Grid Integration Challenges: Best Practices in Conducting Grid Integration Studies

Jessica Katz, Clayton Barrows, Jaquelin Cochran
National Renewable Energy Laboratory

December 8, 2015

Overview

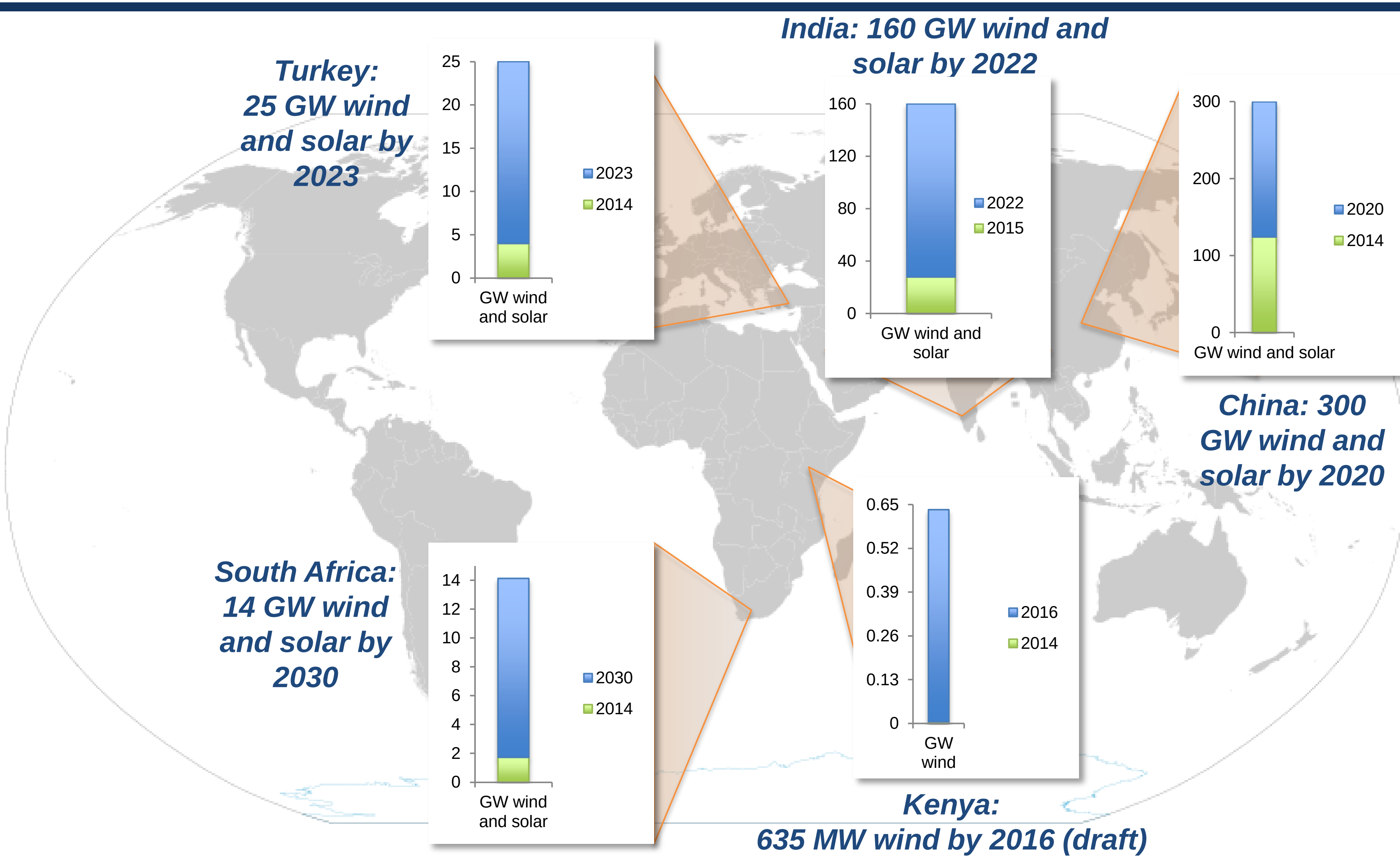
- **Why conduct a grid integration study?**
  - *Grid integration studies represent the analytical basis for determining system-specific grid integration challenges and potential mitigation actions.*
  - *These studies give stakeholders the confidence they need to implement grid integration actions.*

- **What can a grid integration study address?**
  - *Integration studies are tailored to the specific questions a given power system wants to answer.*

- **What is the process for conducting a grid integration study?**
  - *Modeling is important, but needs to be informed by stakeholder engagement and high-quality data.*

WHY CONDUCT A GRID INTEGRATION STUDY?

Motivation: ambitious renewable energy (RE) targets will add significant wind and solar to the grid



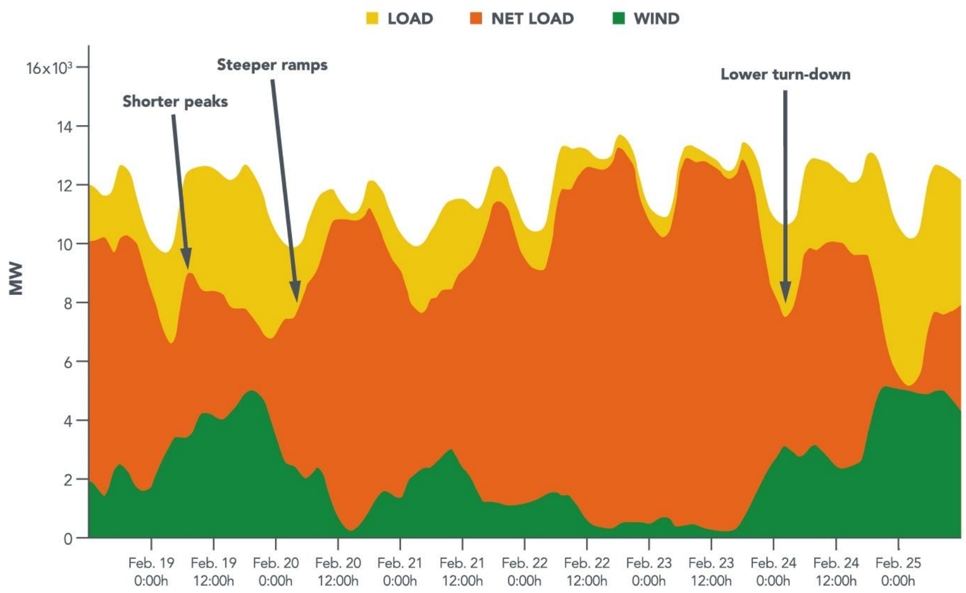
CLEAN ENERGY SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY

Source: Bloomberg New Energy Finance country profiles, accessed September 2015

Review: operational issues associated with variable renewable energy

RE is variable, uncertain, and geographically dispersed

…raising new considerations for grid planning and operations



1. Balancing requires more flexibility
2. Existing thermal assets used less frequently, affecting cost recovery
3. More reserves
4. More transmission, better planning needed
5. Voltage control, inertia response come at added cost

Review: the importance of flexibility in systems with high variable RE penetrations

Due to increased variability and uncertainty, current operational practices may not be adequate to efficiently manage high penetration levels of RE

- **Low variable RE penetrations:** Most systems sufficiently flexible*
- **Medium variable RE penetrations**: Likely least-cost source of flexibility is to change how the system is operated (institutional measures)
- **High variable RE penetrations:** Might need new physical sources of flexibility

"Low," "medium," and "high" are power system-specific thresholds

**Flexibility* refers the ability of the power system to respond to change in demand and supply

How will variable RE impact a specific power system?

