specific analyses, it does include a toolkit with links to additional resources, recommendations for topic-specific actions, and real-world examples from grid integration studies.

*Source guidebook*: <https://www.nrel.gov/docs/fy20osti/72143.pdf>

# **<Page 2> What is a Grid Integration Study?**

A grid integration study provides an analytical framework for power system stakeholders to evaluate a power system with high levels of variable renewable energy (VRE) such as wind and solar. Grid integration studies can be undertaken by various organizations, including power sector regulatory commissions, energy ministries, power system operators, and research organizations. The primary goal of a grid integration study is to address concerns about whether a power system can operate reliably and cost-effectively under high renewable energy (RE) scenarios. Such studies can identify future generation and transmission portfolios to achieve RE targets, simulate power system operation under different scenarios, identify reliability constraints, and determine the cost of integrating high levels of VRE. It is important to note that a grid integration study is not the same as a grid impact or grid connection study, which focus on the technical feasibility of interconnecting a single wind or solar power plant.

## When to Conduct a Grid Integration Study

A grid integration study is a substantial undertaking that can take several months to a few years to complete. It is important to consider the following questions and factors to ensure that investing the necessary time and resources yield a relevant, high-quality product:

* **Potential to inform decision making**: How effectively will a grid integration study address the primary questions and concerns that stakeholders have regarding the integration of VRE into the power grid?
* **Data availability**: Are high-quality wind and solar resource data, as well as detailed information about the power system, readily available for the type of analyses being considered?
* **Stakeholder convening mechanism**: Is there a convening authority and willingness among key energy sector stakeholders to actively participate in the grid integration study process, such as joining a technical review committee (TRC)?
* **Modeling staff capacity**: Do trained modelers have the necessary mandate and funding within their professional roles to conduct the analyses required for a grid integration study, and are they available?
* **Tool availability**: What commercially available or internally developed software tools are available to address the primary questions of interest in a grid integration study, and what is the estimated time and resources required to develop the necessary tools?

If critical elements are missing, it may be more effective to invest in filling the gaps before conducting a grid integration study. There are several actions that power systems stakeholders can take to integrate significant VRE generation without a full study, such as implementing wind and solar power forecasting, aggregating output over large regions, and enabling plants to provide ancillary services. While there is no one-size-fits-all approach to grid integration, these approaches can be adapted to fit the specific needs and characteristics of a power system, and can be implemented alongside efforts to conduct a grid integration study.

# **<Page 3> Types of Grid Integration Analyses**

Grid integration studies are tailored to address specific concerns relevant to a given power system and involve modeling using one or more of three categories: capacity expansion, production cost, and power flow. While a best-in-class grid integration study uses all three types of analyses, many studies focus only on one or two methods. The choice of which analysis or combination of analyses to implement depends on the policy-relevant questions that best address a country's priorities.

***Figure 1***

## Capacity Expansion Analysis

Capacity expansion analyses are conducted to determine optimal generation and transmission resources to provide reliable electricity at the lowest cost. A capacity expansion analysis serves as the foundation for a power sector master plan or integrated resource plan, utilizing models that optimize the least-cost generation and transmission capacity mix. Capacity expansion analyses are utilized to identify the appropriate type, amount, timing, and location of solar and wind generation capacity required to meet renewable energy (RE) or other policy targets. For example, a capacity expansion analysis can assess systemwide capital costs and identify cost-effective installed capacity and locations for variable renewable energy (VRE).

| **Modeling Horizon** | * Medium to long-term (i.e. 20-50 years) |
| --- | --- |
| **Temporal Resolution** | * Annual for each year within the modeling horizon, with representation of seasonal and reduced-form intraday constraints |
| **Key Inputs** | * High spatial resolution RE data * Annual electricity demand & projections * Capital costs of generation technologies * Fuel price projections * Generation and transmission investment constraints * Operational constraints |
| **Example Questions Addressed** | * Where, when, how much, and what types of infrastructure would achieve VRE targets at least cost? * How will factors such as new policies, technological advancement, and electricity demand growth affect planning for generation and transmission infrastructure in the future? * How will different VRE penetration scenarios impact economic development indicators? |

***Table 1***: Characteristics of a capacity expansion analysis and example questions addressed.

## Production Cost Flow Analysis

Production cost analyses evaluate the effects of one or more VRE penetration scenarios on power scheduling and economic dispatch, with the goal of minimizing operational costs of different future scenarios. A production cost analysis can be used to evaluate the feasibility of high RE penetrations from an operational perspective and test institutional and physical options for improving system flexibility.

| **Modeling Horizon** | * One future year (i.e. 10-20 years in the future) |
| --- | --- |
| **Temporal Resolution** | * Hourly to sub-hourly unit commitment or dispatch intervals |
| **Key Inputs** | * Time-synchronous demand and RE generation data * Detailed system characteristics (i.e. generator ramping, fuel and other operational costs, transmission system attributes, and emissions restrictions) |
| **Example Questions Addressed** | * What are the impacts of VRE penetration scenarios on bulk power scheduling and economic dispatch? * What are the expected VRE curtailment levels, GHG emissions, generator ramps, plant load factors, reserve requirements, transmission constraints, and other generator-level impacts under different VRE scenarios? * What are the relative systemwide operating impacts associated with different VRE expansion scenarios? |

***Table 2***: Characteristics of a production cost flow analysis and example questions addressed.

## Power Flow Analysis

Power flow analyses test the stability of the transmission system under different RE penetration scenarios. Power flow analyses model real and reactive power flow, fault tolerance, and frequency response over short periods of system stress. A power flow analysis can inform system operators about mitigation measures to keep system voltage and frequency within reliability parameters, or determine whether different renewable energy deployment scenarios meet grid code requirements.

