Principles for Increasing the Accessibility and Transparency of Power System Planning

U.S. DEPARTMENT OF ENERGY

January 2017

ACKNOWLEDGEMENTS

The U.S. Department of Energy's Office of Energy Policy and Systems Analysis (DOE-EPSA) produced this report with the cooperation and support of three DOE National Laboratories, including the National Renewable Energy Laboratory, the Oakridge National Laboratory, and the Pacific Northwest National Laboratory. Within DOE, David Rosner led report development with support from Carol Battershell, Aaron Bergman, Alex Breckel, Colin Cunliff, Carla Frisch, and Judi Greenwald. Substantial input was provided by Aaron Boom, Bethany Frew, and Scott Gossett of the National Renewable Energy Laboratory, Stanton Hadley and Alfonso Tarditi of the Oakridge National Laboratory, and Michael Kintner-Meyer and Mike Hoffman of the Pacific Northwest National Laboratory. We would like to thank the technical reviewers who provided helpful comments on the document. These reviewers helped to make this report as technically sound as possible; however, any remaining errors or omissions are those of the authors.

Table of Contents

INTRODUCTION

Providing reliable electricity to end users depends on the coordinated analysis of numerous long-term and short-term planning objectives. As the demand for electricity that is reliable, affordable, sustainable, and resilient continues to grow,[a] new and more sophisticated tools, practices, and analytical methods are being developed to economically and reliably plan and operate the power systems of the future.

This paper provides energy system regulators, environmental regulators, and power system operators with a common set of concepts, resources, and questions intended to facilitate dialog, increase consistency, transparency, understanding, and, ultimately, power system reliability. To accomplish these goals, this paper defines three principles for planning:

1. Conduct open planning processes
2. Formulate relevant reliability questions to guide scenario planning
3. Understand and leverage vetted resources.

These principles are intended to inform stakeholders new to the power system planning process, while also providing utility to the experienced practitioners and planners by providing information about common practices, publically available resources of data, and methodologies that are vetted and internally consistent when data from a real-world power system are not available to inform the planning process. In addition, this paper shows how these principles can be applied in scenario planning.

Power system reliability planning, consistent with North American Electric Reliability Corporation (NERC) reliability standards, addresses only the bulk power system, and has been focused on identifying elements of the transmission system that do not meet performance requirements over the planning period. A part of the transmission system planning process is to propose corrective plans in circumstances when performance is not achieved, which can include new transmission lines, system upgrades, or other solutions that would enable the transmission system to reliably transfer the electric power from generators to load over the planning period.

However, numerous drivers are shifting planners away from this paradigm, including smart loads, integration of wind and solar technologies, as well as policies to reduce the environmental footprint of electricity production, among others. These drivers are already affecting power system planning, design, and operation and are likely to continue to do so in the future. This in turn creates a need for a broader and, in many cases, a more integrated and expansive view of reliability planning. The following are among the trends rewriting the traditional rulebook:

Why Reliability Matters

The United States benefits from a highly reliable power system. Reliable, affordable electric power fuels the economy and supports our quality of life. Each time a person turns on a light, plugs in a phone, approaches a traffic signal, or logs onto a computer, they trust that the power system will be working to enable the services we expect. Power system reliability is the ability of the system to deliver expected service through many types of planned and unplanned events.

The high level of reliability provided by the U.S. grid is not an accident. The Federal Energy Regulatory Commission (FERC), U.S. Department of Energy, North American Electric Reliability Corporation (NERC), States' Public Utility Commissions, regional planning authorities, utilities, power system operators, and other organizations have worked to increase and ensure the reliability of the U.S. power system through mandatory reliability standards, FERC-regulated planning, coordination, and industry investment.

From Department of Energy (DOE), *Maintaining Reliability in the Modern Power System* (Washington, DC: DOE, 2016).

[a] U.S. Energy Information Administration (EIA), "Table 8. Electricity Supply, Disposition, Prices, and Emissions," in *Annual Energy Outlook 2016* (Washington, DC: EIA, September 15, 2016), https://www.eia.gov/outlooks/aeo/index.cfm.

- Large amounts of thermal generation and inelastic demand (i.e., demand that remains constant regardless of the price of electricity) are being replaced with resources that present both new constraints and new opportunities to power system planning. For example, variable renewable generation like wind and solar power offers environmental benefits, but may also require additional system flexibility. Smart grid technologies like demand response give power system operators new tools for managing demand and in turn ensuring power system reliability.
- Natural gas use in the electric power sector has expanded significantly, which makes integrated natural gas-electric systems simulation increasingly important in regions transitioning large portions of their generating mix from coal to natural gas, according to the staff of the Federal Energy Regulatory Commission (FERC), as well as many system operators, state regulators, and other stakeholders [1]
- Rapidly growing distributed photovoltaic (PV) generation means that systems designed for one-way flow of power from producer to consumer now must accommodate two-way flows of power.
- The need for coordinated transmission and distribution planning is increasing, in part due to growing prevalence of distributed energy resources on the power system in some regions.[2]
- Federal, state, local, and tribal environmental policies and goals are also playing a role in accelerating the changes described above in the energy sector. Clean and renewable energy standards, energy efficiency standards, state carbon policies, and the Federal Clean Power Plan, among others, are examples of policies that are contributing to energy system transition.

An effective reliability plan evaluates the existing electricity system as well as the suite of potential investment options—including infrastructure, generation, and operational practices—that could be deployed to adequately meet the future demand for electricity. This paper focuses on established planning methods for the electricity sector, with discussion on ways to integrate the broader energy system into a reliable planning process.

Indeed, many of these drivers call for a broader planning paradigm in which *electricity* is increasingly part of a more integrated system of *energy* systems (Figure 1). In this world of "energy systems integration"[3] comprehensive reliability planning considers the combined impacts of these broader energy systems, including transmission, distribution, natural gas, and even transportation.

Planning for Reliability: Traditional and Emerging Approaches

Power system planners use two basic approaches to reliability planning: (1) reliability-based and (2) value-based.[4]

Under the reliability-based planning approach, system planners begin with a model of the existing power system and a forecast of load for the planning period. In the next step, planners assess the generation capacity additions and their location that are needed to meet load. Planners will also account for state clean energy standards (and/or other state requirements) and the list of planned generation in the region's interconnection queue. Planners will also evaluate the potential for imports and exports of energy from other regions. Finally, using modeling and other tools, planners will then conduct a performance assessment that includes steady state, short circuit, and stability.[b,c]

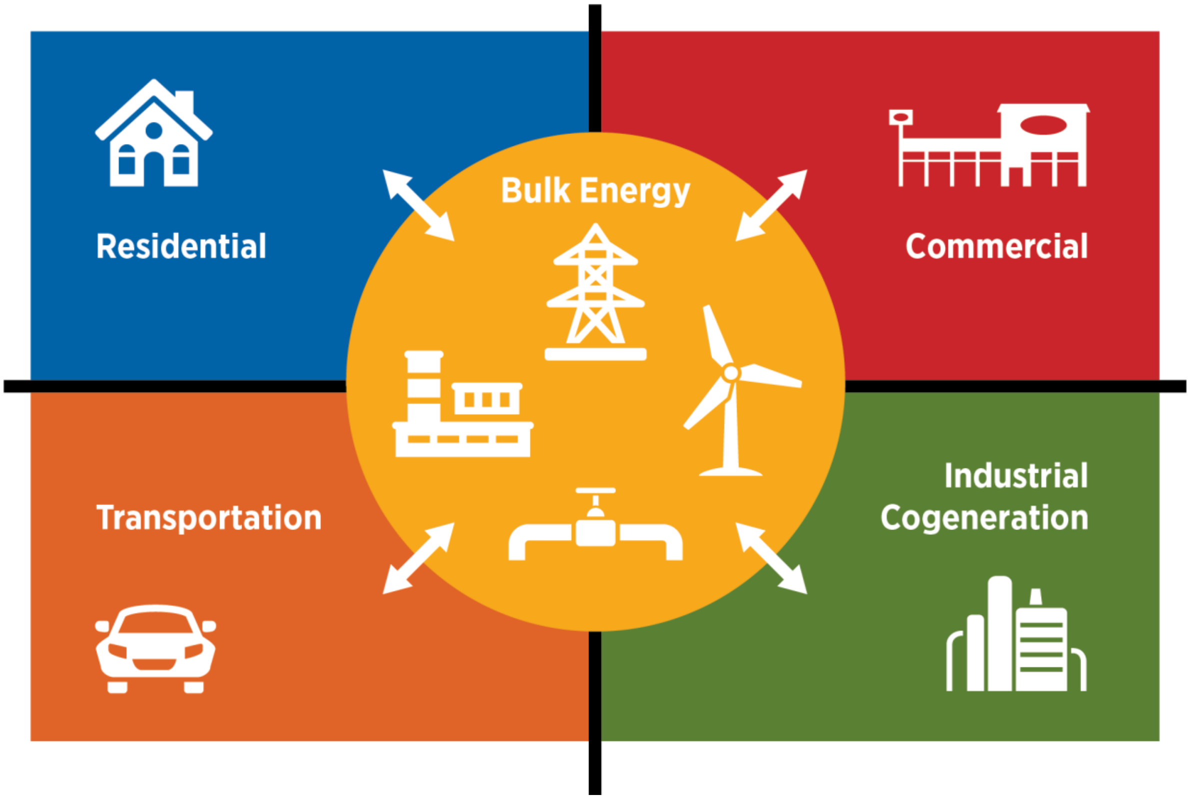

Figure 1. Compared to the traditional paradigm, energy system reliability planning now encompasses more natural gas generation, more two-way flows of power, and greater acknowledgement of energy systems integration.

In the event that performance requirements are not met, planners will then work to develop corrective plans and economic assessments, which are then used to estimate the cost of the plans and to support project approval decision-making.

Increasingly, regional transmission organizations and independent system operators (RTOs/ISOs) are using value-based economic analysis to understand the potential mixes of generation and transmission that maintain a determined level of reliability while maximizing the economic benefits of the required investment.[5] Using value-based analysis, power system planners can evaluate the economic (including capital cost, production cost, marginal energy cost, reserve margin, export,

---

[b] Modeling and transmission planning simulations are done in compliance with the relevant NERC mandatory standards for Modeling, Data, and Analysis and Transmission Planning. For more details, see "All Reliability Standards," North American Electric Reliability Corporation, http://www.nerc.com/pa/Stand/Pages/AllReliabilityStandards.aspx?jurisdiction=United%20States.

[c] Power flow analyses model the voltages, currents, and real and reactive power flows in a system under a given load condition in order to plan ahead and account for hypothetical situations. Power transfer limit studies determine the maximum amount of power that can transfer between geographic areas without compromising system security; this helps to identify potential bottlenecks. Contingency analyses study system performance under given component outages or failure scenarios (e.g., N-1, N-2, etc.). Power system stability includes steady-state, transient, and dynamic stability, and refers to the ability of the power system to return to a stable condition without losing synchronism (i.e., frequency, voltage, and phase sequence) when subjected to a disturbance. Steady-state stability considers small and gradual changes in the system operating conditions. Dynamic (also known as small-signal) stability refers to power system stability when subjected to continuous and small disturbances, while transient stability refers to large and sudden disturbances. Voltage stability is the ability of a system to maintain steady voltages after experiencing a disturbance.

and environmental costs) and quantitative (including reliability, right of way, flexibility, and fuel diversity) benefits of investments over the financial life of an asset under a variety of scenarios, and can allocate costs for those investments to the end-users in the system for whom the benefits accrue.[6]

These two reliability planning approaches typically focus solely on the bulk power system. However, given the various drivers of change in the electricity sector, there is a growing awareness in the planning community that changes in the distribution system and fuel deliverability can strongly influence electricity reliability. While awareness of this increasing complexity is growing, current practices generally still address bulk power and distribution system planning independently. Notable exceptions include the California Public Utilities Commission and the New York State Department of Public Service Reforming the Energy Vision Initiative, which are moving towards aligning infrastructure planning processes by requiring consistency among load forecasts, resource adequacy assessments, and transmission planning processes.[7]

Common practice today is to perform a reliability analysis in each of these domains separately. However, there is growing interest in power system planning processes that consider the combined impacts of, and interdependencies among, the distribution, transmission, and natural gas systems.