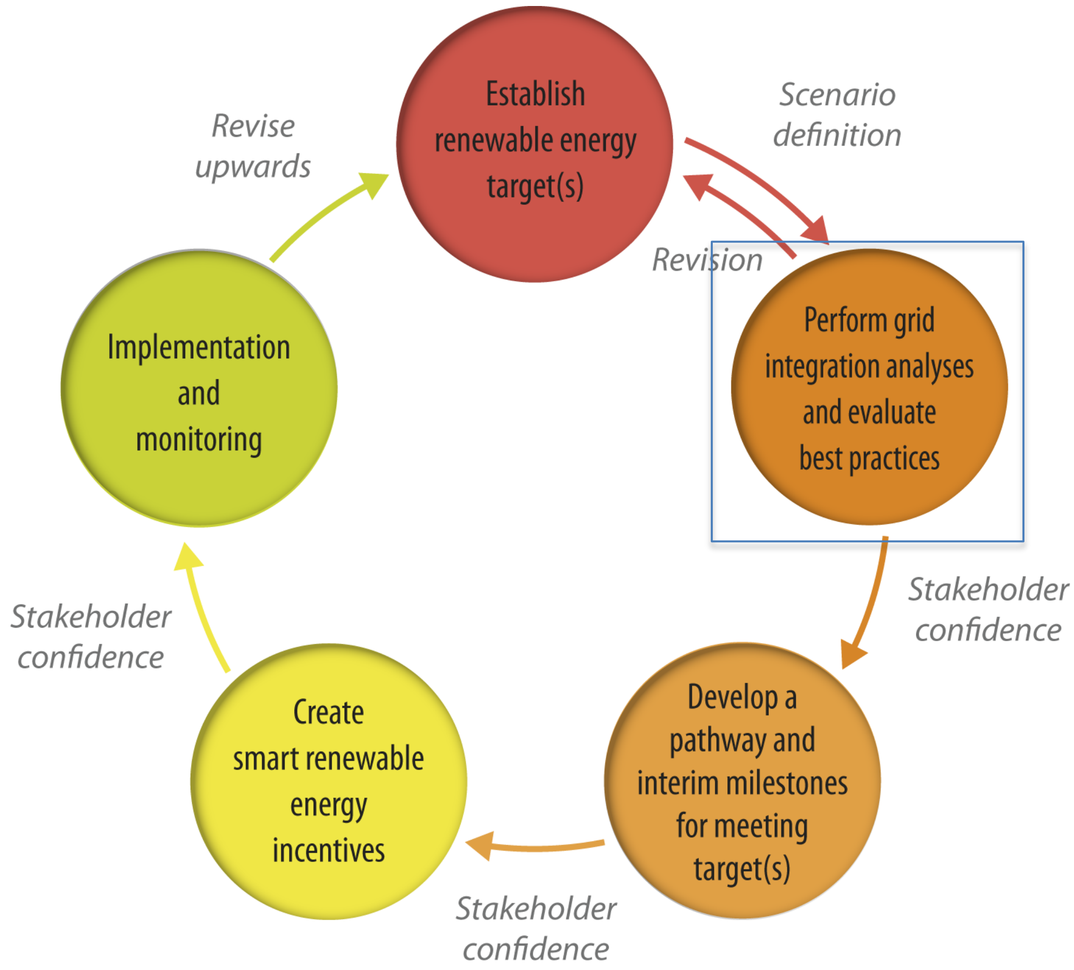
A ***grid integration study*** is an analytical framework for evaluating a power system with high levels of variable RE.

Outcomes

- Simulates operation of the power system under different future scenarios.
- Identifies reliability constraints.
- Determines relative costs of actions to help integrate RE.
- Addresses system operator concerns that the system can work reliably and cost-effectively.

Note: grid integration study ≠ grid impact study

Grid integration studies are critical to meeting (and exceeding) RE targets



Source: Greening the Grid *Scaling Up Renewable Energy Generation: Aligning Targets and Incentives with Grid Integration Considerations*

Example: Integration studies have helped inform California's RE targets

Year Passed	RE Generation Target	Integration studies to meet target
2002	20% by 2017	
2003	20% by 2010	California ISO (2007, 2010)
2011	33% by 2020	California ISO (2011)
2015	50% by 2030	E3 (2014)

Key Findings:

- Strong stakeholder engagement is key to building confidence in the conclusions of the studies.
- System operators have been creative in solving challenges to meet each interim target.

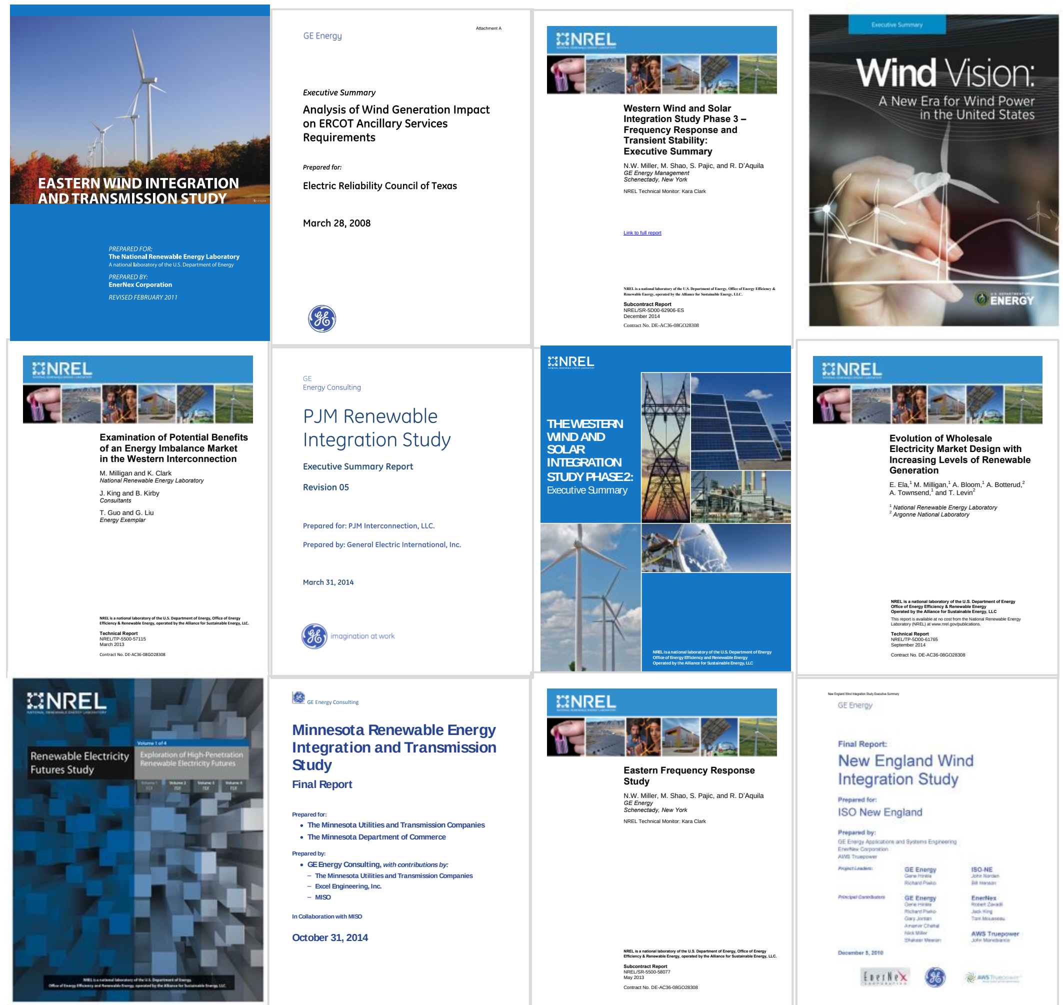
WHAT CAN A GRID INTEGRATION STUDY ADDRESS?

No two grid integration studies look alike—each study is customized to investigate a particular concern

Impacts of high RE on:

- Capacity expansion—generation and transmission
- Hourly system balancing, costs, emissions
- Operations at sub-hourly timeframes
  - Ancillary services
  - Cycling impacts on thermal fleet
- Grid stability following a disturbance
- Market design

Study examples

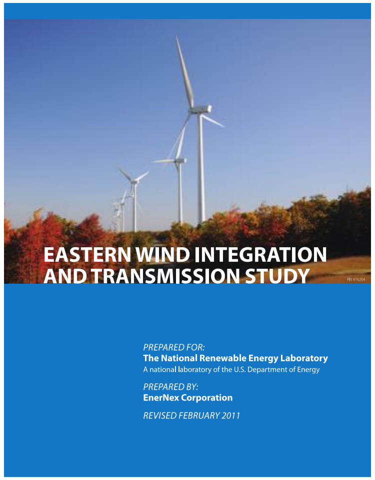


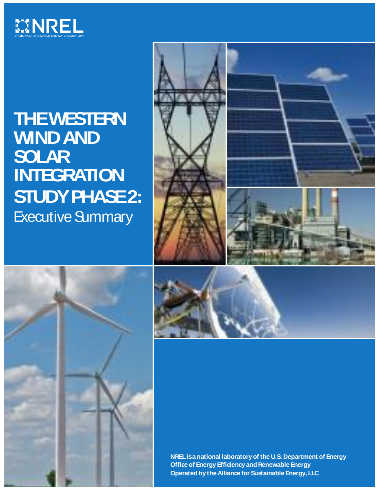
No two grid integration studies look alike—each study is customized to investigate a particular concern

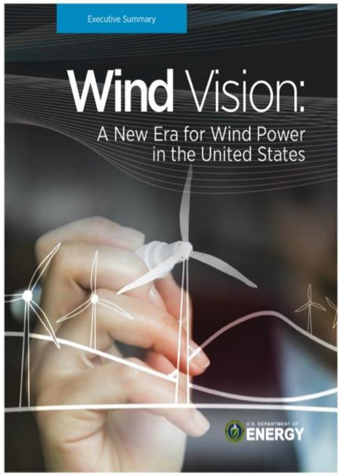
Impacts of high RE on:

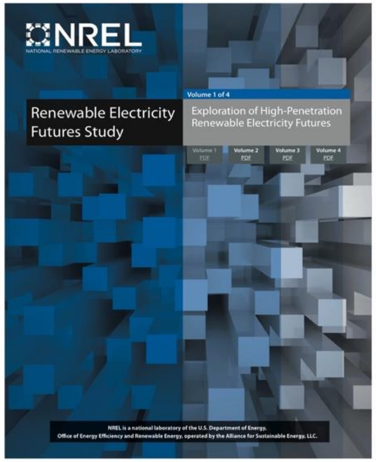
- Capacity expansion—generation and transmission
- Hourly system balancing, costs, emissions
- Operations at sub-hourly timeframes
  - Ancillary services
  - Cycling impacts on thermal fleet
- Grid stability following a disturbance
- Market design

