NERC

NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Task 1.6

Probabilistic Methods

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RELIABILITY | ACCOUNTABILITY

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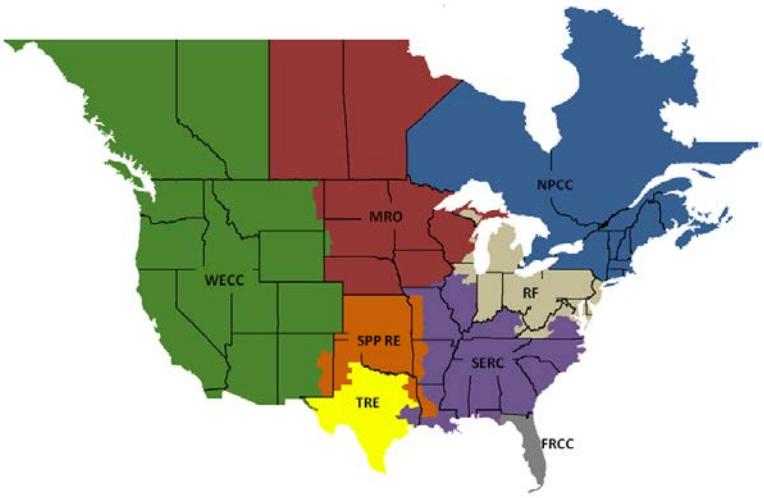
Preface

The North American Electric Reliability Corporation (NERC) is a not-for-profit international regulatory authority whose mission is to ensure the reliability of the bulk power system (BPS) in North America. NERC develops and enforces Reliability Standards; annually assesses seasonal and long-term reliability; monitors the BPS through system awareness; and educates, trains, and certifies industry personnel. NERC's area of responsibility spans the continental United States, Canada, and the northern portion of Baja California, Mexico. NERC is the electric reliability organization (ERO) for North America, subject to oversight by the Federal Energy Regulatory Commission (FERC) and governmental authorities in Canada. NERC's jurisdiction includes users, owners, and operators of the BPS, which serves more than 334 million people.

The North American BPS is divided into several assessment areas within the eight Regional Entity (RE) boundaries, as shown in the map and corresponding table below.



FRCC	Florida Reliability Coordinating Council
MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
SPP-RE	Southwest Power Pool Regional Entity
TRE	Texas Reliability Entity
WECC	Western Electricity Coordinating Council

Acronyms

BA – Balancing Area

CAISO – California ISO

CREZ – Competitive Renewable Energy Zone

ELCC – Effective Load Carrying Capability

EPRI – Electric Power Research Institute

EUE – Expected Unserved Energy

EWITS – Eastern Wind Integration and Transmission Study

GIS – Geographical Information System

HILP – High-Impact, Low-Probability

IEEE – Institute of Electrical and Electronics Engineers

IRRE – Insufficient Ramping Resource Expectation

IVGTF – Integration of Variable Generation Task Force

LOLE – Loss of Load Expectation

LOLH – Loss of Load Hours

LOLP – Loss of Load Probability

MISO – Midcontinent (formerly Midwest) ISO

NREL – National Renewable Energy Laboratory

NXT – Network Expansion Tool

RAS – Remedial Action Schemes

SCDT – Study Case Development Tool

SCED – Security Constrained Economic Dispatch

SCUS - Security Constrained Unit Commitment

TransCARE – Transmission Contingency and Reliability Evaluation

PV – Photovoltaic

VG – Variable Generation

WECC – Western Electricity Coordinating Council

WREZ – Western Renewable Energy Zone

Executive Summary

The 2009 NERC Integration of Variable Generation Task Force (IVGTF) special report *Accommodating High Levels of Variable Generation* concluded that as the penetration of variable generation (VG) reaches relatively high levels, the characteristics and operation of the bulk power system (BPS) will be significantly altered due to overall system variability and the amount of uncertainty encountered in the challenges of system operation (referred to in this report as decision problems). The IVGTF report highlighted the need for risk assessment and probabilistic methods to assist in the integration of VG, primarily in the context of planning, but also for operations.

The purpose of this report is to inform industry of the variety of probabilistic methods currently being researched, to encourage further probabilistic research development, and to highlight the need for using risk assessment to assist in the integration of variable generation (VG). Variability and uncertainty are not new to the power system, but increased attention on probabilistic methods reflects advancements in computing speed and algorithms. Growing levels of wind and solar energy also serve as catalysts for these efforts.

This report notes that most activity in probabilistic methods for integrating VG in power systems is still in the research domain. The probabilistic tools and techniques being developed by the research community have not yet been widely adopted by industry. However, this is an area of very active and vibrant research. Certain power system planning and operating problems have inherently probabilistic components; and while deterministic methods and models have served us well in the past, the use of probabilistic methods can complement these deterministic methods to ensure more optimal and effective solutions in the future. One such example, the growing penetrations of variable generation, with the attendant variability and uncertainty of the meteorological variables that fuel such generation, will further serve to make probabilistic methods useful and valuable.