The following are four common types of power system planning studies that evaluate the reliability and economics of the power system:[8]

- Resource adequacy
- Production cost
- Integrated gas-electric systems simulations
- Power flow and transient stability.

Figure 2 shows the bulk power system study types identified by FERC (shown in the orange boxes) in context of broader types of integrated analyses (e.g., distribution systems and natural gas modeling, shown in the green and blue boxes, respectively) needed to provide insights into today's increasingly integrated energy systems. While the principles discussed in this report are applicable to traditional planning processes, we expand on this framework throughout this paper by suggesting principles, tools, methods, and data sources for performing these types of analyses. In addition to providing guidance in how to conduct and evaluate energy system plans, this report provides a guide to modeling tools, publicly vetted datasets, and generally accepted assumptions that can be used in modeling activities across the electricity and broader energy systems.

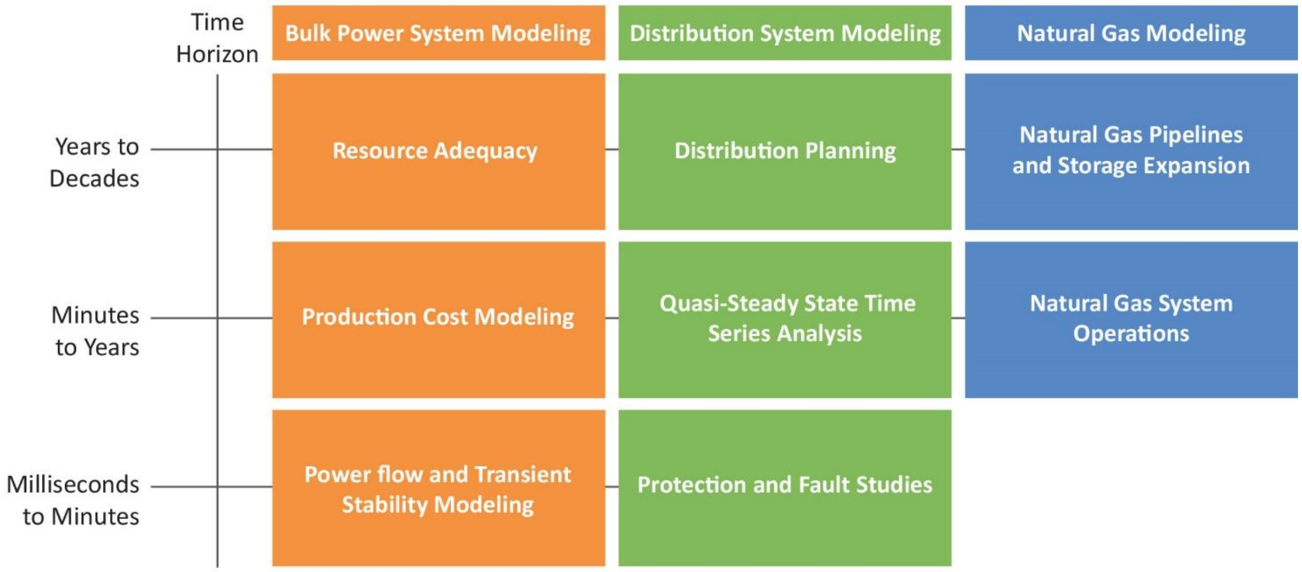

Figure 2. Components of 21st-century energy systems planning (*top*) and the time horizon (*left*) considered by each component

PRINCIPLE 1: CONDUCT OPEN PLANNING PROCESSES

Enlisting energy, environmental, and electricity regulators, policymakers, and other stakeholders in the planning process can help formulate an effective process for maintaining reliability of the power sector and increase stakeholder commitment and acceptance to the resulting plan.

Open and inclusive planning processes can help lead to more robust reliability plans and can improve the ability of system operators to gain support from all relevant stakeholders for the final plan. Open processes could include the following:

- Allowing and encouraging environmental, energy, and electricity regulators, policymakers, and other stakeholders to participate in regional transmission planning and inter-regional transmission coordination activities and groups, such as those established through FERC Order 1000 (see FERC and NERC Guidelines text box below). Awareness and understanding of planning in neighboring regions can help planners understand the challenges they are anticipating, and how they might impact your system. For example, if a region relies on a coal-fired power plant in a neighboring region to meet peak load, then retiring that plant could force the grid operator (or equivalent entity) to add generation capacity or change transmission practices.
- Establishing procedures and tools to share information with and gather feedback from stakeholders. Effective means of information sharing include webinars, public meetings, and publications. Examples of information that should be made available to stakeholders include the following:
    - **Assumptions**: a clearly defined and well documented set of assumptions about present and future system needs and capabilities, which together provide the foundation for the proposed reliability assessment plan
    - **Data**: information on geographically-relevant grid topology, system performance, technology cost and performance data, and electric loads that can help inform projections of future electric generating capacity requirements
    - **Methods**: management of plan development and how the information is evaluated in order to build a robust reliability plan
    - **Tools**: computer software and code utilized for quantitative assessments of power system capacity and operational needs for reliability purposes
    - **Decision Process**: how responsibility for building the plan is shared, how stakeholder input will be incorporated into the plan, and a timeline with milestones and release dates.

For each of these items, consideration should be given to their relevance and likely impact on the plan, their rationale (i.e., why a specific item is being considered) and sensitivity for public disclosure (i.e., what can be shared with which stakeholders?). The planning process may access data and/or provide analysis or conclusions that can be sensitive. For example, the analysis could be based on data that are proprietary, that has implications on energy infrastructure security, or that has a potential impact (both positive and negative) on particular groups or communities. In these situations, the open, transparent process can still be in place, but with the caveat that the level of detail provided in the disclosed information is carefully vetted. The general practice for sharing sensitive information is to disclose only what is relevant for the purpose of justifying the assumptions or the proposed actions contained in the reliability plan.

Federal Energy Regulatory Commission (FERC) and North American Electric Reliability Corporation (NERC) Guidelines for Transmission Planning

- FERC Order 1000 outlines requirements for transmission planning and cost allocation for public utility transmission providers, including regional planning and inter-regional coordination in transmission planning, and the consideration of transmission needs driven by public policy requirements.[9] Public utility commissions have formed 14 transmission planning regions as part of their compliance with Order 1000.[10]
- FERC's critical energy infrastructure information (CEII) regulations provide guidance on release of information, including information that may be proprietary, related to system security, or otherwise considered sensitive.[11]
- NERC Standard TPL-001-4 establishes performance requirements for transmission planning that ensure the bulk power system operates reliably under a wide variety of conditions and contingencies.[12]

Applying Principle 1: Western Electricity Coordinating Council Benefits from Open Planning Process

The Western Electricity Coordinating Council (WECC) planning process is one example of an open and transparent stakeholder engagement process. The WECC engages stakeholders in its planning processes and uses its website to make planning information (e.g., meeting minutes, meeting announcements, datasets, scenario definitions, assumptions, and requests for information from stakeholders) publicly available.[13] Meeting schedules are posted on the WECC calendar for each committee or working group.[14] The relevant documents and materials prepared for each meeting are embedded in the calendar and can be accessed by stakeholders.

The Western Interstate Energy Board (WIEB), an organization that works to promote the cooperative development of energy policy in its members, which include 11 Western states and three Canadian provinces, made the following points regarding the WECC planning process:[15]

1. Planning processes must be open and inclusive, and should encourage broad stakeholder participation.
2. Databases should be made available to the public in order to enable stakeholder review and vetting; doing so is critical for validation, credibility, and support.
3. There is considerable value in planning across the entire Western Interconnection, as the systems in the region are interdependent.
4. Planning in the electric sector needs to be flexible to respond to important emerging issues.
5. The WECC Transmission Expansion Planning Policy Committee's (TEPPC) Common Case produces an expected 10-year future that is an important benchmark for policy analysis and contributes to other important research in the West.

PRINCIPLE 2: FORMULATE RELEVANT RELIABILITY QUESTIONS TO GUIDE SCENARIO PLANNING

Geographic regions differ in generation capacity, transmission infrastructure, load profiles, market structures, and economics. Understanding these unique characteristics can help determine priorities for reliability planning. When system planners ask well-defined reliability questions, they can help frame a range of scenarios that realistically bound the realm of potential possibilities.

The goal of reliability planning is to engage relevant energy system planners—RTOs/ISOs, transmission utilities, distribution system utilities, and increasingly natural gas pipeline operators —to identify and implement economically efficient solutions to manage *realistic* events that may stress the reliability and resiliency of the power system.

The word realistic is important. Planners can only model a finite number of scenarios due to the cost and time required for each study. Similarly, simplifying assumptions on input data are often required to make modeling scenarios computationally tractable. To simplify the task of modeling power systems and better frame the discussion, energy system planners strive to identify critical questions that must be answered to address near-term and/or long-term needs of their particular systems.

For example, a region that expects retirements of existing generating resources might consider the following:

- Impact of retirements on both the current and future systems
- Availability of sufficient natural gas pipeline and supply infrastructure if natural gas use is expected to increase
- Use of energy efficiency rather than new generation to meet demand
- Effect of adding renewable resources and/or transmission lines
- Vulnerability of electric sector infrastructure to climate change and extreme weather.

Regional characteristics also dictate the degree to which other related systems like natural gas infrastructure or distribution networks should be included in bulk power system reliability analyses. Furthermore, the relative importance of the traditional focus areas for reliability planning—resource adequacy, production cost, and power flow and transient stability (see Figure 2)—may vary by reliability questions of interest. The following section provides examples of regions tailoring reliability questions to important aspects of their local systems.

Applying Principle 2: Formulate Relevant Reliability Questions

The proper issues to investigate during reliability planning can depend on regional characteristics. Regionally-tailored reliability questions could include the following:

- *What is the anticipated level of load growth, or how will load change and how load be served?*
  For example, the Northwest Power and Conservation Council's Seventh Northwest Conservation and Electric Power Plan "…provides guidance on which resources can help ensure a reliable and economical regional power system over the next 20 years…" in the Pacific Northwest.[16] The plan anticipates that load growth in the region will be met with expanded energy efficiency measures, demand response programs to control peak demand, increased use of existing natural gas generating capacity, and deployment of new renewable resources.[17]

Understanding Scenario Analysis

Focused and appropriately targeted questions lead to development of scenarios, essentially "what if…?" questions about changing conditions and potential risks faced by the system that can direct modeling and analysis activities. Scenarios provide a means to evaluate conditions that might exist in the future, bound uncertainty, and explore the sensitivity of the system to various input parameters. A "Reference," "Central," or "Business as Usual" (BAU) scenario is typically used as a default case upon which subsequent scenarios iterate. Often, this reference scenario is the current system, which is assumed to be reliable, projected into the future. A conceptual description of the importance of using a wide range of scenarios is shown in Figure 3. The center point represents a typical reference scenario. The inner square region represents a traditional range of scenarios that are used for planning and operational decisions. The larger outer square reflects a broader set of possible futures, which, if designed properly, capture a meaningful share of the plausible outcomes. Considering a broader set of possible future may be appropriate but depends on the likely drivers of change in the region—scenarios should be informed by questions realistically bound to the realm of potential possibilities. The goal with scenario analysis is to capture this broader space by identifying these bounding scenarios. Finally, the gray outer area in the figure represents the full, unlimited space of possible futures, which cannot be feasibly captured within any current modeling framework.