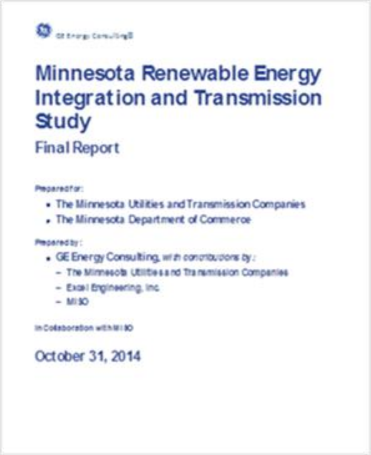
Study examples

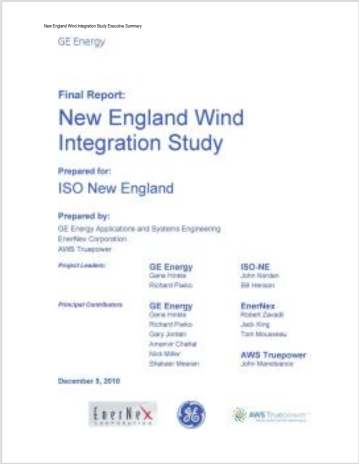










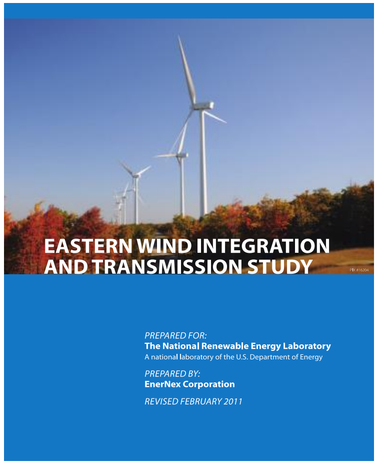


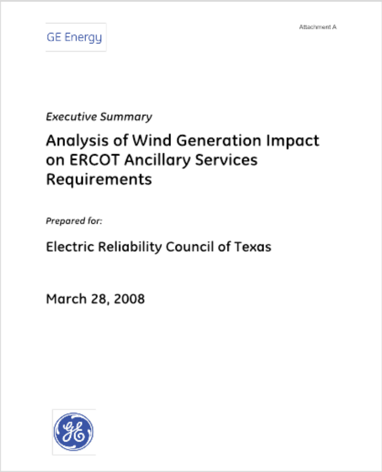
No two grid integration studies look alike—each study is customized to investigate a particular concern

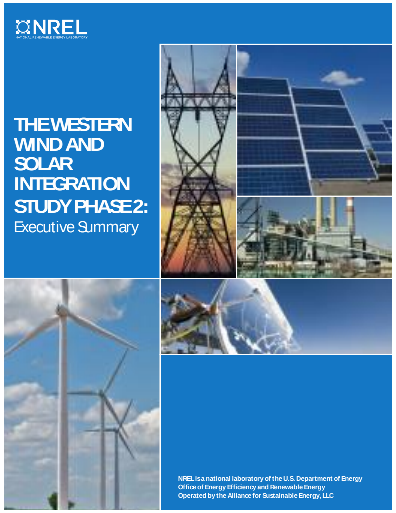
Impacts of high RE on:

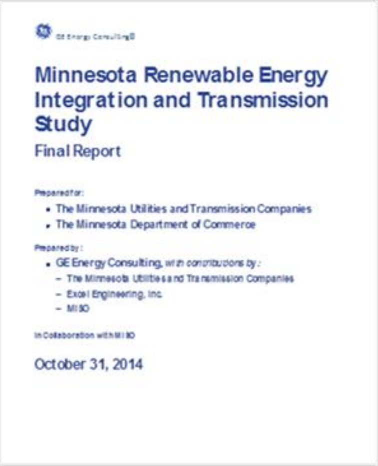
- Capacity expansion—generation and transmission
- Hourly system balancing, costs, emissions
- Operations at sub-hourly timeframes
  - Ancillary services
  - Cycling impacts on thermal fleet
- Grid stability following a disturbance
- Market design

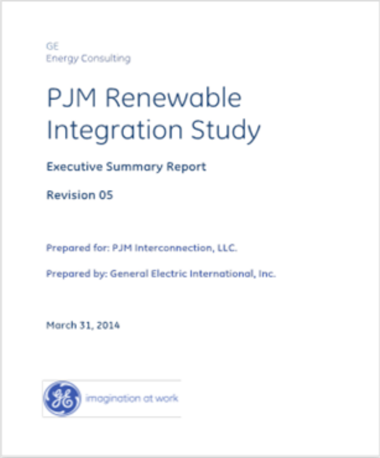
Study examples

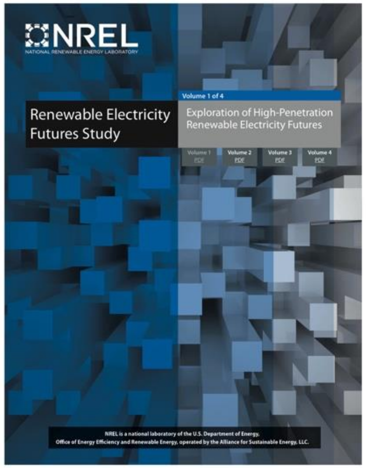












No two grid integration studies look alike—each study is customized to investigate a particular concern

Impacts of high RE on:

- Capacity expansion—generation and transmission
- Hourly system balancing, costs, emissions
- Operations at sub-hourly timeframes
  - Ancillary services
  - Cycling impacts on thermal fleet
- Grid stability following a disturbance
- Market design

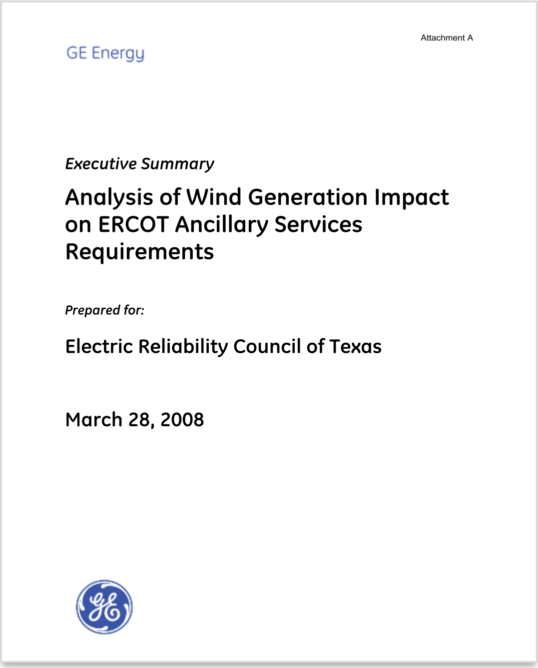
Study examples

No two grid integration studies look alike—each study is customized to investigate a particular concern

Impacts of high RE on:

- Capacity expansion—generation and transmission
- Hourly system balancing, costs, emissions
- Operations at sub-hourly timeframes
  - Ancillary services
  - Cycling impacts on thermal fleet
- Grid stability following a disturbance
- Market design

Study examples


Attachment A

GE Energy

Executive Summary

Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements

Prepared for:

Electric Reliability Council of Texas

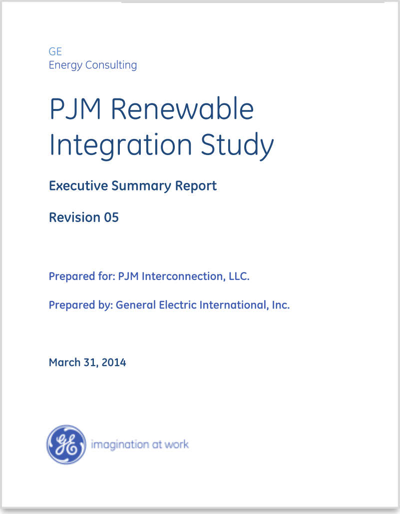
March 28, 2008

No two grid integration studies look alike—each study is customized to investigate a particular concern

Impacts of high RE on:

- Capacity expansion—generation and transmission
- Hourly system balancing, costs, emissions
- Operations at sub-hourly timeframes
  - Ancillary services
  - Cycling impacts on thermal fleet
- Grid stability following a disturbance
- Market design

Study examples


GE
Energy Consulting

PJM Renewable Integration Study

Executive Summary Report

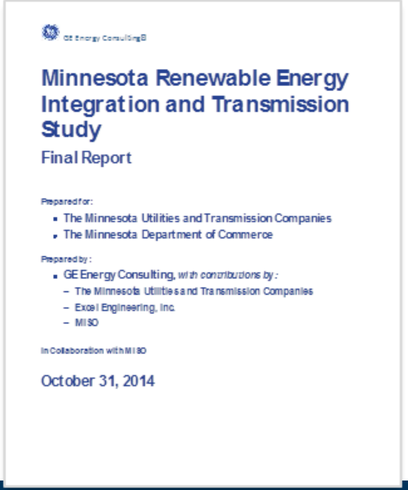
Revision 05

Prepared for: PJM Interconnection, LLC.

Prepared by: General Electric International, Inc.