| **Modeling Horizon** | * Several minutes, corresponding to periods of system stress |
| --- | --- |
| **Temporal Resolution** | * Second to minutes |
| **Key Inputs** | * Renewable energy generation profiles at discrete sites * Details about generators’ ability to respond to contingencies, transmission line impedances, transformer details, and tap settings |
| **Example Questions Addressed** | * How do high penetrations of wind and solar impact the transient stability and frequency response of the electric power system? * Can the power system sustain and recover from temporary and significant disturbances and with high levels of nonsynchronous generation? * What is the expected system recovery time under various variable RE deployment scenarios? |

***Table 3***: Characteristics of a power flow analysis and example questions addressed.

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# **<Page 4> Components of a Grid Integration Study**

There are five main components of a grid integration study: 1) stakeholder engagement, 2) data collection, 3) scenario development, 4) power system modeling, and 5) analysis and reporting.

***Figure 2***

## Stakeholder Engagement

Engaging a diverse group of stakeholders in a grid integration study can contribute to a comprehensive, relevant, and actionable planning process that reflects the concerns of both industry and policymakers. Key stakeholders involved in a grid integration study include government agencies, power system operators, electricity regulators, utilities, transmission providers, data providers, renewable energy (RE) plant operators and developers, academic researchers, and public advocates.

The two main mechanisms for engaging stakeholders in a grid integration study are technical review committees (TRC) and modeling working groups (MWG). A TRC is a group of decision-makers from various organizations that provide expert technical expertise and direction throughout a grid integration study. Specifically, a TRC helps to link industry and policy concerns to deepen understanding of high-penetration RE issues and solutions. On the other hand, a MWG is a technical team that conducts analytical and modeling activities for a grid integration study.

To build a stakeholder-driven grid integration study, the study leadership team can determine which organizations should be represented in the TRC and MWG, facilitate TRC and MWG meetings, and establish transparent lines of communication and documentation processes for both the TRC and MWG.

For more information on establishing a stakeholder-driven process, check out the links below:

* [Department Circular for Philippines Grid Integration Study](https://www.doe.gov.ph/sites/default/files/pdf/issuances/dc_2015-11-0017.pdf?withshield=1)
* [Principles for Technical Review Committee (TRC) Involvement in Studies of Wind Integration into Electric Power Systems](https://www.uvig.org/)

## Data Collection

In order to conduct a robust grid integration study, it is crucial to obtain high-quality data, which involves developing wind and solar resource profiles. At a minimum, grid integration analyses require one year of RE resource data for locations under consideration for wind or solar generation. High spatial and temporal resolutions can capture the variability of wind and solar generation and facilitate modeling integration impacts and solutions. Accurate system data on electricity generation, demand, and transmission grid characteristics are also essential for model development. Data collection may require a substantial time investment, so it is important to ensure data collection begins well in advance of modeling activities. Data for a grid integration study can come from various sources such as system operators, energy ministries, electricity regulators, and commercial vendors. The table below provides a general overview of data requirements for each type of grid integration analysis:

|  | **Capacity Expansion** | **Production Cost** | **Power Flow** |
| --- | --- | --- | --- |
| **RE Resource Data** | Average or typical  meteorological year (TMY)2 | Operational time-series for full modeling horizon; archive forecast and forecast error (optional) | Operational time series for full modeling horizon |
| **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 | | |

***Table 4***: General data needs for capacity expansion, production cost, and power flow analyses.

Best data collection practices for the study leadership team involve generating a data requirements list, evaluating available resource data, determining if a nondisclosure agreement is needed, and working with the MWG to facilitate data management.

Follow the links below to check out some additional information on data requirements and access publicly available wind and solar datasets used in grid integration studies:

* [Grid Integration Studies: Data Requirements Fact Sheet](https://www.nrel.gov/docs/fy15osti/63043.pdf)
* [International Energy Agency’s Expert Group Report on Recommended Practices (16 Wind Integration Studies)](https://community.ieawind.org/viewdocument/task-25-recommended-practice16-win)
* [Meteorological Data for RES-E Integration Studies: State of the Art Review](https://publications.jrc.ec.europa.eu/repository/)
* [National Solar Radiation Database](https://nsrdb.nrel.gov/)
* [Renewable Energy Data Explorer](https://www.re-explorer.org/re-data-explorer/subscribe)
* [The Eastern Wind Integration Data Set and Western Wind Integration Data Set](https://www.nrel.gov/grid/eastern-western-wind-data.html)
* [Solar Power Data for Integration Studies](https://www.nrel.gov/grid/solar-power-data.html)

## Scenario Development

Scenarios represent possible future electric generation systems and provide insights into how different options for the future power generation fleet, transmission network, and operational practices affect least-cost power system development and operations. Developing scenarios is a critical early activity in a grid integration study, incorporating input from the TRC to ensure scenarios reflect important questions for power system stakeholders. Grid integration studies examine the following types of scenarios:

* **The reference scenario**: The reference scenario, which is crucial for validating a grid integration model, focuses on the current power system. The reference scenario is particularly useful for the production cost and power flow modeling phases.
* **The base or business-as-usual (BAU) scenario**: A BAU scenario assumes that policies and operational practices will remain relatively unchanged with respect to their treatment of VRE. BAU scenarios can be used as a starting point for defining transmission and generation capacity additions. The BAU scenario includes minimal new wind or solar generation relative to the reference case.
* **High-RE Scenarios**: High-RE scenarios include higher levels of wind and/ or solar generation relative to the BAU scenario.

Sensitivity analyses can also enhance grid integration studies.

## Power System Modeling

## Analysis and Reporting

## Cost of Conducting a Grid Integration Study

# **<Page 5> From Study to Roadmap Creation: Using the Results of a Grid Integration Study**

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