There are many challenges facing the widespread deployment of probabilistic methods. Research scale tools and models are being developed and deployed on small representative test systems, but despite faster and relatively inexpensive computation platforms, they are not yet demonstrated to be practical for the full detail of real systems. There is an understandable reluctance on the part of industry to adopt probabilistic methods that initially appear to be very complex and difficult to understand. Furthermore, probabilistic methods require significant amounts of data that may not exist or are difficult and expensive to acquire.

Despite these challenges, the potential benefits and the changing nature of the power system could outweigh the present limitations in the use of probabilistic methods; therefore, the power industry as a whole should continue investigating the application of probabilistic methods for some circumstances. Sophisticated probabilistic methods will help system operators and planners address the challenges in the future state of increased reliance on non-traditional sources such as variable generation, distributed generation, demand response, and other elements which increase variability and uncertainty in both the operational and planning time horizons. This report includes recommendations to encourage the continuing development of these methods.

Introduction

In April 2009, the IVGTF released its landmark special report *Accommodating High Levels of Variable Generation.*[1] One of its primary findings was that as the penetration of variable generation (VG) reaches relatively high levels, the characteristics and operation of the BPS will be significantly altered. The primary drivers of this change are the increases in the overall system variability and amount of uncertainty encountered in decision problems.

The IVGTF report resulted in a number of conclusions and recommendations for developing the planning and operational practices, as well as the methods and resources needed to integrate variable generation resources into the BPS. The report highlighted the need for risk assessment and probabilistic methods to assist in the integration of VG. It did so primarily in the context of planning, but numerous references throughout the report also suggested that operations could benefit from improved methods, broadly referred to as "probabilistic methods."

Multiple tasks arose from the recommendations of the NERC IVGTF report. Task 1.6, which focused on probabilistic methods, is the subject of this report and reflects the increased attention that these methods are receiving. Variability and uncertainty are not new to the power system; part of this increased attention on probabilistic methods reflects advancements in computing speed and algorithms—methods that were previously intractable due to data size and computer processing time are increasingly within our reach. But growing levels of wind and solar energy are clearly serving as catalysts for these efforts. For example, the NERC *2012 Summer Reliability Assessment*[2] points out that more probabilistic-based methods will be needed as the penetration of wind energy (and solar energy) increases on the BPS.

To various degrees, other IVGTF tasks are related to probabilistic methods and are referenced as appropriate in this report. Task 1.2, "Methods to Model and Calculate Capacity Contributions of Variable Generation for Resource Adequacy Planning,"[3] and Task 1.4, "Flexibility Requirements and Metrics for Variable Generation: Implications for System Planning Studies"[4] are particularly relevant and in many ways are subsets of the probabilistic methods reported here.

The objective of this report is to summarize the potential influence on power system operating and planning decision problems of increased uncertainty caused by high VG penetration levels, and to describe the role that probabilistic methods can play in improving the basis on which the various decisions are made. While the construction of facilities to maintain a certain level of resource adequacy is outside of NERC's purview, this report endeavors to cover the topic of probabilistic methods in a comprehensive way and explore potential opportunities for enhanced planning approaches.

Decision Problems and Associated Uncertainties

There are six classes of decision problems in power systems engineering that are influenced by uncertainties associated with increased levels of VG penetration. They are:

1. Reserves: How much and what type of regulation and contingency reserves are necessary in the next 10 minutes, next hours, and next day?
2. Dispatch: How will generation be dispatched in the next 10 minutes?

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[1] http://www.nerc.com/files/IVGTF_Report_041609.pdf
[2] http://www.nerc.com/files/2012SRA.pdf
[3] http://www.nerc.com/files/ivgtf1-2.pdf
[4] http://www.nerc.com/files/IVGTF_Task_1_4_Final.pdf

3. Commitment: How should unit commitment be scheduled in the next hours and next day?
4. Maintenance: When should generation and transmission be allowed to be scheduled out of service for maintenance in the next month, season, or year?
5. Generation planning: How much and what type of capacity should be developed, and where, over next one to five years; next 10 years?
6. Transmission planning: How much and where should additional transmission capacity be developed over the next one to five years; next 10 years?

Associated uncertainties may be grouped into three classes: a) operating conditions (e.g., megawatt generation and load); b) element unavailability due to failure or maintenance (e.g., generation resource, transmission circuit, protective device); and c) performance of an element (e.g., speed of breaker to open or speed of a unit to ramp). Decision problems influenced by VG encounter increased uncertainty in the first two classes (a and b) and increased significance of the uncertainty in the third class (c). The most obvious of these is that for class a, operating conditions become more uncertain due to the inherent uncertainty in the wind and solar forecast for each VG installation, as well as operating characteristics of VG that may differ from conventional generation. The uncertainty of class b exists at three levels: an entire VG may experience an outage due to failure at its point of interconnection, or it may experience a sharp decrease in megawatt production due to failure of a collector circuit or due to a fast change in wind or solar resource. The uncertainty of class c related to the speed of a unit to ramp is made more significant by the presence of high VG penetration levels because of the increased variability and consequential need for greater reserves and faster ramping capability.