March 31, 2014

imagination at work


GE Energy Consulting

Minnesota Renewable Energy Integration and Transmission Study

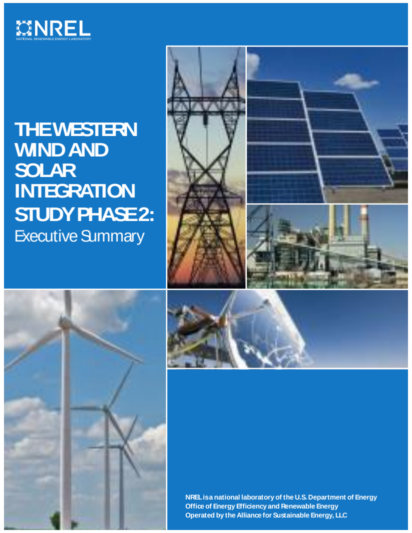
Final Report

Prepared for:
- The Minnesota Utilities and Transmission Companies
- The Minnesota Department of Commerce

Prepared by:
- GE Energy Consulting, with contributions by:
  - The Minnesota Utilities and Transmission Companies
  - Excel Engineering, Inc.
  - MISO

In Collaboration with MISO

October 31, 2014


NREL

THE WESTERN WIND AND SOLAR INTEGRATION STUDY PHASE 2: Executive Summary

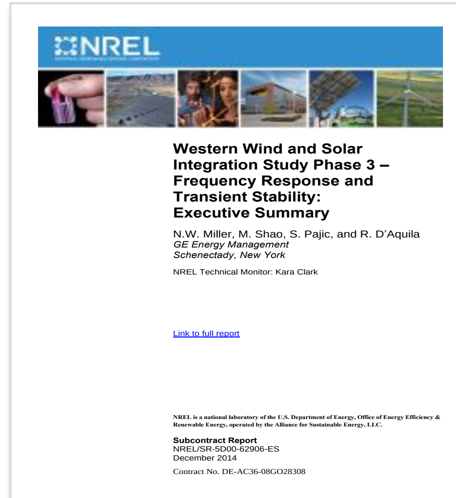
NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

No two grid integration studies look alike—each study is customized to investigate a particular concern

Impacts of high RE on:

- Capacity expansion—generation and transmission
- Hourly system balancing, costs, emissions
- Operations at sub-hourly timeframes
  - Ancillary services
  - Cycling impacts on thermal fleet
- Grid stability following a disturbance
- Market design

Study examples


NREL

Western Wind and Solar Integration Study Phase 3 – Frequency Response and Transient Stability: Executive Summary

N.W. Miller, M. Shao, S. Pajic, and R. D'Aquila
GE Energy Management
Schenectady, New York

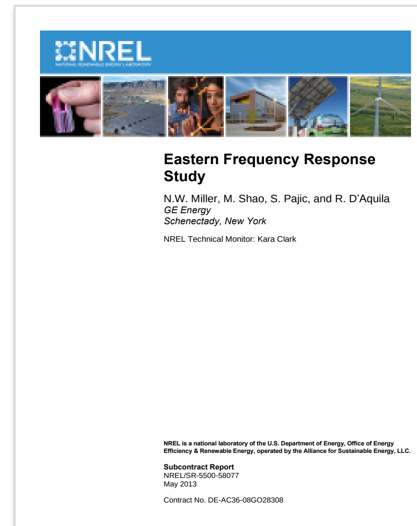
NREL Technical Monitor: Kara Clark

Link to full report

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Subcontract Report
NREL/SR-5D00-62906-ES
December 2014

Contract No. DE-AC36-08GO28308


NREL

Eastern Frequency Response Study

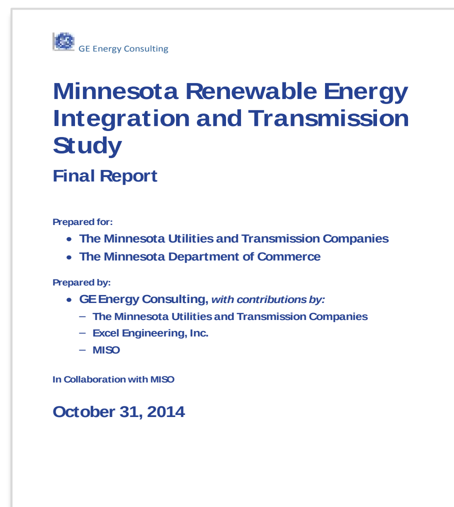
N.W. Miller, M. Shao, S. Pajic, and R. D'Aquila
GE Energy
Schenectady, New York

NREL Technical Monitor: Kara Clark

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Subcontract Report
NREL/SR-5500-58077
May 2013

Contract No. DE-AC36-08GO28308


GE Energy Consulting

Minnesota Renewable Energy Integration and Transmission Study

Final Report

Prepared for:
- The Minnesota Utilities and Transmission Companies
- The Minnesota Department of Commerce

Prepared by:
- GE Energy Consulting, *with contributions by:*
  - The Minnesota Utilities and Transmission Companies
  - Excel Engineering, Inc.
  - MISO

In Collaboration with MISO

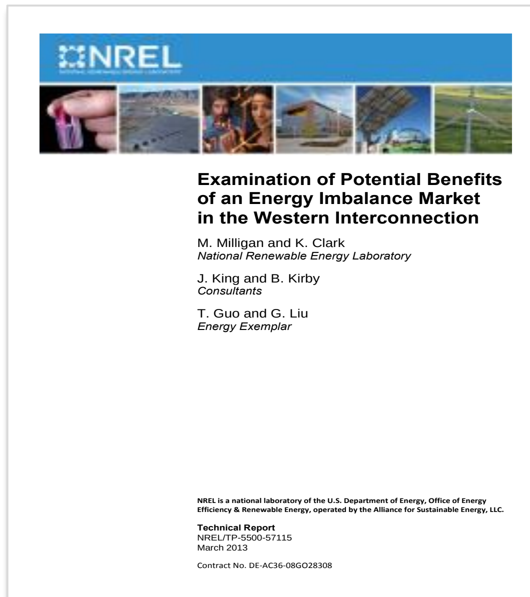
October 31, 2014

No two grid integration studies look alike—each study is customized to investigate a particular concern

Impacts of high RE on:

- Capacity expansion—generation and transmission
- Hourly system balancing, costs, emissions
- Operations at sub-hourly timeframes
  - Ancillary services
  - Cycling impacts on thermal fleet
- Grid stability following a disturbance
- Market design

Study examples


NREL

Examination of Potential Benefits of an Energy Imbalance Market in the Western Interconnection

M. Milligan and K. Clark
National Renewable Energy Laboratory

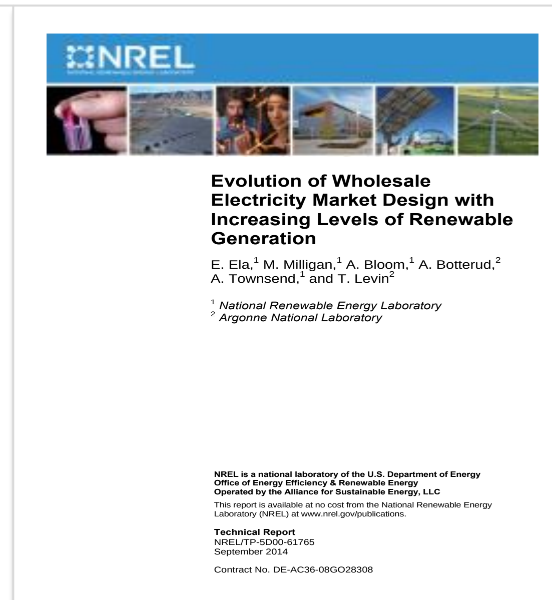
J. King and B. Kirby
Consultants

T. Guo and G. Liu
Energy Exemplar

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5500-57115
March 2013

Contract No. DE-AC36-08GO28308


NREL

Evolution of Wholesale Electricity Market Design with Increasing Levels of Renewable Generation