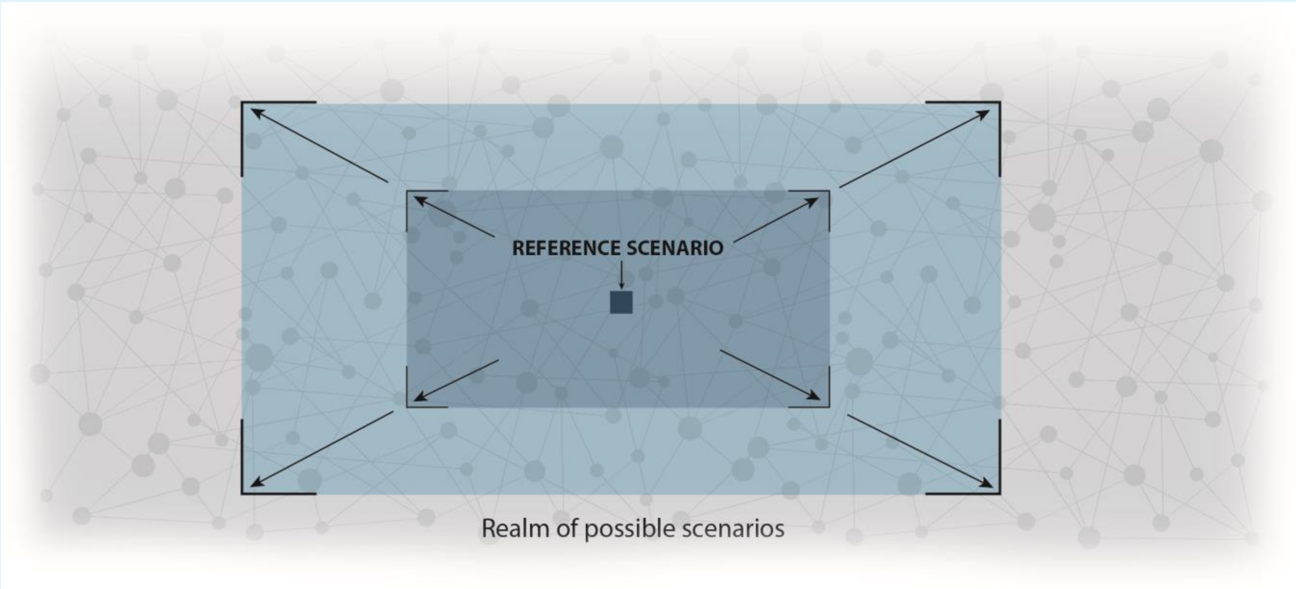

Figure 3. Using scenarios to bound a range of possible futures

- *How can we accommodate reverse power flows as distributed PV expands?*
  In 2014, the California Energy Commission commissioned a regional transmission and distribution network impacts assessment for PV[18] using a high-definition regional power system simulation model.[19] This effort took into consideration both transmission and distribution system features to evaluate wide-area grid impacts for PV interconnections. The study used actual utility data to evaluate the impact of distributed PV on a 3,500-square mile service territory with 51 distribution feeders and regional transmission. The study results indicated that using a single model to include many generation projects, distribution feeders, substations, and transmissions makes it easier to evaluate alternative interconnection schemes and better understand reverse power flow for reducing impacts of load fluctuation. See the Modeling Distribution Systems text box for guidance on distribution system modeling as a planning activity.

Modeling Distribution Systems

Power flow and reliability assessment in the distribution system is a relatively new field. It is data intensive, and these data—describing infrastructure and customer load profiles, for example—are often proprietary. Planning authorities may take advantage of open-source distribution system simulation tools (e.g., CYME,[20] Easy Power,[21] OpenDSS,[22] and GridLab-D[23]). At present, there are significant technical challenges with the simulation of power flow because distribution systems involve numerous dynamic components, which require detailed data inputs and significant computational resources to model. One way to overcome data limitations and perform detailed distribution system modeling is by using representative customer profiles. The U.S. Department of Energy's Pacific Northwest National Laboratory has developed "archetypical" feeder models that generate representative customer load profiles for distribution circuits based on customer class composition, climate zone, level of urbanization, and other criteria.[24] These archetypical feeder models can serve as proxy in modeling activities when acquisition of actual data is not feasible. Incorporating infrastructure into distribution system modeling presents additional challenges, as detailed specifications of the impedance of distribution system components must be specified in order to accurately model power flows in distribution circuits. In addition, these data may not be available for some distribution system assets—particularly for those that have been in operation for many decades and have undergone many replacement cycles.

- *Is it worthwhile to extend planning across borders to enhance overall system reliability?*
  At the borders between states, regions, interconnects, RTOs, and ISOs, various issues can arise, including transmission rights between markets, energy dispatch at market borders, and investment in transmission or generation between market and nonmarket regions. The RTO PJM Interconnection and Midcontinent Independent System Operator (MISO) collaborated on long-term planning for capacity delivery and interface pricing to reduce potential conflicts.[25] The result: hourly price matching between PJM and MISO for particular flow gates between the regions. Also, cross-border bids are compared and those that match are allowed to happen.
- *Is the power system robust in the face of climate change, particularly lower rainfall?*
  Because the Northwest region relies heavily on hydro power for both generation and flexibility, regional planning efforts may want to incorporate increased focus on resource adequacy and power flow. The Northwest Power Council addressed climate change questions in its adequacy assessment for 2020-2021.[26]
- *Are regional markets adequate for facilitating regional power transfers?*
  The California ISO energy imbalance market is growing quickly to integrate renewable resources across the WECC region by "…allowing participants to buy and sell power closer to when electricity is consumed and by allowing system operators real-time visibility across neighboring grids, which supports balancing supply and demand at less cost."[27] Analyses have shown economic and reliability benefits of this market.[28]
- *How do we value renewable technologies such as distributed PV?*
  On January 28, 2016, the California Public Utilities Commission (CPUC) voted to adopt new rules that uphold net metering for future solar customers of the state's large investor-owned utilities (IOUs).[29] But in neighboring Nevada, the state Public Utilities Commission announced in late 2015 a PV rate change that may have impacts on Nevada's rooftop solar market.[30]
- *Can we accommodate rapid realignment of generation sources?*
  Traditionally, system operators would seek to build additional conventional capacity to maintain reliability. However, current utilities have many additional tools to reduce peak demand, including energy efficiency, demand response, construction of new transmission lines to enable importing more power from other regions, as well as other options. For example, in 2010, one East Coast transmission company faced a scenario where a generator was deactivated and resources were not adequate to meet load.[31] Rather than constructing new transmission, the utility resolved the problem relatively inexpensively by purchasing sufficient synchronous generation capability sites.[32]

PRINCIPLE 3: UNDERSTAND AND LEVERAGE VETTED RESOURCES

Reliability planning can benefit from building on work that has been done by others and by using vetted models, tools, and datasets. Understanding and using available resources can improve the efficiency of, and confidence in, the planning process and increase adoption of consistent approaches and methodologies.

Modeling Tools

There is a large universe of tools that are used to model the power sector and examine potential reliability impacts of an evolving energy system. Different tools have varying capabilities and address different aspects of reliability, and no one type of model can address all aspects of reliability. Power sector models are distinguished by their degree of spatial and temporal resolution and fall into four categories, each with its individual strengths and weaknesses. Robust analysis will often use multiple tools in concert; however, the starting point is to choose the right tool to answer the question that is being asked. The four types of modeling tools, sorted by degree of increasing resolution, include the following:

1. *Spreadsheet/Calculator Tools*—provide high-level analyses of the power sector, and can be useful for first-pass planning and for refining questions that other tools can be used to answer
2. *Capacity Expansion Models*—over a long period of time (e.g., over multiple years or decades), simulate generation and transmission capacity investment given assumptions about future electricity demand, fuel prices, technology costs and performance, and policy and regulation
3. *Production Cost Models*—simulate the operation of a power system over a short period of time (e.g., 1 week to 1 year) at higher temporal resolution (e.g., 1 hour to a few minutes) than capacity expansion models to determine the least cost dispatch of a power system to meet load
4. *Power Flow and Transient Stability Models*—highly detailed simulations of the transmission network that simulate alternating current (AC) power flow over very short time periods (e.g., over a few seconds).

More detailed descriptions of these models and the types of questions they are designed to answer are provided in Table 1 and in the FERC Staff White Paper, *Guidance Principles for Clean Power Plan Modeling*.[33]

Table 1. Overview of Power System Planning Models

Model Type	Geographic Resolution	Time Horizon	Best Use/ Common Questions	Examples
Spreadsheet/Calculator	Ranges from a state to entire country	Decades	First-pass planning of statewide compliance Used to explore changes to the bulk power system and to a limited extent, resource adequacy. Common questions include the following: What is the current generation mix and associated emissions in my state? What emissions reductions are achieved by a given generation mix?	Advanced Energy Economy (AEE) State Tool for Electricity Emissions Reduction (STEER) Environmental Protection Agency's (EPA's) AVoided Emissions and geneRation Tool (AVERT) MJ Bradley's & Associates Clean Power Plan (CPP) Compliance Tool Synapse's Clean Power Plan Planning Tool (CP3T)
Capacity Expansion	Whole country or regional	Years to Decades	Simulate generation and transmission capacity investment Used to explore changes to the bulk power system and resource adequacy questions Common questions include the following: What are the impacts of power sector policies on the generation and capacity mix in the mid- to long-term? What is a potential future mix of generators required to meet load? How can sensitivity assumptions (e.g., fuel cost assumptions, technology costs, and other parameters) affect the projected generation and capacity mix?	National-level models: ICF International's Integrated Planning Model (IPM) International Energy Agency's MARKAL (MARKet ALlocation model) Resources for the Future's Haiku National Renewable Energy Lab's Regional Energy Deployment System (ReEDS) U.S. Energy Information Administration's National Energy Modeling System (NEMS) Utility-scale models: ABB's System Optimizer ABB's Strategist Energy Exemplar's PLEXOS EPIS, LLC's Aurora National Renewable Energy Lab's Resource Planning Model

Model Type	Geographic Resolution	Time Horizon	Best Use/ Common Questions	Examples
Production Cost	Regional	Minutes to Hours Models dispatch over a period of weeks to a year	Identify least-cost dispatch of a specified power system Used to assess resource adequacy and other aspects of power system reliability Common questions include the following: What are the impacts of capacity retirements/additions on system operations? How will a future change to the generation mix affect transmission congestion and locational marginal prices?	ABB's Gridview ABB's PROMOD Energy Exemplar's PLEXOS GE's Maps
Power Flow and Transient Stability	High geographic resolution (e.g., specific system attributes such as a transmission line)	Seconds	Simulates the AC transmission network to perform "deep-dive" simulations of specific situations Common questions include the following: How could a contingency event (e.g., unexpected loss of a generator or transmission line) affect frequency response or voltage stability in the system? How could a contingency event affect transient stability in the power system (e.g., will generators remain synchronized)?	GE's PSLF Siemens' PSS®E

Data

Figure 2 introduced an expanded set of potential focus areas for reliability planning (bulk power system modeling, distribution system modeling, and natural gas system modeling). Within each of these domains, Figure 2 also showed that comprehensive reliability planning covers a wide range of time scales, from milliseconds to decades. Though the focus of the modeling required to address specific reliability questions can vary across domain and time scale, all modeling requires robust and comprehensive data as a foundation for the analysis. Table 2 summarizes common data inputs for different types of modeling, and Appendix A provides further description of examples of data inputs.