Table 1. Bulk Power System Uncertainty Classes

	UNCERTAINTY									
TIME FRAME	**Variable generation (wind farm level)**			**Conventional generation (unit level)**			***Demand (bus level)**		****Transmission (cct level)**	
Real-time market (10 mins)	Forced unavailability	10 min forecast		Forced unavailability	10 min ramp capability		10 min forecast	10 min ramp capability	Forced unavailability	
Intra-day scheduling (1-6 hrs)	Forced unavailability	Hrs-ahead forecast		Forced unavailability	10 min & 1 hour ramp capability		Hrs-ahead forecast	10 min & 1 hour ramp capability	Forced unavailability	
Day-ahead market (1 day)	Forced unavailability	1 day forecast		Forced unavailability	10 min & 1 hour ramp capability		1 day forecast	10 min & 1 hour ramp capability	Forced unavailability	
Seasonal planning (3 months)	Forced & scheduled unavailability	3 month forecast		Forced & scheduled unavailability	10 min & 1 hour ramp capability		3 month forecast	10 min & 1 hour ramp capability	Forced & scheduled unavailability	
Mid-term planning (1-5 years)	Forced & scheduled unavailability	5 year forecast	Location & type of new VG	Forced & scheduled unavailability	10 min & 1 hour ramp capability	Location & type of new gen	5 year forecast	10 min & 1 hour ramp capability	Forced & scheduled unavailability	Location & capacity of new xmission
Long-term planning (>10 years)	Forced & scheduled unavailability	10 year forecast	Location & type of new VG	Forced & scheduled unavailability	10 min & 1 hour ramp capability	Location & type of new gen	10 year forecast	10 min & 1 hour ramp capability	Forced & scheduled unavailability	Location & capacity of new xmission

* Demand includes bilateral transmission schedules.
** Transmission uncertainty may also include weather- or seasonal-dependent ratings.

Probabilistic and Deterministic Methods

There are various names for probabilistic methods, with no consensus on the distinction between probabilistic methods and risk assessment methods. Therefore, the scope ranges from methods that calculate loss of load probabilities (LOLP) and other reliability indices, to expected consequences,[5] variance, and value at risk. Deterministic methods are limited in their ability to comprehensively identify the full range of potential risks areas associated with wide integration of VG.[6]

Methods based on LOLP are well known and are often applied to resource adequacy assessments. For example, two otherwise identical power systems might be designed with the same deterministic planning reserve margin (percentage by which installed generation exceeds peak load), but they may have a different probabilistic loss of load expectation (LOLE).[7] In the traditional "N-1" deterministic power systems analysis approach, there is no difference between a "10 km transmission line supplying a highly meshed part of the network" and a "200 km line supplying a less meshed load center" with significantly different probabilities of occurrence and consequences.[8] These N-k deterministic methods are based on a level of redundancy and do not have any explicit economic considerations around the consequences of expected unserved energy (EUE).

Probabilistic methods allow many situations that can only be treated in an ad hoc way using deterministic rules to be treated rationally and systematically. Probabilistic methods provide greater insights to assess the planning and operational aspects giving estimates of how much, how long, and how often the expected consequences of investments (planning) or operator actions (expected cost of operation) will be, as well as quantifying them. Interestingly, probabilistic methods have been investigated in conjunction with deterministic approaches in an attempt to combine the best aspects from both approaches.[9]

A part of its effort to adopt more probabilistic methods in general, NERC is running a Pilot Probabilistic Assessment to produce enhanced resource adequacy metrics for its long-term reliability assessments. NERC traditionally gauged resource adequacy using a deterministic Planning Reserve Margin metric. The pilot is investigating two probabilistic metrics: Loss of Load Hours (LOLH) and Expected Unserved Energy

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[5] Li, W.; Risk Assessment Of Power Systems: Models, Methods, and Applications, John Wiley & Sons, 13 May 2005 325pp http://books.google.ie/books?id=wvmHYncAZhYC&lpg=PP1&pg=PP1#v=onepage&q&f=false

[6] Li, W.; Choudhury, P.; "Probabilistic Transmission Planning," Power and Energy Magazine, IEEE , vol.5, no.5, pp. 46-53, Sept.-Oct. 2007, doi: 10.1109/MPE.2007.904765 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4295037&isnumber=4295014

[7] Milligan, M.; Porter, K. (2008). Determining the Capacity Value of Wind: An Updated Survey of Methods and Implementation; Preprint. 30 pp.; NREL Report No. CP-500-43433. Available at http://www.nrel.gov/docs/fy08osti/43433.pdf

[8] CIGRE 2010 "Review of the Current Status of Tools and Techniques for Risk-Based and Probabilistic Planning in Power Systems" CIGRE October 2010

[9] Billiton, R.; Hailing Boa; Kari, R.; "A Joint Deterministic - Probabilistic Approach To Bulk System Reliability Assessment," Probabilistic Methods Applied to Power Systems, 2008. PMAPS '08. Proceedings of the 10th International Conference on , pp.1-8, 25-29 May 2008 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4912682&isnumber=4912596

(EUE).[10] Unserved energy can be monetized, although this is a difficult problem.[11, 12]

Probabilistic methods allow for the quantification of tail events, making it possible to then assess their risk. The distribution mean measures only the central tendency of the variable in question and does not provide an accurate risk assessment.