E. Ela,[1] M. Milligan,[1] A. Bloom,[1] A. Botterud,[2] A. Townsend,[1] and T. Levin[2]

[1] *National Renewable Energy Laboratory*
[2] *Argonne National Laboratory*

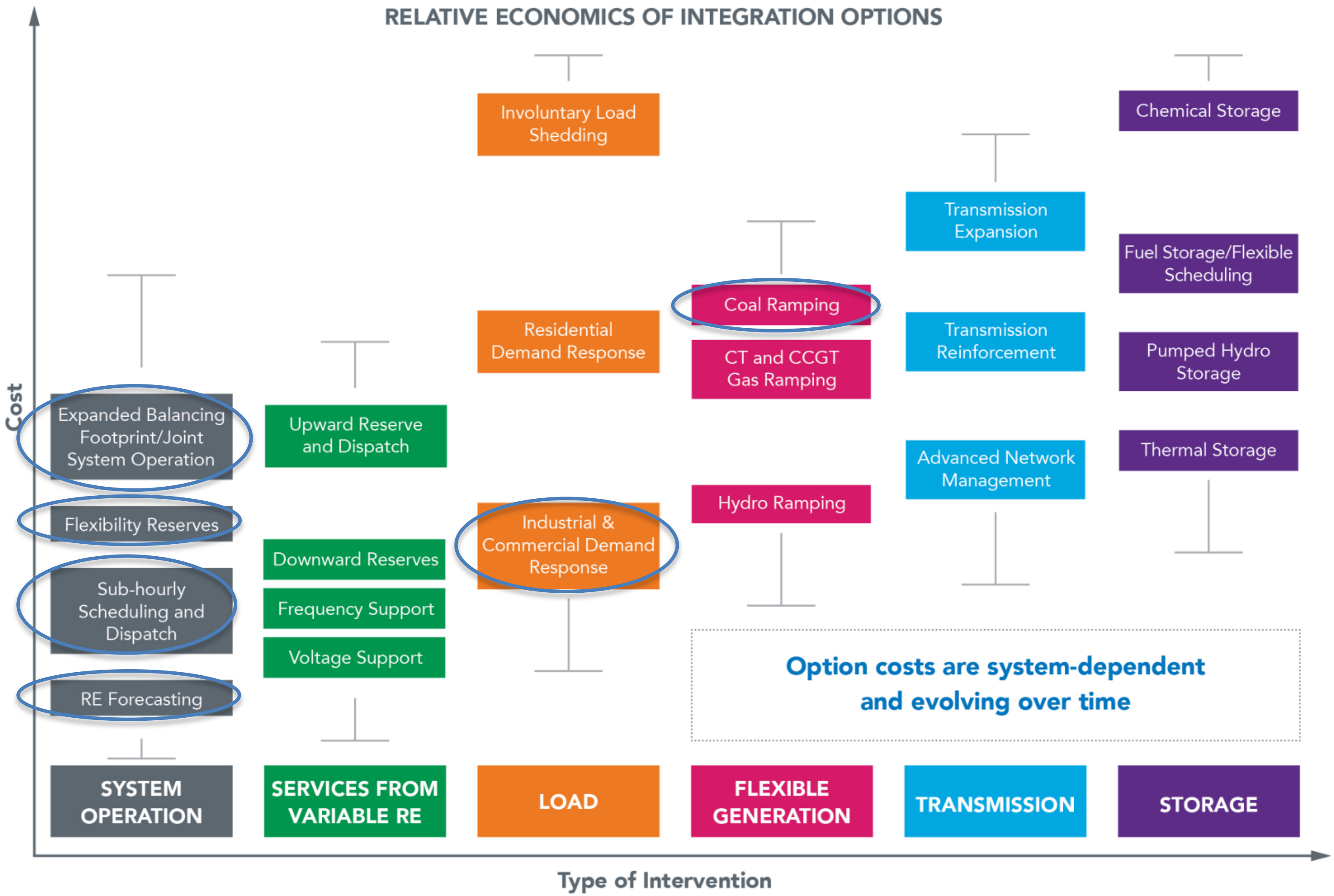
NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-5D00-61765
September 2014

Contract No. DE-AC36-08GO28308

A grid integration study can show relative costs of integration options



Source: Cochran et al. (2014). *Flexibility in 21st Century Power Systems*

Integrating RE through informed policy

Enablers

- Implement known effective solutions
- Collect data
- Build modeling capacity

Analysis

- Capacity Expansion Studies
  - Optimal generation resource location and operation to meet future demand
  - Transmission expansion planning
- Production Cost Study
  - Cost/benefit analysis of system operations
- Power Flow Study
  - Technical feasibility/reliability analysis

Policy development

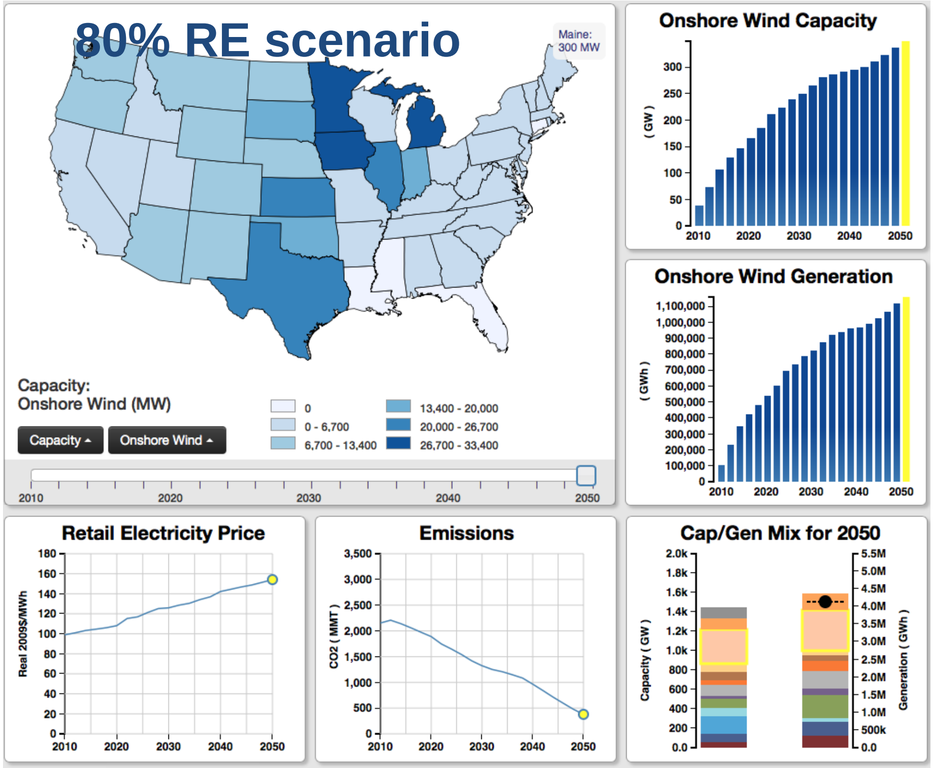
Optimize resource planning through **Capacity Expansion Modeling**

- **Approach**: policy and planning focus; optimize least cost (capital and operations) solution subject to (modeling and policy) constraints.
- **Scenario drivers**: policy, technological advancement, transmission, fuel prices, weather/drought
- **Modeling horizon**: medium- to long-term (e.g., 20-50 year horizon).
- **Key inputs**: high resolution data on RE resource availability, capital costs
- **Modeling tools:** often developed on an ad hoc basis
- **Key outcomes**: Effects of climate and energy policies; can inform generation build-out for production cost studies.

Source: Schroeder 2014 (NREL PIX 31732)

Example: RE could supply 80% of total U.S. load by 2050

Key Study Question:
To what extent can RE supply meet the electricity demands of the continental U.S. through 2050?



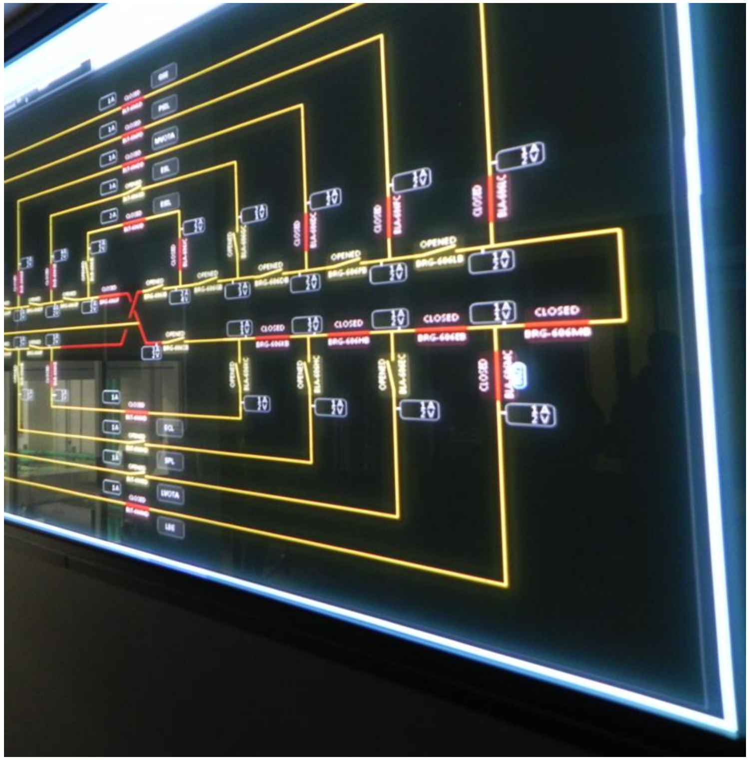
Findings:

- 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 greenhouse gas emissions and water use.
- Improvement in cost and performance of RE technologies will be important to reducing incremental costs.