Table 2. Common Data Inputs for Reliability Planning Models

Model Type	Common Data Inputs	Examples of Data and Tools
Spreadsheet/ Calculator	What emissions reductions are achieved by a given generation mix?	Advanced Energy Economy (AEE) State Tool for Electricity Emissions Reduction (STEER) EPA's AVoided Emissions and geneRation Tool (AVERT) ACEEE's State and Utility Pollution Reduction Calculator Version 2 (SUPR 2)
Capacity Expansion	Capital and operating costs and fuel costs Time-synchronous load and variable renewable resource time series data, i.e., data that are historically time consistent Fuel prices Water usage/availability.	ICF's Integrated Planning Model (IPM) International Energy Agency's MARKAL Resources for the Future's Haiku National Renewable Energy Laboratory's (NREL's) Annual Technology Baseline NREL's Regional Energy Deployment System (ReEDS) U.S. Energy Information Administration's National Energy Modeling System (NEMS)
Production Cost	Operational costs Detailed parameters for system components, such as transmission line ratings, transmission flow limits, generator-level emission rates, generator-level heat rates, and thermal plant capabilities Variable renewable resource profiles, fuel costs, and thermal plant capabilities Time-synchronous, i.e., load and variable renewable resource time series data are historically time consistent, ideally at sub-hourly temporal resolution System configuration data.	Clean Power Research's SolarAnywhere high-resolution dataset IBM's Hybrid Renewable Energy Forecasting NREL Eastern Renewable Generation Integration Study (ERGIS) Public Model NREL Solar Power Data for Integration Studies NREL Wind Integration National Dataset (WIND) Toolkit WECC Anchor Data Set (ADS) WECC TEPPC Model
Power Flow and Transient Stability	Power flow: topology of network, impedance of lines, load characterization in real and reactive parts, and generator characterization in real and reactive Transient stability analysis: Load and generation dynamic characterization.	WECC databases for the Western Interconnection Reliability First Multiregional Modeling Working Group databases for the Eastern Interconnection

Pulling It Together: Scenario Analysis

Scenario analysis applies all of the principles and helps determine the final reliability plan and answer the identified questions. Scenario analysis consists of selecting the appropriate modeling tool(s), acquiring vetted input data and assumptions for that tool, and finally, properly designing a suite of scenarios that can answer the identified questions.

Coordination and consistency is critical, particularly when selecting relevant tools, data, assumptions, and scenarios to maintain internal consistency across these various modeling tool categories and time horizons. For example, for bulk power system planning, the features and interactions with the distribution system and natural gas systems should all be taken into consideration when appropriate, recognizing the physical linkage between each of these systems. At the same time, the interaction between various time horizons should be captured. For example, investment decisions from resource adequacy modeling have a direct impact on the operational considerations that are evaluated in production cost modeling, and vice versa.

Coordination and consistency aids in the analysis at hand, and also provides a foundation for systematic future analyses. For example, National Renewable Energy Laboratory's (NREL's) Western Wind and Solar Integration Study (WWSIS) maintained a consistent study footprint, and, where possible, a consistent baseline scenario across each of its three phases.[34]

As energy systems become more integrated, coordination between electricity and natural gas, as well as the transportation sector, will likely become increasingly relevant for coherent reliability planning. The details of transportation modeling, including the representation of electric vehicles and rail, are outside of the scope of this document. However, as transportation becomes more electrified, the representation of its behavior will likely become embedded within bulk power and distribution system modeling efforts. The same may be true of demand response technologies.

In Figure 2, each of the modeling tool categories considers different parameters (i.e., "levers") that represent modeling drivers and/or sources of uncertainty. These levers can reflect individual components (e.g., the price of natural gas) or a set of parameters like flexibility features (e.g., faster generator ramp rates, the inclusion of a flexible reserve product, and responsive demand). These levers, pulled in isolation or in combination, are what constitute a scenario. Table 3 provides examples of these levers, as well as relevant model outputs, for each modeling tool type.

Table 3. Examples of Scenario Parameters and Metrics for Each Modeling Tool Category

	Modeling Tool Category	Typical Scenario "Levers"	Key Impact Metrics
Bulk Power System Modeling	Resource adequacy	Technological improvements and load growth over many years; policies; generator capital and fuel cost projections.	Generator and transmission deployment; emissions.
	Production cost modeling	Generator and transmission deployment/retirement; transmission line flow limits; load profiles; operational and fuel costs.	Generation; production costs; emissions.
	Power flow and transient stability	Siting and penetration levels of variable renewables; transmission/distribution system	Power flow magnitudes and timing; frequency and voltage levels.

	Modeling Tool Category	Typical Scenario “Levers”	Key Impact Metrics
		component settings; governor and load modeling.	
Distribution System Modeling	Distribution planning	Distribution system upgrades, such as (a) transformer upgrades, (b) re-conductoring of underground cables, and (c) new greenfield integrations.	Owner quality, reliability metrics (e.g., the system average interruption frequency index or the system average interruption duration index) peak demand head space. Circuit loading, load factor of high cost assets, and utilization of grid assets.
	Quasi-steady state time series analysis	Testing the efficacy of volt/var control strategies for voltage control, determining hosting capacity for renewable technologies (i.e., distributed PV), deployment of smart grid devices.	Hosting capabilities (kW of PV by sections of distribution system circuits, line losses, load shape changes, peak demand reductions.
	Production and fault studies	Protection system capable of bi-directional power flow. Voltage ride-through to explore protective relay settings.	Capabilities of system protection by circuits.
Natural Gas System Modeling	Natural gas pipelines and storage expansion	Economics of pipeline expansion; cost of infrastructure; fuel cost projections; policies; demand growth over many years.	Pipeline capacity and utilization.
	Natural gas system operations	Gas demand; scheduling of gas system operations; physical characteristics of gas system infrastructure.	Pipeline pressure; quantity of gas that can be delivered, often at high temporal resolution.

Scenarios for Modeling Resource Adequacy

For resource adequacy modeling tools, scenarios are often constructed to evaluate the impact of technological improvements, policy changes, or economic conditions on investment decisions over the course of many years. An example of a suite of resource adequacy modeling scenarios to explore a range of possible futures is NREL’s Standard Scenarios, which used NREL’s *Annual Technology Baseline* (ATB) for cost inputs and the Regional Energy Deployment System (ReEDS) capacity expansion model to determine the key drivers in the evolution of the U.S. electricity sector from present to 2050.[35] Key sensitivity parameters included fuel prices, generator and transmission costs, load growth, generator retirement schedules, water usage constraints, and policy assumptions such as renewable and/or clean portfolio standard requirements.

Penetration is defined as the share of generation provided by renewable energy. The Mid-case Scenario applies reference-level assumptions; the bidirectional scenarios explore lower-level and higher-level assumptions for fuel costs, technology capital costs, electricity demand, and retirements. The dashed line in Figure 4 shows historical values.

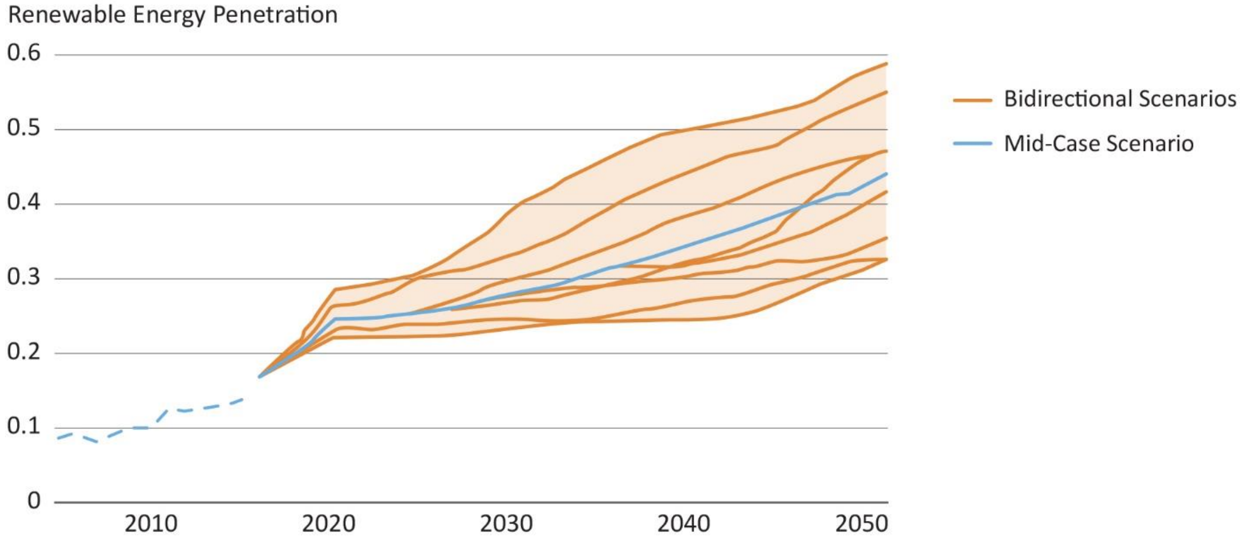

Figure 4. Renewable energy penetration across a subset of the scenarios explored in the NREL Annual Technology Baseline[36]

Scenarios for Modeling Production Cost

Because of its inherent operational timescale, production cost modeling scenarios evaluate the impact of exogenous system configuration and cost assumptions on system operation, cost, and emissions, typically for a temporal extent of 1 year or less. Examples of sensitivity parameters are load profiles, fuel prices, the treatment of ancillary services, transmission line flow limits, generator performance parameters, and variable renewable penetration levels. For example, NREL's Low Carbon Grid Study (LCGS) explored the potential to reduce carbon emissions by 50% in the State of California. It conducted a rigorous scenario-based analysis that not only allowed them to compare generation mixes, but also operational assumptions like flexibility (see Figure 5).[37]