The use of probabilistic methods in power system planning and operations has been a growing trend for the past 30 years but is significantly accelerating due to the increase in VG penetration, as well as many other drivers, including the following:

- The development of competitive markets and the consequential separation of transmission and generation planning have led to increased uncertainty, which has spurred the development and use of probabilistic methods to account for it. The time difference between the construction of generation (e.g., three years) and transmission (e.g., 10 years) increases this uncertainty.
- The availability of inexpensive computing resources has allowed computationally intensive probabilistic methods to be more readily explored and eventually implemented in practice.
- The societal push for less environmentally impactful solutions (e.g., public opposition to transmission infrastructure) has led to a growing need to extend the limits of the system and quantify the risk/reward trade-offs.
- There is increasing interest in capturing High-Impact, Low-Probability (HILP) events.

Variable Generation

The addition of VG into the power system does not fundamentally change the problems that must be solved, both in operations and in planning. Power system operators will still need to keep the system balanced and operating in a reliable and efficient manner. Sufficient generation and transmission must be planned for and operated. However, by its variable and uncertain nature, VG increases in complexity since fixed quantities cannot be readily used (if they are being used in conventional deterministic methods for planning and operations). In this sense, probabilistic methods may be the only proper way to inform decisions for systems with significant penetrations of variable generation.

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[10] NERC 2012B; “Pilot Probabilistic Assessment” North American Electric Reliability Corporation, 2012. http://www.nerc.com/files/2012_ProbA.pdf

[11] Herman, R.; Gaunt, T.; “Probabilistic interpretation of customer interruption cost (CIC) applied to South African systems,” Probabilistic Methods Applied to Power Systems (PMAPS), 2010 IEEE 11th International Conference on, pp.564-568, 14-17 June 2010; doi: 10.1109/PMAPS.2010.5528947
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5528947&isnumber=5526245

[12] Leahy, Eimear & Toll, Richard S.J., 2011. “An estimate of the value of lost load for Ireland,” Energy Policy, Elsevier, vol. 39(3), pages 1514-1520, March.

As VG penetration grows, demand-side management is also growing and has the potential to significantly help in the integration of VG by increasing system flexibility.[13, 14, 15] Accounting for demand-side management increases the need for the use of probabilistic methods for power system studies.[16, 17]

While all load and generation contributes to uncertainty, VG drives the trend to develop probabilistic methods in the following ways:

- VG is a distributed resource with uncertainty around its future locations. The resource quality of each possible location can come in multi-kilowatt to gigawatt blocks and is a low-capacity factor resource. This makes planning transmission and distribution networks far more challenging.
- VG can have particularly short construction times relative to transmission, requiring transmission planners to consider a range of possible generation expansion scenarios; therefore, coordinated risk-based transmission and generation planning becomes more important.
- On the operational time scales, the uncertainty in VG forecasting (due to the nature of weather) is adding to the short-term temporal power system uncertainty.[18]
- From a resource adequacy perspective, VG is largely an energy resource. Its capacity contribution can be relatively small (and it declines gradually with higher penetrations). However, even this energy contribution is subject to significant variation over seasonal and annual time scales.[19]
- VG has uncertain impacts on the rest of the system that need to be accounted for. Its operating characteristics may be significantly different from conventional sources. For example, there is an increased need for access to flexibility in the remaining generation fleet,[20] but quantification and encouragement of this flexibility is difficult.[21, 22] As VG displaces other energy resources, it is important to ensure that necessary flexible capacity is available to the system operator.[23] To

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[13] GE Energy, 2010: Western Wind and Solar Integration Study. Golden, CO: National Renewable Energy Laboratory, New York, May, 536pp. http://www.nrel.gov/wind/systemsintegration/wwsis.html

[14] R. Shoshonis, "Evaluating the Impacts of Real-Time Pricing on the Cost and Value of Wind Generation," IEEE Transactions on Power Systems, Vol 25, No 2, pp 741-748, May, 2010.