Source: NREL. (2012). *Renewable Electricity Futures Study.*

Test impacts of future RE scenarios through **Production Cost Modeling**

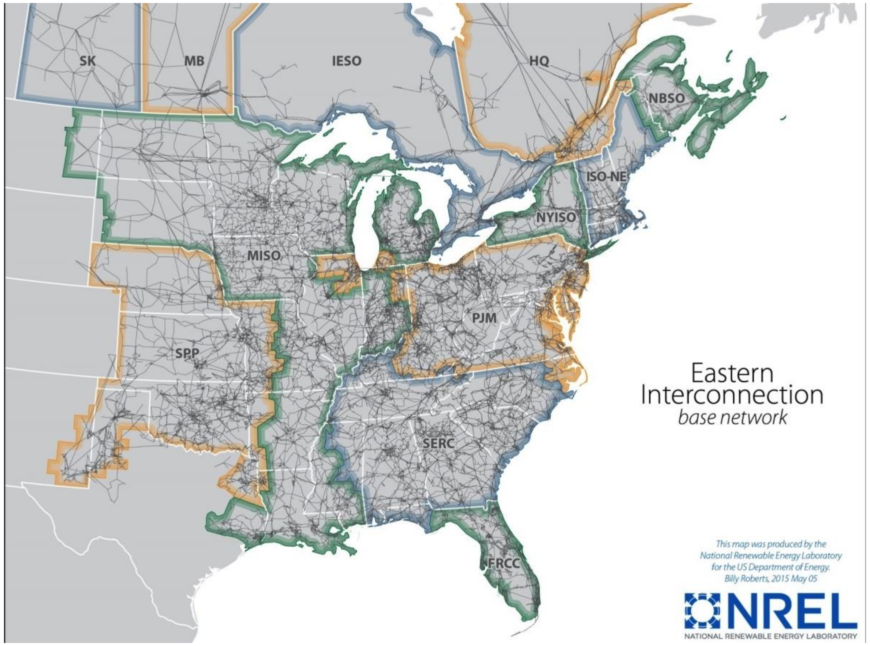
- **Approach**: system operations focus; unit commitment and dispatch analysis subject to physical and economic constraints.
- **Scenario drivers**: RE penetration, flexibility measures (forecasting, demand response, thermal cycling, storage), fuel costs
- **Modeling horizon**: hourly resolution, one-year horizon.
- **Key inputs**: detailed data on generation fleet characteristics, time synchronous RE and load data.
- **Modeling tools:** industry-accepted commercially available models available
- **Key outcomes**: Operational feasibility and costs of policies and new/retired generation; can inform power flow studies.



Source: Adams 2013 (NREL PIX 24927)

Example: the Eastern Interconnection could handle significant RE penetration

Key Study Question:
What effect will 30% energy generation by wind and solar have on power system operations?



480 GW peak

Source: NREL. (Forthcoming). *Eastern Renewable Generation Integration Study.*

Methods:

- Analyze wind and solar potential for the whole region
- High resolution representation of power system (60,000 lines, 7500 generators, 5-min dispatch, etc.)
- Simulate 2026 operations
- Additional focused analysis of "interesting periods" (e.g., high wind, large ramp)

Findings:

- High (30%) solar penetrations in Florida cause negative net load about 8% of the hours each year.
- Southwest Power Pool can supply Southeast Reliability Corporation with large amounts of wind generation (up to 2/3 of its local generation). Balancing will likely need to be shared between these two system operators.

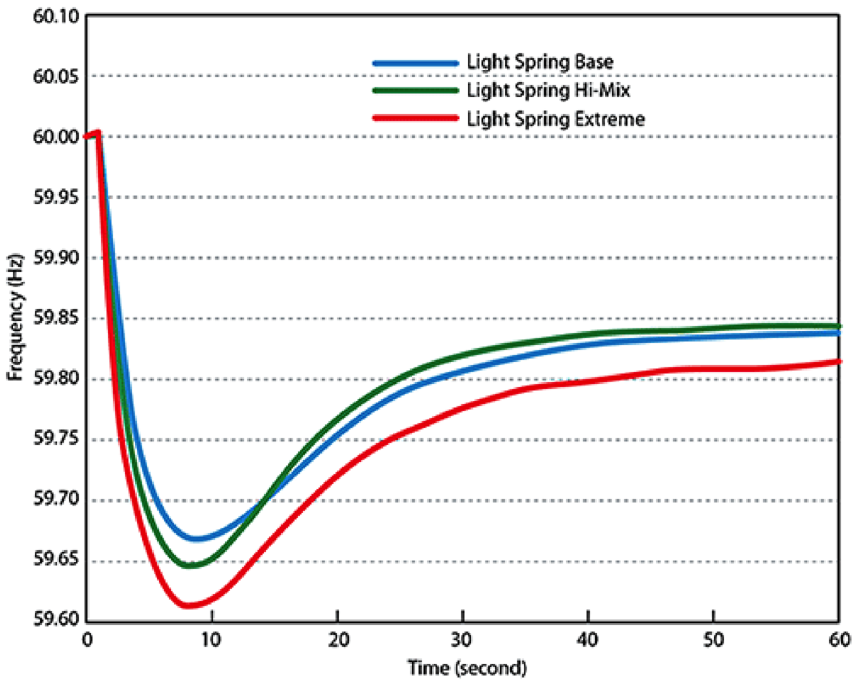
Determine technical feasibility and reliability impacts through **Load Flow Modeling**

- **Approach:** model real and reactive power flow, voltage stability, fault tolerance, and contingency response.
- **Scenario drivers**: RE penetration, disturbances, extreme conditions (e.g., high RE/low load, low RE/high load).
- **Modeling horizon**: short (<5s), correlating to periods of system stress.
- **Key inputs**: dynamic generator modeling parameters, transmission line impedances, transformer details and tap settings.
- **Modeling tools:** industry-accepted commercially available models
- **Key outcomes**: Technical feasibility and reliability impacts of operational changes; necessary mitigation procedures

Source: Gretz (NREL PIX 10924)

Example: No barriers to achieving system stability or frequency response targets under high RE penetrations

Key Study Question:
How would high penetrations of wind and solar impact the large-scale transient stability and frequency response of the U.S. Western Interconnection?



Findings:

- There are no fundamental barriers to the Western Interconnection meeting transient stability and frequency response objectives with higher levels of wind and solar generation.
- Good system planning and power system engineering practices (e.g., transmission system improvements) are necessary to achieving high RE penetrations.
- Sharing frequency-responsive resources across balancing areas can help mitigate the potential impacts of distributed PV on the bulk power system.

Source: Miller et al. (2014). Western Wind and Solar Integration Study Phase 3– Frequency Response and Transient Stability.

WHAT IS THE PROCESS FOR CONDUCTING A GRID INTEGRATION STUDY?

The process of a grid integration study typically includes these major steps

Step 1:
Collect Data

- **Wind / Solar Profile Development** (Resource +Location)
- **Existing system data** (load, grid, power plants, etc.)
- **Stakeholder Meetings**

Step 2:
Develop Scenarios
(one or more of these):

- **Resource Scenarios** (wind, solar, conventional, demand response, storage)
- **Transmission Scenarios**
- **System Management Scenarios** (Design/Planning/Reserves/Operational Methods/Markets)
- **Stakeholder Meetings**

Step 3:
Simulate the power system
(one or more of these):

- **Production Cost Simulation and Flexibility Assessment**
- **Dynamics**
- **Load Flow**
- **Capacity Value/Reliability**
- **Stakeholder Meetings**

Step 4:
Analyze and Report

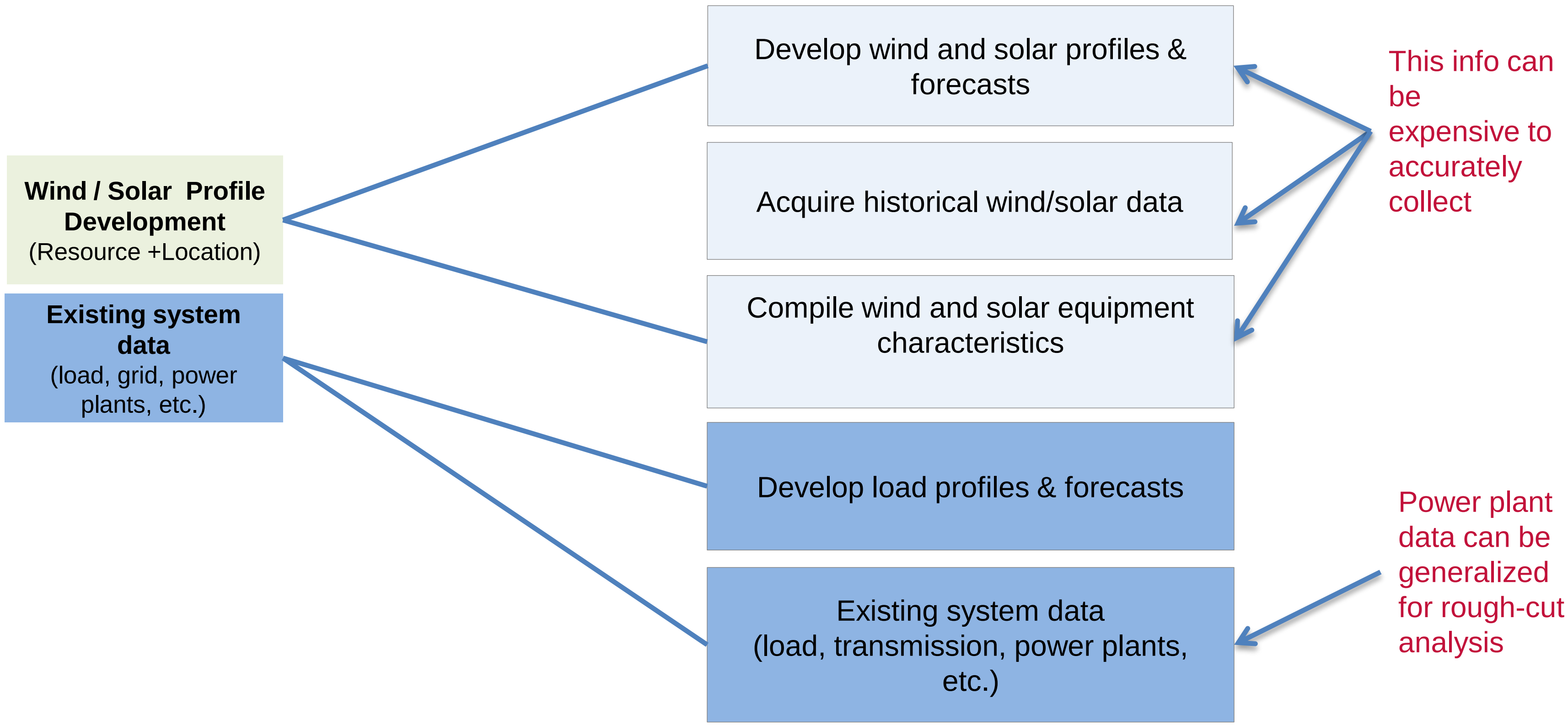
- **Data analysis and output synthesis**
- **Final Report**
- **Stakeholder Meetings**