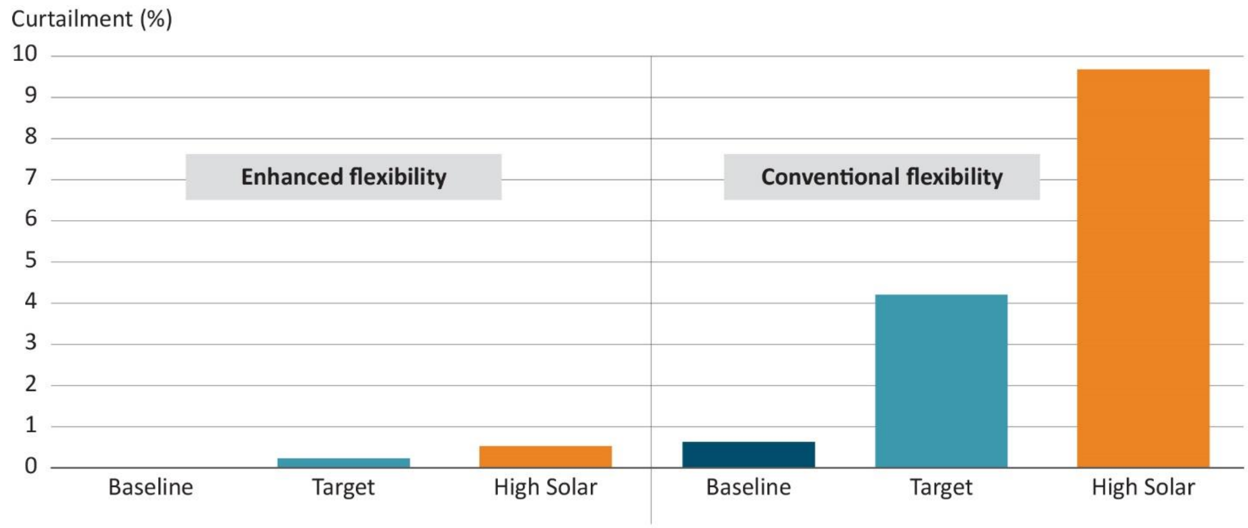

Figure 5. Curtailment in six selected Low Carbon Grid Study scenarios[38]

Scenarios for Modeling Power Flow and Transient Stability

Scenarios run in power flow and transient stability tools typically evaluate the short-term impact of system configuration parameters, including siting and penetration levels of variable renewables, transmission/distribution system component settings, and governor (a device that detects changes in grid frequency and automatically adjusts operations of the generator to maintain a target frequency) and load modeling.[d] For example, NREL's WWSIS Phase 3 operational study evaluated a set of scenarios with various levels of load and renewable (wind and solar) penetration to capture a wide range of possible frequency and voltage responses under these extreme system conditions (shown in Table 4).[39] Four primary study scenarios were developed to represent different system conditions (i.e., light and heavy load) as well as different renewable penetration levels (i.e., base and high renewables). In addition, a sensitivity scenario with extremely high renewable penetration under light load conditions was also considered.

[d] Governor modeling represents the presence and response of governors that are embedded within generators. When signaled by the system operator, a governor controls the frequency response of their generator by adjusting the mechanical power output of the generator. Load modeling captures the end-use, multi-sector demand for electricity (or energy in the case of natural gas or heating/transportation fuels).

Table 4. Load and Renewable Energy Scenarios Considered by the Western Wind and Solar Integration Study, Phase 3

	Light Spring Base	Light Spring High Renewables	Light Spring Extreme	Heavy Summer Base	Heavy Summer High Renewables
Wind (GW)	20.9	27.2	32.6	5.6	14.3
Solar (GW)	4.8	25.6	32.2	1.6	27.2
Penetration (% of total generation)	21%	44%	53%	4%	20%

Energy Systems Integration: Accounting for Evolving Factors

Moving forward, scenarios in each of these categories will likely need to include evolving factors that could impact the buildout and operation of the grid. For example, as the power system shifts to more natural gas-fired production, reliability of the bulk power system will likely have greater sensitivity to natural gas supply, storage, and pipeline constraints, and vice versa, as more and more of the natural gas system is powered with grid-connected electric compressors. The impacts from extreme conditions, such as the Polar Vortex,[e] as well as evolving demand-side factors such as electrification of vehicles, should also be considered during scenario formation.

Utilities and regional reliability organizations are devoting increasing attention to the capability of the natural gas system to deliver natural gas when it is required by end users. Currently, there are a limited number of commercial models available for this type of analysis. Further complicating the ability of entities to analyze these questions are issues with data availability on the natural gas system, due in part to the history and independent nature of the natural gas pipeline network. In addition, certain data (for both electric and natural gas system infrastructure) may qualify as CEII under FERC regulations; data with this designation are subject to more stringent controls on access.

Despite the challenges of undertaking integrated modeling, some entities have pursued integrated electricity and natural gas system analysis in the recent past. For example, Energy Exemplar provides a product for electric unit commitment and security constrained economic dispatch, called PLEXOS, that can represent coupled electric and natural gas systems simulations. Levitan & Associates used a combination of models, the AURORAxmp electricity dispatch model from EPIS, Inc. and their own Gas Pipeline Competition Model (GPCM), to examine natural gas deliverability for the Eastern Interconnection Planning Collaborative.[40] Going forward, integrated natural gas and electric system modeling is likely to become a more common planning tool for stakeholders in regions that are using increasing amounts of natural gas for electricity generation. Growing natural gas and electric system interdependence is just one example of the emerging need for integrated systems modeling; the interaction between the distribution system and the bulk power system also may merit consideration in some regions.

[e] The Polar Vortex was a sustained extreme cold weather event that occurred January 6–8, 2014. The cold temperatures led to several issues with natural gas availability for power generators that threatened the reliability of the bulk power system. Despite the loss of available generation capacity, reliability was maintained throughout the event. For more information, see North American Electric Reliability Corporation (NERC), *Polar Vortex Review* (Atlanta, GA: NERC, September 2014), http://www.nerc.com/pa/rrm/January%202014%20Polar%20Vortex%20Review/Polar_Vortex_Review_29_Sept_2014_Final.pdf.

Applying Principle 3: California Harnesses New Modeling Techniques to Integrate Distributed Energy Resources

In 2013, the State of California adopted amendments to the state's Public Utilities Code to require utilities create distributed resource plans.[41] Specifically, AB-327 instructed that, "Not later than July 1, 2015, each electrical corporation shall submit to the commission a distribution resources plan proposal to identify optimal locations for the deployment of distributed resources…This evaluation shall be based on reductions or increases in local generation capacity needs, avoided or increased investments in distribution infrastructure, safety benefits, reliability benefits, and any other savings the distributed resources provides to the electric grid or costs to ratepayers of the electrical corporation."[42]

In response to AB-327 California's IOUs began developing distributed resource plans (DRPs) to more fully incorporate distributed energy resources (DER), such as rooftop solar, electric vehicles (EVs), or energy storage, into the grid.[43] These DRPs are designed to help utilities develop a methodology to determine the value of DER in specific locations, forecast the growth of DER, demonstrate DER projects, and identify issues surrounding safety, data, and tariffs that can help or hinder DER development.[44] These DRP plans have become increasingly important because of California's unprecedented deployment of DER, like rooftop solar, which has begun to impact the current economic and operational structure of the grid.

Key to IOU efforts to develop DRPs was the use of modeling tools. For example, Pacific Gas and Electric Company (PG&E) utilized their Load Forecast Analysis tool, LoadSEER, to create load profiles, which they then compared against representative DER profiles to determine the DER's hourly impact on every individual feeder in PG&E's distribution system. [45] They then utilized a Power Flow Analysis tool, CYMDIST, to understand the power flow effects on the distribution lines at a granular level.[46] Using this information, PG&E was able to map which of its lines were best suited to additional capacity from DER resources to help inform its customers about where DER investments might be made while maximizing the benefit to the system.[47]

Applying Principle 3: MISO begins to Coordinate Electricity Generation and Natural Gas Deliveries

In October 2012, MISO established the Electric and Natural Gas Coordination Task Force (ENGCTF).[48] ENGCTF's charter directed it to, "Identify challenges related to an expectation of increasing reliance upon natural gas while ensuring reliability of the electric system," and develop, "an approach to resolving identified gas-electric coordination challenges…[and] recommendations for on-going operations, market impacts, and compliance for regulatory deadlines, as associated with gas-electric interdependency." [49]

The creation of ENGCTF was prompted by the changing generation mix in MISO due to its increasing reliance on natural gas as a fuel for electricity generation. Spurred by this transition, MISO convened meetings with stakeholders, including members from both the natural gas and electricity industries, and commissioned several studies of the capability of the natural gas distribution system to meet the growing gas demand offered by power plants. These studies were released in phases. Phases 1 and 2, released in February and July 2012, respectively, examined the northern and central portions of MISO.[50] These studies concluded that, "additional gas pipeline infrastructure is needed to accommodate fuel switching,"[51] and, "to ensure generator availability, gas storage may be required."[52] The result of these MISO studies and stakeholder meetings illustrated the need for a specific MISO entity to address the growing gas-electricity interdependency. Thus, ENGCTF was created.

Since its creation, ENGCTF has "devoted a significant amount of time to cross-industry education," including presentations from various sectors in each industry. Additionally, cross-industry teams were formed to create summary papers containing recommendations on key issues, such as, "Potential Competition between Generator Demand & Upcoming Gas Storage injection" [53] and "Process & Timeline for Natural Gas Infrastructure Build-Out." [54] Beyond ENGCTF, MISO has increased coordination between the electricity and natural gas sectors in other ways. In 2013, MISO conducted an updated Phase 3 analysis[55], which "featured an expanded study footprint, including the newly integrated South Region, and an enhanced methodology, adding a dynamic pipeline modeling component,"[56] that concluded, "*infrastructure expansion is still needed to move gas into the region and to address area-specific capacity constraints.*"[57] This analysis was conducted in addition to other "recommendations aligned with the goals of the ENGCTF."[58] MISO has also begun to use the PLEXOS Integrated Energy Model, which runs "gas and electric models [that] are solved simultaneously allowing decision makers to trade-off gas investments, constraints and costs against other alternatives"[59] to give MISO a "better understanding and planning for future gas-electric system interactions."[60]

Additionally, MISO has updated their control room to include an overlay of the natural gas infrastructure. [61] This overlay is linked to critical notices for pipelines and operational flow orders from all pipelines in the MISO footprint, as well as to a database linking gas-fired generators to their fuel sources. [62] Beginning in November 2016, MISO will align the day-ahead markets for both electricity and natural gas.[63] This will mean listing the results from the day-ahead electricity market at least 30 minutes earlier in order to give "committed" gas-fired units time to procure gas and pipeline transportation during the gas industry's "Timely" scheduling window.[64]

APPENDIX A: DATA SOURCES

Each of the power system planning study types defined in Figure 2 require different input data. For resource adequacy tools, investment cost and natural gas fuel price assumptions are key drivers in capacity expansion model results. The National Renewable Energy Laboratory (NREL) has established a formal, annual process for producing an internally-consistent set of investment and operating cost inputs for conventional and renewable resources in its *Annual Technology Baseline* (ATB) database.[65] Capital cost trajectories from the 2015 ATB for select technologies are shown in Figure A-1. Another common source for cost data is the EIA's *Annual Energy Outlook* (AEO). The delivered electric sector natural gas fuel price trajectories for four scenarios from AEO 2015 are summarized in Figure A-2.[f] In addition, the National Energy Technology Center (NETL) publishes cost and performance data for fossil-based generators through its Baseline Studies for Fossil Energy Plants.[g]

Similar to NREL's ATB cost inputs for its capacity expansion modeling efforts, Western Electricity Coordinating Council (WECC) is developing a standardized dataset to align assumptions used in production cost, power flow, and dynamics modeling work. This Anchor Data Set (ADS) intends to provide a consistent and coordinated planning dataset of loads, resources, and transmission topology 10 years into the future.[66]

Key model inputs for production cost models include temporally and spatially resolved wind and solar data. Data sources for such U.S. wind and solar profiles include NREL's Wind Integration National Dataset (WIND) Toolkit, which includes 5-minute wind resource and hourly forecast datasets, and the National Solar Radiation Database (NSRDB), which includes hourly solar resource data. Examples of these types of data are shown in Figures A-3 and A-4.[67] NREL is developing wind datasets for select countries, including Mexico and Canada.