[15] Kirby, B, M.J. O'Malley, O. Ma, P. Cappers, D. Corbus, S. Kiliccote, O. Onar, M. Starke, and D. Steinberg, "Load participation in Ancillary Services," Workshop Report. Department of Energy, USA, 2011. http://www1.eere.energy.gov/analysis/pdfs/load_participation_in_ancillary_services_workshop_report.pdf

[16] Kashyap, A.; Callaway, D.; "Estimating the probability of load curtailment in power systems with responsive distributed storage," Probabilistic Methods Applied to Power Systems (PMAPS), 2010 IEEE 11th International Conference pp.18-23, 14-17 June 2010; doi: 10.1109/PMAPS.2010.5528896 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5528896&isnumber=5526245

[17] Kazerooni, A.K.; Mutale, J.; "Network investment planning for high penetration of wind energy under demand response program," Probabilistic Methods Applied to Power Systems (PMAPS), 2010 IEEE 11th International Conference pp.238-243, 14-17 June 2010, doi: 10.1109/PMAPS.2010.5528517 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5528517&isnumber=5526245

[18] Holttinen, Hannele; Kiviluoma, Juha; Estanqueiro, Ana; Gómez-Lázaro, Emilio; Rawn, Barry; Dobschinski, Jan; Meibom, Peter; Lannoye, Eamonn; Aigner, Tobias; Wan, Yih Huei; Milligan, Michael. 2011. Variability of load and net load in case of large scale distributed wind power. Proceedings of 10th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Farms, 25 - 26 October, 2011, Aarhus, Denmark. Energynautics, pp. 177-182

[19] Wiser, R. Bolinger, M.; "2011 Wind Technologies Market Report" U.S. Department of Energy, Energy Efficiency & Renewable Energy, DOE/GO-102012-3472 August 2012 http://www1.eere.energy.gov/wind/pdfs/2011_wind_technologies_market_report.pdf

[20] NERC (2010b). Integration of Variable Generation Task 1.4, "Flexibility Requirements and Metrics for Variable Generation: Implications for System Planning Studies" North American Electric Reliability Corporation, 2010

[21] Lannoye, E., Flynn, D., O'Malley, M., "Evaluation of Power System Flexibility" IEEE Transactions on Power Systems, Vol. 27, pp. 922 – 931, 2012.

[22] Gottstein, M.; Skillings, S.A.; "Beyond capacity markets — Delivering capability resources to Europe's decarbonised power system," European Energy Market (EEM), 2012 9th International Conference on the , vol., no., pp.1-8, 10-12 May 2012

[23] Hogan, M., Gottstein, M.; What Lies "Beyond Capacity Markets"? Delivering Least-Cost Reliability Under the New Resource Paradigm. August 2012. http://www.raponline.org/document/download/id/6041

ensure this flexible capacity is available requires a) physical response capability, which can be either generation, demand response, or storage, and b) possessing the proper incentives to invest in and operate the flexible capability when needed. This could be accomplished with markets, regulatory oversight, or a combination of both.

While considering the application of probabilistic paradigms and methods, the tendency is to focus on long-term resource and transmission planning needs. However, it is critical to note that system operation will be increasingly subject to the same uncertainties but to a more limited extent. Currently, an operator only needs to focus on the uncertainties in demand variations, together with generation and transmission outages, when performing its operations planning (scheduling and committing resources within hours to days of real time) or system operation (dispatch of available dispatchable resources within minutes to hours of real time) responsibilities. These tasks are currently performed using well-established deterministic paradigms and methods. However, a large penetration of VGs significantly increases the magnitude of the uncertainty that the operator needs to deal with when performing its various tasks. The primary uncertainty involves VG's uncertain output level even in the near future. Although this uncertainty is significantly smaller than the one dealt with in longer-term planning, the timeline to deal with unforeseen events is also shorter, with significantly fewer options to deal with adverse effects. Hence, from our viewpoint, the introduction of probabilistic paradigms and methodologies into system operation will also be critical.

Below, two descriptive examples illustrate the impact that VG will have on planning and operations.

Example: Planning with VG

Typical mid- to long-term transmission planning studies (as well as generation interconnection studies) are based on one or more study scenarios (base cases) that are snapshots of critical system operating conditions in the future. The system snapshots typically correspond to the peak system load condition, off-peak (very low) system load condition, and shoulder peak (medium) system load conditions. In every one of these study scenarios, all generators' output and load values are assumed to be at specific megawatt levels. In most current systems, such system snapshots are reasonably accurate, and the transmission upgrades that would be derived from these studies would be reasonable as well. Given the highly uncertain VG output levels—especially at bus levels—the operational picture for these study snapshots will be less predictable and deterministic as VG penetration grows.