Input
Scenario
Simulation
Output

Important Considerations

- Significant data collection and preparation
- Stakeholder engagement at each phase

Step 1: Collect Data



Inputs

- Area of study (province- or state-level, regional, national…)
- Solar and wind resource data (hourly, location-specific). New addition to traditional planning!
- System data (load profile, historical load forecast errors, individual power plant capabilities)
- Operating parameters (how system is operated, e.g., scheduling, market rules)

The importance of time-synchronous data

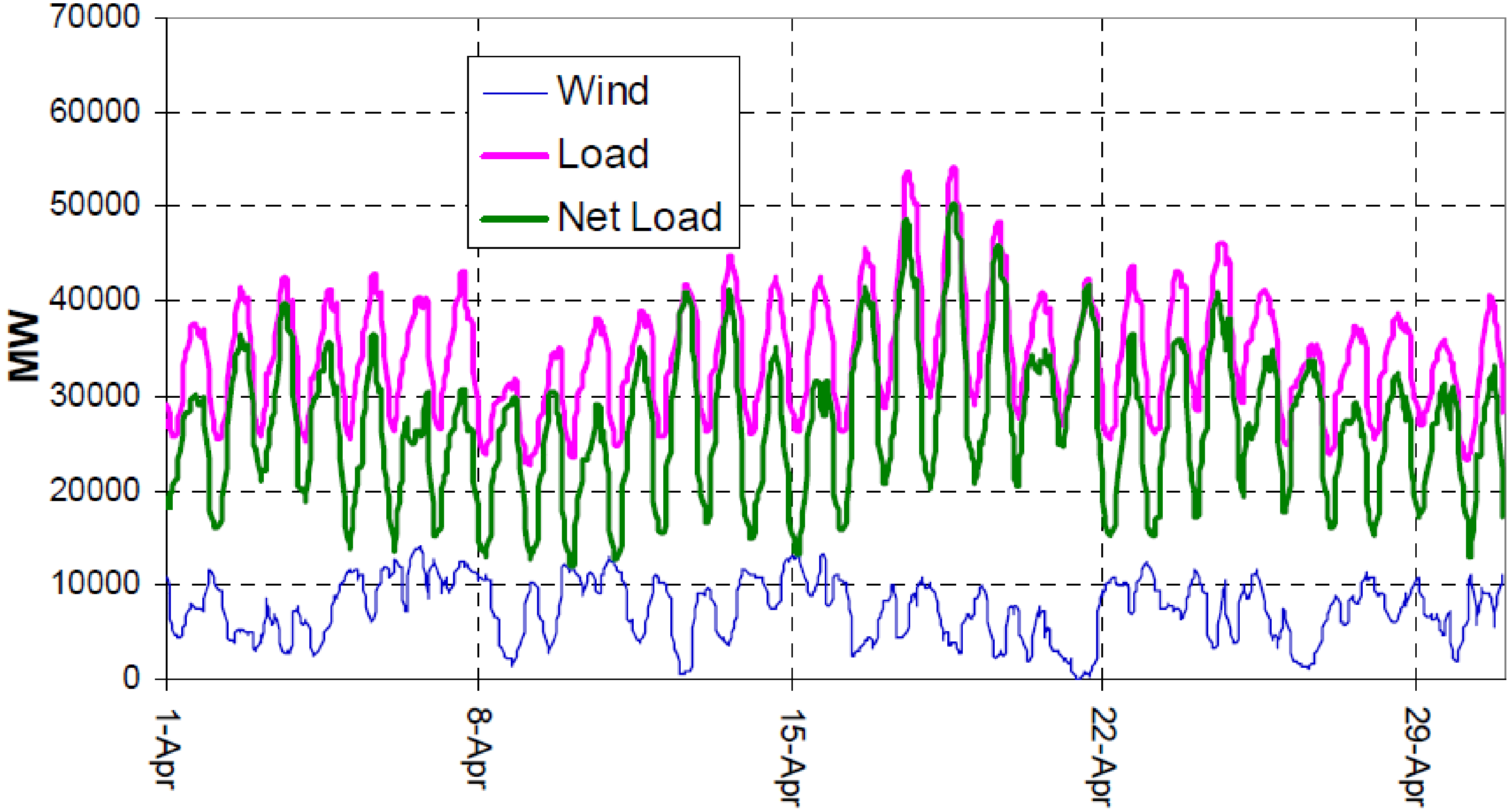
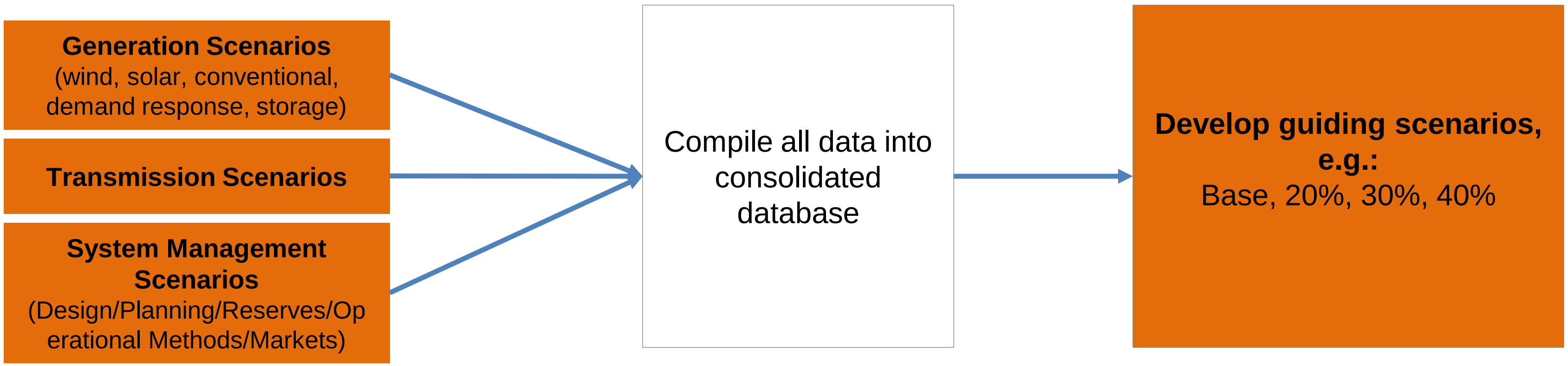