Production cost tools also require detailed parameters for system components, such as thermal generators. An example of production cost model thermal plant data, which was used in NREL's Eastern Renewable Generation Integration Study (ERGIS), is summarized by generator type in Table A-1.[68]

[f] These prices reflect the 2015 average heat content for natural gas of 1,000 cubic feet (Mcf)= 1.032 million British thermal units (MMBtu). See "Table A4. Approximate Heat Content of Natural Gas," Energy Information Administration, *Monthly Energy Review*, December 2016, https://www.eia.gov/totalenergy/data/monthly/pdf/sec13_4.pdf.
[g] See "Baseline Studies Overview," National Energy Technology Laboratory, http://www.netl.doe.gov/research/energy-analysis/baseline-studies.

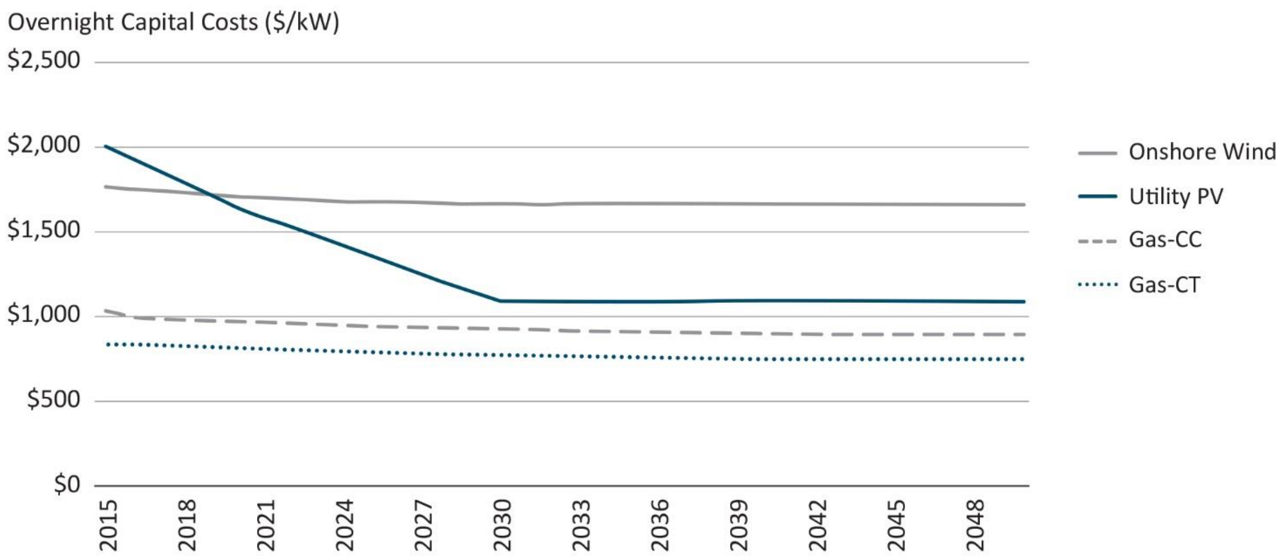

Figure A-1. NREL's ATB capital cost trajectories (2015$)

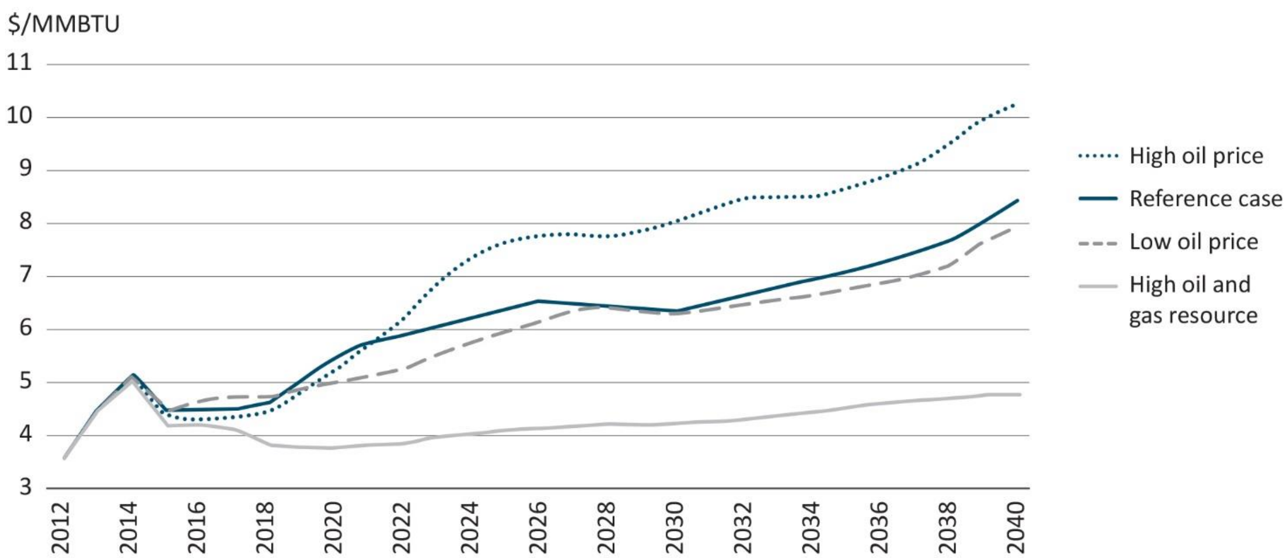

Figure A-2. AEO 2015 natural gas fuel projections (2015$)

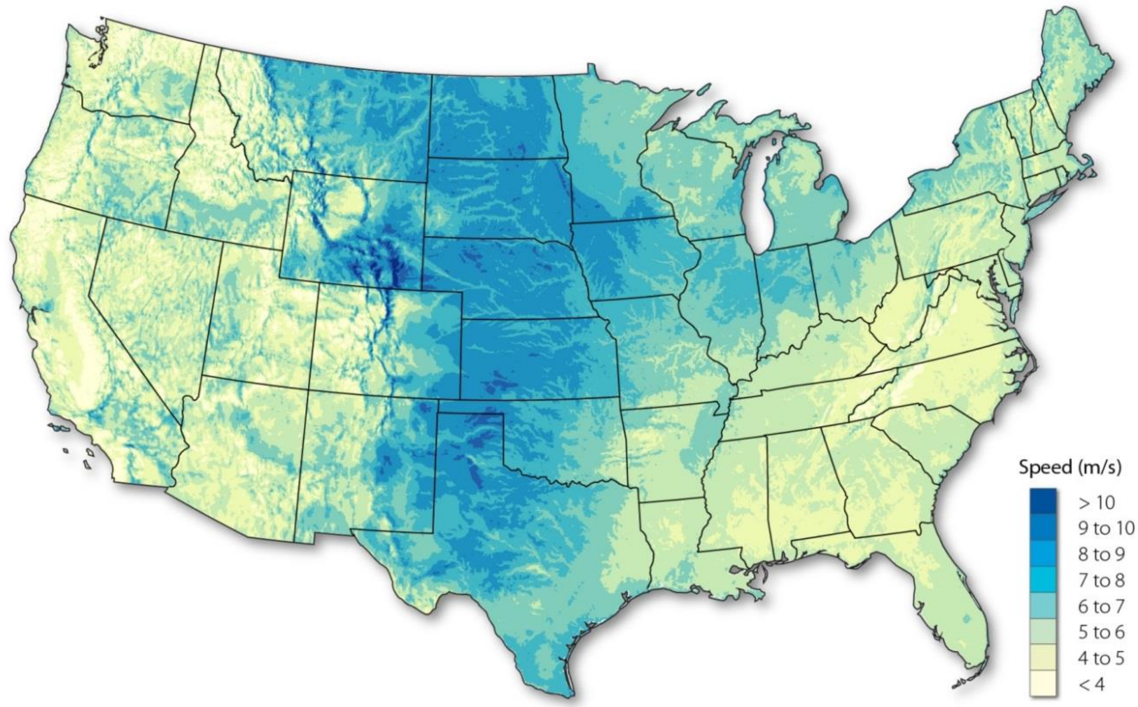

Figure A-3. Average annual wind speed at 100m as modeled by AWS, which is reflective of the type of data available in NREL's WIND Toolkit wind resource dataset

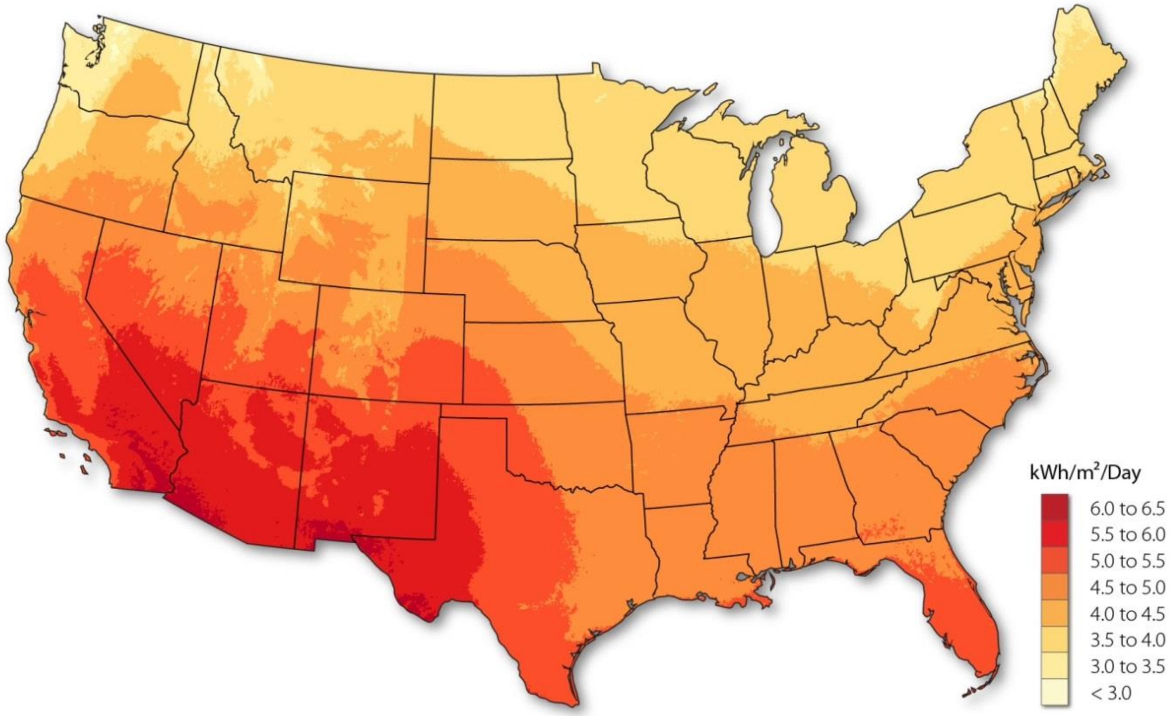

Figure A-4. Average annual global horizontal irradiance in NREL's NSRDB solar resource dataset

Table A-1. Thermal Plant Capability Data from Eastern Renewable Generation Integration Study

Category	CT	CC	Coal	Oil/Gas Boiler	Nuclear
Minimum Generation Level[a] (% of Maximum Capacity)	60	50	50 (<600 MW) 30 (>600 MW)	30 (<600 MW) 20 (>600 MW)	100
Average Heat Rate at Minimum Generation Level[a] (% of Full-Load Average Heat Rate)	100	113	106	110	100
Minimum Up Time[a] (Hours)	0	6	24	10	N/A
Minimum Down Time[a] (Hours)	0	8	12	8	N/A
Ramp Rate[b] (% of Maximum Capacity per Minute)	8	5	2	4	N/A
Startup Cost[c] ($/MW of Maximum Capacity)	69	79	129	129	0
Variable Operations and Maintenance Cost[c] ($/MWh)	0.6	1	2.8	0.9	2.8
Annual Outage Rates[d] (Sum of Forced and Maintenance Outages) (% of Year)	7.6–12.0	10.9	12.1–17.1	9.8–26.0	8.9–14.1

[a] Adopted from the Eastern Interconnection Planning Collaborative with minor changes (see text for details).