To cope with such strong uncertainty, some transmission planners would assume the worst case conditions when building their study scenarios (e.g., assuming that wind generators are generating zero power at the time of summer peak load condition and maximum power at the time of minimum system load). Others assume an arbitrary generation value for VG resources for their study scenario; for instance, 20 percent of nameplate for wind at summer peak system load condition and 100 percent at off-peak and shoulder-peak load conditions. As one can imagine, the outcome of such "arbitrary" scenario selections can lead to over- or underestimation of the need for transmission upgrades. While deterministic transmission planning provides a certain degree of insight, probabilistic approaches enable deeper insights over a wider range in which VG output (and potentially that of conventional generation and load) levels would vary within a range based on a probability distribution in the presence of large VG penetration. In a probabilistic planning paradigm, one would not rely on the traditional deterministic planning criteria of no loss of load under Category B (N-1) contingency conditions or some planned loss of load under Category C (common mode N-2) contingency conditions to develop, test, or accept a "least cost, best fit" transmission upgrade. Instead, one would rely on a threshold for the LOLP of one event in ten years or other similar measures to develop a transmission upgrade or weigh the benefits of a set of proposed upgrades.

Example: Operations with VG

Typical short-term operations planning studies examine the operation of the power system under one or more operational snapshots—from a few hours up to one week in advance. The deterministic study criteria here are similar to those of planning described above: no loss of load under Category B (N-1) and some planned loss of load under Category C (common mode N-2) contingency conditions. Of course, unlike long-term planning, the purpose of operations planning is not to determine the transmission or generation upgrades needed to maintain system reliability, but to ensure system operation will remain secure given the resources that are available and could be made available (committed) within time frames available prior to actual real-time system operation. With low VG penetration when short-term operations planning studies are performed, the status of the system is fairly accurately known; as such, operations planning results are deemed accurate and certain. However, given its uncertainty and variability, high VG penetration can introduce a somewhat higher level of uncertainty in operations planning study results. Under these circumstances, given the critical nature of the operations planning studies, the tendency of the operations planners could be to assume the worst possible operational characteristics for VG, resulting in extremely secure—yet less efficient—system operation. Here again, probabilistic operations planning studies can be used to strike a better balance between the need for system operational security and efficiency. Probabilistic operations planning studies would look at a range and probability for VG output as well as system contingency conditions and verify the power system operational security based on an acceptable threshold for LOLP or other probabilistic system performance measures.

Numerous sources of uncertainty and variability impact the power system simultaneously.[24] VG increases both variability and uncertainty, but the combined variability and uncertainty must be dealt with to reliably and economically operate the power system. Researchers are developing probabilistic techniques to evaluate the uncertainties of the balancing capacity, ramping capability, and ramp duration requirements in power systems operations and operations planning.[25, 26] The approach proposed by Makarov, et al. includes three steps: forecast data acquisition, statistical analysis of retrospective information, and prediction of grid balancing requirements for a specified time horizon and a given confidence level. It includes a probabilistic algorithm based on histogram analysis that is capable of incorporating multiple sources of uncertainty—both continuous (wind and load forecast errors) and discrete (forced generator outages and startup failures).

A new method, called the “flying-brick” technique, was developed to evaluate the look-ahead required generation performance envelope for the worst-case scenario within a user-specified confidence level. A framework for integrating the proposed methods with an energy management system (EMS) was also developed. To improve the system control performance, maintain system reliability, and minimize expenses related to system balancing functions, it is necessary to incorporate expected wind and load uncertainties into scheduling and load following, and to some extent, into regulation processes. Some wind forecast service providers in North America and Europe offer uncertainty information for their forecasts, including probabilities of extreme ramping events. The proposed method addresses the uncertainty problem comprehensively by including all types of uncertainties (e.g., load, variable generation, etc.) and all aspects of uncertainty, including the ramping requirements. The main objective is to provide rapid (every five minutes) look-ahead (five to eight hours ahead) assessments of the resulting

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[24] Makarov, Y.V.; Shuai Lu; Samaan, N.; Zhenyu Huang; Subbarao, K.; Etingov, P.V.; Jian Ma; Hafen, R.P.; Ruisheng Diao; Ning Lu, “Integration of uncertainty information into power system operations,” IEEE Power and Energy Society General Meeting, July 2011

[25] Makarov, Y.V.; Etingov, P.V.; Jian Ma; Zhenyu Huang; Subbarao, K., “Incorporating Uncertainty of Wind Power Generation Forecast Into Power System Operation, Dispatch, and Unit Commitment Procedures,” IEEE Transactions on Sustainable Energy, Volume: 2 , Issue: 4, 2011, pp. 433 – 442.

[26] Makarov, Y. V.; Etingov, P. V.; Huang, Z.; Ma, J.; Chakrabarti, B. B.; Subbarao, K.; Loutan, C.; Guttromson, R. T., “Integration of wind generation and load forecast uncertainties into power grid operations,” Proc of the 2010 PES Transmission and Distribution Conference and Exposition, 2010

uncertainty ranges for the balancing effort in terms of the required capacity, ramping capability, and ramp duration.

The report used case studies with the prototype tool to test the uncertainty assessment approach and to demonstrate the capabilities of the tool. CAISO's actual data were used in the simulation and the tool development. The actual data used include total load, total wind generation, load forecast (day-ahead, hour-ahead, and real-time forecast), and wind generation forecast. Genetic algorithms were used to optimize unit commitment and economic dispatch. Next steps are to implement the methods in an actual EMS.