Figure 2- Load, 15 GW of wind generation, and net load for April of study year

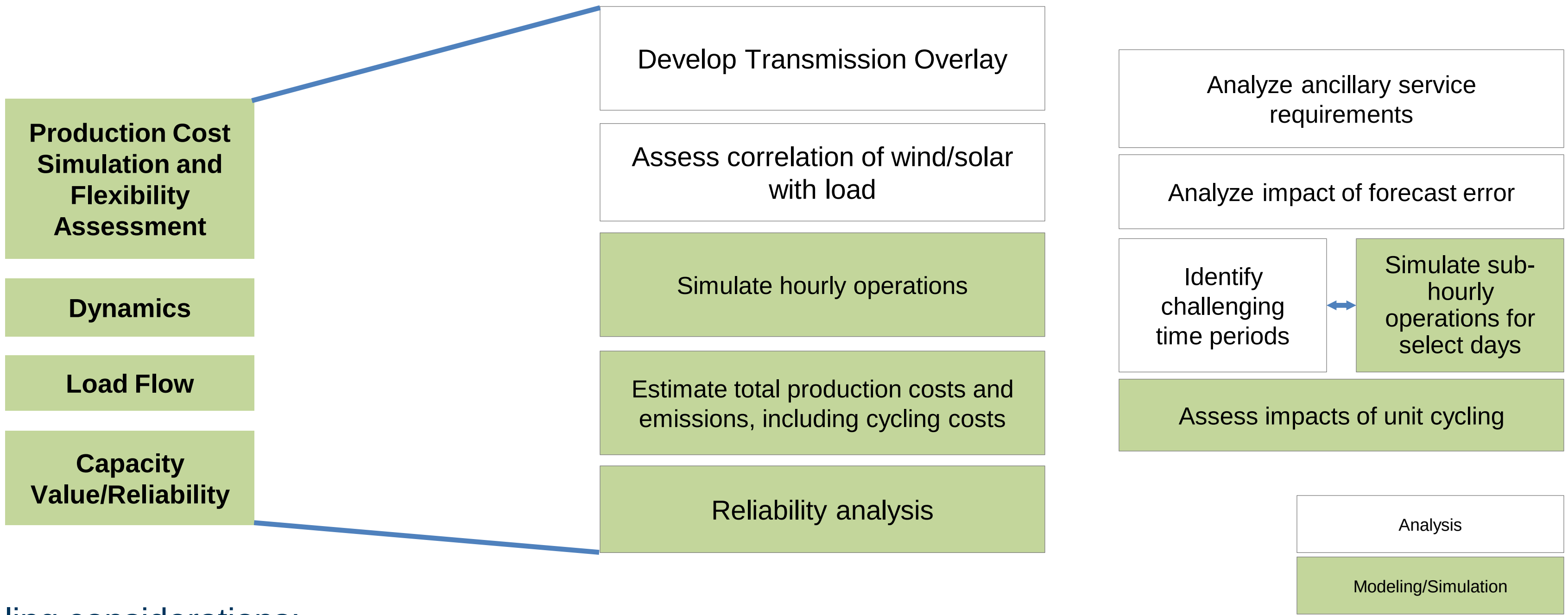
Source: ERCOT 2008

Step 2: Develop Scenarios



- Example scenarios include:
  - Base case (no/current RE or business as usual in a target year)
  - 10-, 20-, 30% energy penetration of variable RE
  - Variations on location (e.g., trade-off between best RE resources and need for new transmission).
- Scenarios may include sensitivity analysis that evaluate actions that can improve RE integration, such as demand response or improved forecasting

Step 3: Simulate the Power System



Modeling considerations:

- Hourly dispatch simulation for at least 1 year using time-synchronized weather-load data
- Sub-hourly operations for challenging time periods
- Impacts on power plant wear & tear, fuel use, emissions
- Ancillary service requirements
- Impacts on market prices
- Planning reliability (e.g., evaluation of capacity value of solar, wind)
- Operational reliability (load flow simulations, dynamic stability analyses)

Step 4: Analyze and report

Data analysis and output synthesis

Final Report

Evaluate performance under normal/abnormal conditions

- Performance concerns (reserve violations, unserved load, curtailment, cycling, etc.)
- Secondary reserves for frequency response
- Review existing practices

Evaluate mitigation measures

- Comparative approach
- Measures of efficacy

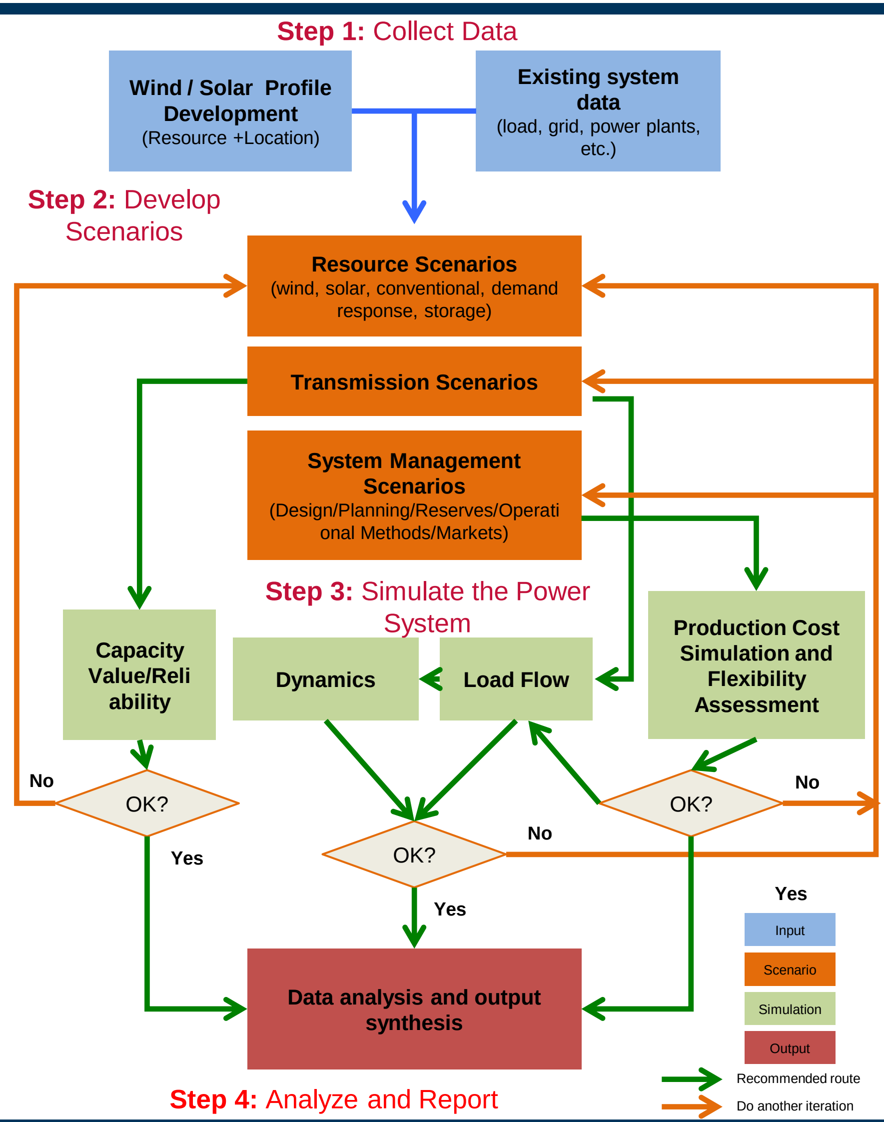
Report outputs

- Production costs
- Capacity and generation by plant type, including RE curtailments
- Fuel consumption
- Energy transfers and power flows
- Operational feasibility (including solutions to infeasibilities)
- Cost/benefit of specific integration options, including options aimed at mitigating negative effects of RE integration.

Study Phases

Significant Iteration:

- Step 1 (data) strongly influences Step 2 (scenario development).
- Step 2 (scenarios) and Step 3 (modeling and analysis) strongly interact, and multiple iteration loops can be necessary to identify system performance boundaries and cost impacts.
- Results of Step 3 (modeling and analyses) strongly influence outputs and mitigation options, and help identify the long-term solutions for grid integration.



Source: Adapted from IEA Task 25, 2013

Stakeholder engagement is critical to ensure the study is relevant to industry and technically accurate

Technical review committees (TRC) are an example mechanism to engage stakeholders

- Assist modelers in guiding study objectives, scenarios, and sensitivities
- Reviews study assumptions and results on multiple occasions throughout course of study.
- Endorses technical rigor of the study.

Example TRC members:

- System operators
- Utilities (if distinct from system operator)
- RE plant owners/operators/developers
- Conventional plant owners/operators/developers
- Transmission developers
- Regulators
- Public Advocates

Stakeholder engagement is critical across all stages of a study

Example: Western Wind and Solar Integration Study Technical Review Committee (select organizations)

System Operators

- Xcel Energy
- PacifiCorp
- Bonneville Power Administration
- California Independent System Operator (ISO)
- New England ISO

Other private sector; government

- GE Energy
- Energy Exemplar
- NextEra Energy Resources
- U.S. Department of Energy

Research institutes and organizations

- Electric Power Research Institute
- Western Electricity Coordinating Council
- DOE National Laboratories
- Utility Variable Integration Group
- Western Governors' Association

Tips for your own studies

- Clearly defined study questions
  - What is it that you want to learn?
  - Reliability is measured at a variety of time scales and with many metrics
  - Cost efficient for whom, when?
- Best tools for the question
  - Are the right tools being used to answer your questions?
- Data
  - Do you have the data to answer your questions?
  - Where can you get the data?
- Transparency
  - Is the process for developing methods and assumptions for analysis transparent?
- Peer reviewed
  - Do impartial external experts review the results?

Key Takeaways

- A grid integration study provides a power system-specific assessment of the challenges and solutions associated with future RE scenarios.

- Grid integration studies evolve over time; each study frames the key questions for subsequent efforts.

- Stakeholder input should inform the communication of results to ensure that study outputs are actionable and policy-relevant.

- *The ultimate goal for the studies is to give power sector stakeholders the information and confidence they need to take action to meet RE targets.*

Additional resources on case studies and best practices

- Clean Energy Solutions Center: https://cleanenergysolutions.org*
  - Clean Energy Grid Integration Network (CEGIN): https://cleanenergysolutions.org/cegin
  - Clean Energy Regulators Initiative: https://cleanenergysolutions.org/ceri/resources

- Greening the Grid: http://greeningthegrid.org*

- International Smart Grid Action Network: http://www.iea-isgan.org*

- 21st Century Power Partnership: http://www.iea-isgan.org http://www.21stcenturypower.org

Ask an Expert services offer free, remote, on-demand technical assistance on grid integration (and other) issues

Contacts and Additional Information

Jessica Katz
National Renewable Energy Laboratory
Email: Jessica.Katz@nrel.gov

Clean Energy Solutions Center

https://cleanenergysolutions.org

Greening the Grid

greeningthegrid.org

Email: greeningthegrid@nrel.gov