[b] From Black and Veatch 2012.

[c] From Kumar et al. 2012.

[d] From GADS 2015.

Power flow and transient stability tools include power models without any disturbances, as well as dynamic models with parameters of every dynamic component, such as generators, exciters, turbine governors, DC and AC systems, and loads. Data are required for both the system that is being analyzed as well as neighboring networks.

For transmission network modeling, utilities and operators typically have the best available power flow and dynamic databases for their own systems due to their first-hand knowledge. To model the remainder of the grid, planners rely on databases compiled by interconnection-wide organizations. In the United States, WECC develops databases for the Western Interconnection, and the Reliability First Multiregional Modeling Working Group (MMWG) develops databases for the Eastern Interconnection.

At the distribution system level, much of the modeling effort is now focused on the impact of the increasing number and size of PV systems being interconnected to the grid. This requires examination of many hours across the year at a very fine temporal resolution. Sub-hourly solar resource data are available to the public from NREL (Solar Power Data for Integration Studies[h]) and for a fee from IBM (Hybrid Renewable Energy Forecasting, or HyRef[i]) and Clean Power Research (SolarAnywhere high-resolution dataset[j]).

[h] See "Solar Integration Energy Sets," National Renewable Energy Laboratory, http://www.nrel.gov/electricity/transmission/solar_integration_methodology.html.
[i] See "Made in IBM Labs: IBM Drives the Future of Renewable Energy with New Wind and Solar Forecasting System," IBM, August 12, 2013, http://www-03.ibm.com/press/us/en/pressrelease/41310.wss.
[j] See "SolarAnywhere," Clean Power Research, http://www.cleanpower.com/products/solaranywhere/sa-data/.

ENDNOTES

[1] Federal Energy Regulatory Commission, *Staff White Paper on Guidance Principles for Clean Power Plan Modeling: Docket No. AD16-14-000* (Washington, DC: Federal Energy Regulatory Commission, January 2016), 16, accessed June 27, 2016 http://www.ferc.gov/legal/staff-reports/2016/modelingwhitepaperAD16-14.pdf. See also Eastern Interconnection States' Planning Council, "Study on Long-term Electric and Natural Gas Infrastructure Requirements in the Eastern Interconnection," (Washington, DC: EISPC, 2014), 1, accessed November 1, 2016, http://pubs.naruc.org/pub/536DFAF7-2354-D714-512C-1BA1BBD00009.

[2] Bryan Palmintier, Robert Broderick, Barry Mather, Michael Coddington, Kyri Baker, Fei Ding, Matthew Reno, Matthew Lave, and Ashwini Bharatkumar, *On the Path to SunShot: Emerging Issues and Challenges in Integrating Solar with the Distribution System*, (Golden, CO: National Renewable Energy Laboratory, 2016), NREL/TP-5D00-65331, 1, accessed November 1, 2016, http://www.nrel.gov/docs/fy16osti/65331.pdf.

[3] Mark F. Ruth and Benjamin Kroposki, "Energy Systems Integration: An Evolving Energy Paradigm," *The Electricity Journal* 27, no. 6 (2014): 36–47, http://dx.doi.org/10.1016/j.tej.2014.06.001.

[4] James McCalley, Ward Jewell, Thomas Mount, Dale Osborn, and Jeff Fleeman, "A Wider Horizon: Technologies, Tools, and Procedures for Energy Systems Planning at the National Level," *IEEE Power and Energy* Magazine (2011): 42–54.

[5] R. Gutman and E. R. Wilcox, "21st Century Transmission Planning: The Intersection of Engineering, Economics, and Environment" (presented at the Integration of Wide-Scale Renewable Resources Into the Power Delivery System, CIGRE/IEEE PES Joint Symposium, Calgary, Alberta, July 29–31, 2009), 1-17, http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5211171. See also: Midcontinent Independent System Operator (MISO), *MTEP14 MVP Triennial Review: A 2014 review of the Public Policy, Economic, and Qualitative Benefits of the Multi-Value Project Portfolio* (MISO, 2014), https://www.misoenergy.org/Library/Repository/Study/Candidate%20MVP%20Analysis/MTEP14%20MVP%20Triennial%20Review%20Report.pdf.

[6] Midcontinent Independent Systems Operator (MISO), "Order 890 Planning Compliance Strawman" (presented at Midwest ISO FERC Technical Conference, Pittsburg, Pennsylvania, June 29, 2007), http://www.ferc.gov/CalendarFiles/20070705100428-8-MISO.pdf.

[7] "Alignment of Key Infrastructure Planning Processes," California Public Utilities Commission (CPUC), California Energy Commission (CEC), and California Independent System Operator (CAISO), December 23, 2014, https://www.caiso.com/Documents/TPP-LTPP-IEPR_AlignmentExplanatoryText.pdf. See also: "DPS – Reforming the Energy Vision," New York State Department of Public Services, accessed November 1, 2016, http://www3.dps.ny.gov/W/PSCWeb.nsf/All/CC4F2EFA3A23551585257DEA007DCFE2?OpenDocument.

[8] Federal Energy Regulatory Commission, *Staff White Paper on Guidance Principles for Clean Power Plan Modeling: Docket No. AD16-14-000* (Washington, DC: Federal Energy Regulatory Commission, January 2016), 4-5, accessed June 27, 2016 http://www.ferc.gov/legal/staff-reports/2016/modelingwhitepaperAD16-14.pdf.

[9] "Order No. 1000 - Transmission Planning and Cost Allocation," Federal Energy Regulatory Commission, last modified March 17, 2016, http://www.ferc.gov/industries/electric/indus-act/trans-plan.asp.

[10] "Order No. 1000 Transmission Planning Regions," Federal Energy Regulatory Commission, https://www.ferc.gov/industries/electric/indus-act/trans-plan/trans-plan-map.pdf. See also, "Order No. 1000 - Transmission Planning and Cost Allocation," Federal Energy Regulatory Commission, https://www.ferc.gov/industries/electric/indus-act/trans-plan.asp.

[11] "Critical Energy Infrastructure Information (CEII) Regulations," Federal Energy Regulatory Commission, last modified June 28, 2010, http://www.ferc.gov/legal/maj-ord-reg/land-docs/ceii-rule.asp

[12] "Standard TPL-001-4 — Transmission System Planning Performance Requirements," North American Electricity Reliability Council, http://www.nerc.com/_layouts/PrintStandard.aspx?standardnumber=TPL-001-4&title=Transmission%20System%20Planning%20Performance%20Requirements&jurisdiction=United%20States.

[13] "Datasets," Western Electricity Coordinating Council, accessed November 1, 2016, https://www.wecc.biz/SystemAdequacyPlanning/Pages/Datasets.aspx. See also: "Scenario Planning," Western Electricity Coordinating Council, accessed November 1, 2016, https://www.wecc.biz/SystemAdequacyPlanning/Pages/Scenario-Planning.aspx.

[14] "Calendar," Western Electricity Coordinating Council, https://www.wecc.biz/Pages/Calendar.aspx.

[15] Thomas Carr, "Evolution of Grid Planning in the West" (presented at CREPC/WIRAB Meeting, Salt Lake City, UT, April 27, 2016), 12, accessed July 26, 2016, http://westernenergyboard.org/wp-content/uploads/2016/04/04-27-16_CREPC_WIRAB_carr_future_interconnection_wide_planning_analysis.pdf.

[16] Northwest Power and Conservation Council, *Seventh Northwest Conservation and Electric Power Plan* (Portland, Oregon: Northwest Power and Conservation Council, February, 2016), 1-1, accessed July 26, 2016, http://www.nwcouncil.org/media/7149940/7thplanfinal_allchapters.pdf.

[17] Northwest Power and Conservation Council, *Seventh Northwest Conservation and Electric Power Plan* (Portland, Oregon: Northwest Power and Conservation Council, February, 2016), 1-5, accessed July 26, 2016, http://www.nwcouncil.org/media/7149940/7thplanfinal_allchapters.pdf.

[18] Peter Evans, "Consultant Report prepared for the California Energy Commission: Regional Transmission and Distribution Network Impacts Assessment for Wholesale Photovoltaic Generation," August, 2014, Contract Number: 800-10-001; WA1930.007, http://www.energy.ca.gov/2014publications/CEC-200-2014-004/CEC-200-2014-004.pdf.

[19] "High-Definition™ Network Model" New Power Technologies, http://www.newpowertech.com/energynetplatform/highdefinitionwideareanetworkmodel.html.

[20] "Distribution System Analysis," Eaton, accessed November 1, 2016, http://www.cyme.com/software/cymdist/.

[21] "EasyPower® Electrical Software," Easy Power, http://www.easypower.com/products/EasyPower/EasyPower_family.php

[22] "Simulation Tool – OpenDSS," Electric Power Research Institute, http://smartgrid.epri.com/SimulationTool.aspx

[23]"GridLAB-D," last updated December, 2012, http://www.gridlabd.org/

[24] K. P. Schneider, Y. Chen, D. Engle, and D. Chassin, "A Taxonomy of North American Radial Distribution Feeders," (presented at 2009 IEEE PES General Meeting); see also, K. Schneider, Y. Chen, D. Chassin, R. Pratt, D. Engel, and S. Thompson, *Modern Grid Initiative Distribution Taxonomy Final Report* (Richland, WA: Pacific Northwest National Laboratory, 2008), http://www.gridlabd.org/models/feeders/taxonomy_of_prototypical_feeders.pdf.

[25] Paul Ciampoli, "FERC examines seams coordination between MISO and PJM," *Public Power Daily,* January 27, 2015, http://www.publicpower.org/media/daily/ArticleDetail.cfm?ItemNumber=43054

[26] "Pacific Northwest Power Supply Adequacy Assessment for 2020-21," Northwest Power and Conservation Council, May 6, 2015, http://www.nwcouncil.org/energy/powersupply/2015-05/

[27]"Energy Imbalance Market (EIM) Overview" California Independent System Operator,

https://www.caiso.com/informed/Pages/EIMOverview/Default.aspx

[28] California ISO, "ISO Markets and Energy Imbalance Market Update." (Folsom, CA: California ISO, July 12, 2016), 3, accessed November 1, 2016, https://www.wecc.biz/Administrative/WECC%20MIC%20Update%2020160712.pdf. See also: FERC, "Commission Staff Paper: Qualitative Assessment of Potential Reliability Benefits from a Western Energy Imbalance Market." (Washington, DC: FERC, February 26, 2013), accessed November 1, 2016, http://www.caiso.com/Documents/QualitativeAssessment-PotentialReliabilityBenefits-WesternEnergyImbalanceMarket.pdf.