As the need for probabilistic criteria and methods for risk assessment is a growing area in power system analysis, the Chapter 1 offers an assessment of these methods and the data requirements. Chapter 2 covers VG-related application areas where probabilistic methods are used. Chapter 3 concludes and offers recommendations.

Methods and Data Requirements

A literature review shows that there is research activity in probabilistic methods in power systems analysis, design, and control across the planning and operations domains. The planning area has had the most activity, due to the greater levels of uncertainty. A recent CIGRE report[27] provides a comprehensive review on probabilistic planning in power systems. It concludes that methods and tools are available, but mainly for adequacy issues, with limited capabilities to address other uncertainties such as location, timing, and availability for proposed new generation. The difficulty in obtaining the necessary quality and quantity of data is limiting their applicability, especially for high-impact low-probability (HILP) events. Despite the availability of powerful computational resources, probabilistic areas are still computationally constrained, and the interpretation and translation of results for practical applications is still challenging. The CIGRE report had a number of case studies and, interestingly, only two out of seven had a significant VG dimension (both were wind cases from Denmark), which underlines that VG is but one of many drivers of the development of probabilistic methods in power systems.

A forthcoming CIGRE technical brochure on coping with limits for very high penetrations of renewable energy is also noteworthy.[28] The joint working group that composed the brochure used a quantitative and qualitative survey of 50 CIGRE members from across the world. Some of the survey questions related specifically to "new criteria" (probabilistic planning). CIGRE received thirty completed surveys from 19 countries across Europe, North America, Oceania, and Asia. There was a low rate of response on the probabilistic planning issue, which may be linked to the fact that few consolidated models and planning procedures exist. However, it was noted that probabilistic planning methods are under development, as is the definition of new planning criteria. The group concluded that the use of probabilistic methods to identify network reinforcements is becoming increasingly common but is not yet an accepted standard. CIGRE also had a working group to specifically investigate planning with the uncertainty of wind generation.[29] Another recent CIGRE activity explicitly assessing risk management did not emphasize VG.[30]

Key aspects of probabilistic methods include the identification of the decision problem of interest and associated uncertainties that influence that problem; data inputs; incorporation of uncertainty within the models; model outputs; interpretation and risk formulation; and model execution. These aspects are described below.

Data Requirements

VG is a difficult input to introduce into probabilistic power system studies. Unlike many other uncertain inputs, variable generation output does not conform to a normal distribution. This negates many of the standard statistical assumptions that are made on the basis of a normal distribution. Even if a normal distribution could be assumed, special attention must be paid to HILP events. HILP events such as all VG operating simultaneously near rated capacity or a sudden drop in VG have the potential to disrupt the power system. Because they are low probability, these events may not be captured, or they may be strongly discounted in traditional analyses.

Variable generation data must also be selected carefully due to its time dependence and cross-correlation with other natural events. For example, wind generation may be correlated with load, hydro production, and solar output.[31] Thus, a single year of data may not be extrapolated to other years, and matched data must be used for

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[27] CIGRE 2010; "Review of the Current Status of Tools and Techniques for Risk-Based and Probabilistic Planning in Power Systems"

[28] CIGRE 2012; Technical Brochure on Coping with Limits for Very High Penetrations of Renewable Energy, Joint Working Group C1/C2/C6.18 of Study Committee C6, August 2012, International Conference on Large High Voltage Electric Systems

[29] CIGRE Technical Brochure 293, Electric Power System Planning with Uncertainty of Wind Generation, April 2006, CIGRE WG C1.3 (www.e-cigre.org).

[30] CIGRE 2011; "Assessing and improving power system security, reliability and performance in light of changing energy sources," Special report for session 8 Risk Analysis - CIGRE Report - Asset Management 2011

[31] This correlation is unlikely to occur on an hourly basis but may be present over longer time periods. See the discussion in Keane, A.; Milligan, M.; Dent, C.J.; Hasche, B.; D'Annunzio, C.; Dragoon, K.; Holttinen, H.; Samaan, N.; Soder, L.; O'Malley, M.; "Capacity Value of Wind Power," Power Systems, IEEE Transactions, pp.564-572, May 2011, doi: 10.1109/TPWRS.2010.2062543; URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5565546&isnumber=5753358

meteorological data, load, and other generation resources.[32] Failure to adhere to this can result in data that is not representative of the time period; load from a hot day when peak loads are high can be combined with wind power from a different year when it is cool and rainy. It is important to use data from the same year, whether actual or a high-fidelity simulation.

Incorporating Uncertainty

There are two principal ways to integrate uncertainty into deterministic problems: probability density functions and scenarios. The type of uncertainty representation should reflect the goal of the analysis, the level of underlying uncertainty, and knowledge of the underlying uncertainty.