[29] California Public Utilities Commission," CPUC Ensures Customers Continue to Benefit from Going Solar by Approving New Net Metering Guidelines." (San Francisco, CA: California Public Utilities Commission, January 28, 2016), accessed November 1, 2016, http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M158/K181/158181664.PDF.

[30] State of Nevada Public Utilities Commission, "PUCN to Consider Revised Rates for Customers Who Participate in Net Energy Metering." (Carson City, NV: State of Nevada Public Utilities Commission, December 21, 2015), accessed November 1, 2016, http://pucweb1.state.nv.us/PDF/AXImages/PRESS_RELEASES/300.pdf.

[31] Fairley, P. "Zombie Coal Plants Reanimated to Stabilize the Grid," IEEE Spectrum, July 24, 2015, accessed December 20, 2016, http://spectrum.ieee.org/energy/the-smarter-grid/zombie-coal-plants-reanimated-to-stabilize-the-grid. See also: Rob D'Aquila, "Examining Reliability with High Renewables and Coal Retirements: Experiences from Recent Studies" (Presented at the Joint CREPC-SPSC-WIRAB Meeting, San Diego, California, October 29, 2015), 4, 4, 23, http://westernenergyboard.org/wp-content/uploads/2015/10/10-30-15_CREPC-SPSC-WIRAB_daquila_examining_reliability_high_renewables_and_coal_retirements.pdf.

[32] Rob D'Aquila, "Examining Reliability with High Renewables and Coal Retirements: Experiences from Recent Studies" (Presented at the Joint CREPC-SPSC-WIRAB Meeting, San Diego, California, October 29, 2015), 4, 4, 23, http://westernenergyboard.org/wp-content/uploads/2015/10/10-30-15_CREPC-SPSC-WIRAB_daquila_examining_reliability_high_renewables_and_coal_retirements.pdf.

[33] FERC, "Staff White Paper on Guidance Principles for Clean Power Plan Modeling." Appendix A. Docket No. AD16-14-000. https://www.ferc.gov/legal/staff-reports/2016/modelingwhitepaperAD16-14.pdf. Accessed March 17, 2016.

[34] "Western Wind and Solar Integration Study," National Renewable Energy Laboratory, accessed November 1, 2016, http://www.nrel.gov/grid/wwsis.html.

[35] Wesley Cole, Trieu Mai, Jeffrey Logan, Daniel Steinberg, James McCall, James Richards, Benjamin Sigrin, and Gian Porro, *2016 Standard Scenarios Report: A U.S. Electricity Sector Outlook* (Golden, CO: National Renewable Energy Laboratory, 2016), NREL/TP-6A20-66939, http://www.nrel.gov/analysis/data_tech_baseline.html.

[36] Wesley Cole, Trieu Mai, Jeffrey Logan, Daniel Steinberg, James McCall, James Richards, Benjamin Sigrin, and Gian Porro, *2016 Standard Scenarios Report: A U.S. Electricity Sector Outlook* (Golden, CO: National Renewable Energy Laboratory, 2016), NREL/TP-6A20-66939, vii, http://www.nrel.gov/docs/fy17osti/66939.pdf.

[37] D. Lew, G. Brinkman, E. Ibanez, A. Florita, M. Heaney, B.-M. Hodge, M. Hummon, G. Stark, J. King, S.A. Lefton, N. Kumar, D. Agan, G. Jordan, and S. Venkataraman, *The Western Wind and Solar Integration Study Phase 2* (Golden, CO: National Renewable Energy Laboratory, 2013), NREL/TP-5500-55588, http://www.nrel.gov/docs/fy13osti/55588.pdf. See also: Bloom et al., *Eastern Renewable Generation Integration Study* (Golden, CO: National Renewable Energy Laboratory, August 2016), http://www.nrel.gov/grid/ergis.html.

[38] G. Brinkman, J. Jorgenson, A. Ehlen, and J. Caldwell, "Lowe Carbon Grid Study: Analysis of a 50% Emissions Reduction in California," (Golden, CO: National Renewable Energy Laboratory, November 2016), vii, accessed November 1, 2016, http://www.nrel.gov/docs/fy16osti/64884.pdf.

[39] N. W. Miller, M. Shao, S. Pajic, and R. D'Aquila, *Western Wind and Solar Integration Study Phase 3 – Frequency Response and Transient Stability*, (Golden, CO: National Renewable Energy Laboratory, 2014), NREL/SR-5D00-62906, http://www.nrel.gov/docs/fy15osti/62906.pdf.

[40] "Gas-Electric Documents," Eastern Interconnection Planning Collaborative, accessed November 1, 2016, http://www.eipconline.com/gas-electric-documents.html.

[41] "AB-327 Electricity: Natural Gas: Rates: Net Energy Metering: California Renewables Portfolio Standard Program," State of California Legislative Information, §8, accessed August 1, 2016, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140AB327.

[42] "AB-327 Electricity: Natural Gas: Rates: Net Energy Metering: California Renewables Portfolio Standard Program," State of California Legislative Information, §8, accessed August 1, 2016, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140AB327. See also "DRP Proceeding Overview," State of California Public Utilities Commission, accessed August 1, 2016, http://www.cpuc.ca.gov/General.aspx?id=5071.

[43] "PG&E's Distribution Resources Plan Webinar" PG&E, 5, accessed August 1, 2016, http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=5140.

[44] "PG&E's Distribution Resources Plan Webinar" PG&E, 6, accessed August 1, 2016, http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=5140.

[45] "PG&E's Distribution Resources Plan Webinar" PG&E, 14, accessed August 1, 2016, http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=5140.

[46] "PG&E's Distribution Resources Plan Webinar" PG&E, 14, accessed August 1, 2016, http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=5140.

[47] "PG&E's Distribution Resources Plan Webinar" PG&E, 19, accessed August 1, 2016, http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=5140.

[48] "6.3 Electric-Gas Coordination," MISO, accessed August 1, 2016, http://www.misomtep.org/electric-gas-coordination/.

[49] "6.3 Electric-Gas Coordination," MISO, accessed August 1, 2016, http://www.misomtep.org/electric-gas-coordination/.

[50] Gregory Peters, Gas and Electric Infrastructure Interdependency

Analysis (Richmond, VA: EnVision Energy Solutions, 2012), accessed August 1, 2016, https://www.misoenergy.org/Library/Repository/Communication%20Material/Key%20Presentations%20and%20Whitepapers/Natural%20Gas-Electric%20Infrastructure%20Interdependency%20Analysis_022212_Final%20Public.pdf.

[51] Midcontinent Independent System Operator (MISO), *Gas-Electric Infrastructure Analysis Phase 1 and Phase 2: 2011–2030, MISO Region*. (MISO: Carmel, IN, 2012), 3, accessed August 1, 2016, https://www.misoenergy.org/Library/Repository/Communication%20Material/Key%20Presentations%20and%20Whitepapers/Overview%20Phase%202%20Gas%20Electric%20Instrastructure%20Analysis.pdf.

[52] Midcontinent Independent System Operator (MISO), *Gas-Electric Infrastructure Analysis Phase 1 and Phase 2: 2011–2030, MISO Region*. (MISO: Carmel, IN, 2012), 3, accessed August 1, 2016, https://www.misoenergy.org/Library/Repository/Communication%20Material/Key%20Presentations%20and%20Whitepapers/Overview%20Phase%202%20Gas%20Electric%20Instrastructure%20Analysis.pdf.

[53] "6.3 Electric-Gas Coordination," MISO, accessed August 1, 2016, http://www.misomtep.org/electric-gas-coordination/.

[54] "6.3 Electric-Gas Coordination," MISO, accessed August 1, 2016, http://www.misomtep.org/electric-gas-coordination/.

[55] Gregory L. Peters, Justin Carlson, Rick Notarianni, and Jeff Moore, *Phase III: Natural Gas-Fired Electric Power Generation Infrastructure Analysis; An Analysis of Pipeline Capacity Availability* (Midcontinent Independent Transition System Operator, 2013), https://www.misoenergy.org/Library/Repository/Communication%20Material/Key%20Presentations%20and%20Whitepapers/Phase%20III%20Gas-Electric%20Infrastructure%20Report.pdf.

[56] "MTEP15 Chapter 6.3 Gas-Electric Coordination," MISO, accessed August 1, 2016, http://www.misomtep.org/electric-gas-coordination-mtep15/.

[57] Gregory L. Peters, Justin Carlson, Rick Notarianni, and Jeff Moore, *Phase III: Natural Gas-Fired Electric Power Generation Infrastructure Analysis; An Analysis of Pipeline Capacity Availability* (Midcontinent Independent Transition System Operator, 2013), 123, https://www.misoenergy.org/Library/Repository/Communication%20Material/Key%20Presentations%20and%20Whitepapers/Phase%20III%20Gas-Electric%20Infrastructure%20Report.pdf.

[58] "MTEP15 Chapter 6.3 Gas-Electric Coordination," MISO, accessed August 1, 2016, http://www.misomtep.org/electric-gas-coordination-mtep15/.

[59] "PLEXOS® Integrated Energy Model," Energy Exemplar Pty. Ltd., accessed August 1, 2016, http://energyexemplar.com/software/plexos-desktop-edition/.

[60] "MTEP15 Chapter 6.3 Gas-Electric Coordination," MISO, accessed August 1, 2016, http://www.misomtep.org/electric-gas-coordination-mtep15/.

[61] "6.3 Electric-Gas Coordination," MISO, accessed August 1, 2016, http://www.misomtep.org/electric-gas-coordination/.

[62] "6.3 Electric-Gas Coordination," MISO, accessed August 1, 2016, http://www.misomtep.org/electric-gas-coordination/.

[63] "Electricity and Natural Gas Markets Align," MISO, accessed August 1, 2016, http://www.misomatters.org/2016/04/electricity-and-natural-gas-markets-align/.

[64] "Electricity and Natural Gas Markets Align," MISO, accessed August 1, 2016, http://www.misomatters.org/2016/04/electricity-and-natural-gas-markets-align/.

[65] *Annual Technology Baseline,* National Renewable Energy Laboratory, 2016, http://www.nrel.gov/analysis/data_tech_baseline_legacy.html.

[66] G. Lemler, *WECC Anchor Data Set Proposal* (Western Electricity Coordinating Council, 2016), https://www.wecc.biz/Administrative/Anchor%20Data%20Set%20Proposal%20v4.pdf.

[67] C. Draxl, B. M. Hodge, A. Clifton, and J. McCaa, "The Wind Integration National Dataset (WIND) Toolkit," *Applied Energy* 151 (2015): 355–366, http://dx.doi.org/10.1016/j.apenergy.2015.03.121; see also M. Sengupta, A. Weekley, A. Habte, A. Lopez, C. Molling, A. Heidinger, *Validation of the National Solar Radiation Database (NSRDB) (2005–2012): Preprint* (Golden, CO: National Renewable Energy Laboratory, 2015), NREL/CP-5D00-64981, http://www.nrel.gov/docs/fy15osti/64981.pdf.

[68] Aaron Bloom, Aaron Townsend, David Palchak, Josh Novacheck, Jack King, Matthew O'Connell, Eduardo Ibanez, Gary Jordan, Clayton Barrows, Marissa Hummon, and Caroline Draxl, *Eastern Renewable Generation Integration Study* (Golden, CO: National Renewable Energy Laboratory, 2016), NREL/TP-6A20-64472, http://www.nrel.gov/docs/fy16osti/64472.pdf.