Scenario analysis is the most common representation of uncertainty in probabilistic methods applied to power systems. It is an intuitive way to reduce uncertainty and allows problems to be solved that may be otherwise untenable. Scenario analysis also allows bounding of results by examining, for example, both the best and worst case. Reducing the range of uncertainty to scenarios, however, implies correlations between variables that may be fictional. For example, a high coal price is not necessarily correlated with a high natural gas price even though a “high fossil cost” case may be constructed. It also has the potential to bias results because the highest probability cases may not be those modeled. Conversely, HILP scenarios may be excluded. The most simplistic approach is the deterministic approach, which is scenario analysis with an assumed probability of one.

Probability distributions are the most granular form of uncertainty representation. Their use generally implies the use of multiple input models (e.g., from ensemble-based weather forecasting) or the creation of a large set of plausible outcomes (such as with Monte Carlo techniques). Probability distributions allow the greatest search space, because artificial correlations between variables are not required. Because probability distributions do not include artificial correlations, unintuitive combinations of decision variables can be explored that may produce new best- or worst-case outcomes. Although the large search space produced by probability distributions provides the most neutral analysis of a problem, it may also increase the size of the problem to the point where it cannot be solved in a reasonable amount of time.

The use of scenarios and probability distributions is not mutually exclusive. For example, it may be appropriate to have some variables with very low variability represented using scenarios and other variables with long-tailed distributions as probability distributions.

Model, Model Outputs, and Decision Criteria

Three features of a decision problem are the model, the model output, and the decision criteria. The model may be deterministic or probabilistic.

If a model is deterministic, then all parameters used are single-valued and typically characterize a single condition on which it is assumed the decision can be appropriately based. The condition is often “worst-case,” meaning that the decision will result in satisfactory operation for all other conditions. The output for deterministic models must necessarily be one or more “performance measures”; i.e., parameters characterizing the physical performance of the system. For example, a power flow model for a 20 percent wind energy penetration level (under peak load conditions) may indicate that the flow on a particular circuit is 1000 MW, whereas a 21 percent wind energy penetration may result in a 1020 MW flow on the same circuit. The decision criteria for a deterministic model is based on the acceptance or rejection of certain levels of physical performance. In this example, the decision criteria is that all circuit flows must remain at or below 1000 MW, so the 20 percent wind penetration level is acceptable, whereas the 25 percent level is not.

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[32] Milligan, M.; Ela, E.; Lew, D.; Corbus, D.; Yih-huei Wan; Hodge, B., “Assessment of Simulated Wind Data Requirements for Wind Integration Studies,” Sustainable Energy, IEEE Transactions pp.620-626, Oct. 2012

If a model is probabilistic, then some or all parameters used in it are represented over a range of values characterized by a probability function so that many different operating conditions are captured. The output for probabilistic models is a range of values of one or more performance measures. It is also characterized by a probability function or by attributes of a probability function (i.e., measures of center and spread are enough for Gaussian distributions; measures of shape are also needed for non-Gaussian distributions). For example, a power flow model for a 20 percent wind energy penetration level may result in the flow on a particular circuit (assume Gaussian for this example[33]) having a mean of 700 MW and standard deviation of 150 MW, whereas a 21 percent wind energy penetration level may result in the same circuit flow as a mean of 720 MW and standard deviation of 170 MW. The decision criteria for the probabilistic model is based on acceptance or rejection of certain levels of risk. In this example, the decision criteria might be that all circuit flows must remain at or below 950 MW for 95 percent of the time. Because the characteristics of the Gaussian distributed random variables are well known, one can use the cumulative probability density function to find the z-score of 1.65 that corresponds to the desired risk level. Then one can calculate that with a probability 0.95, the 20 percent wind penetration level (700 + 1.65 × 150 = 947.5) is acceptable, but the 21 percent wind penetration level (720 + 1.65 × 170 = 1000.5) is not.

Probabilistic models can be constructed to produce distinct output types. Three broad categories of results (deterministic, probabilistic, and trade-off) are discussed below.

Deterministic results are answers without embedded probabilistic information. This type of result is easily translated into a single action (e.g., the development of a dispatch instruction or new transmission line) without an indication of that action's risk. Deterministic results are generally the most common and easiest to produce. It is possible for probabilistic methods to produce a single answer without producing information regarding the risk of being wrong. Scenario-tree analysis, for example, can produce a single-output result by calculating a statistically expected outcome. Although there may be value in also producing multiple results with their associated estimated probabilities, in cases requiring quick action, a simpler form of output may be desired.

In addition to single actions, probabilistic models can also be used to produce deterministic rules. These rules indicate the correct actions for different scenarios. One example from the Western Wind and Solar Integration Study[34] explores the development of simple rules to determine operating reserve that is needed to balance load and wind. The rules are suggested from statistical analysis rather than probabilistic analysis, based on covering the variance (3σ) of an assumed normal distribution. One of the example rules for a particular BA is to hold operating reserve equal to 3 percent of load plus 5 percent of wind generation. This is a dynamic method that is based on the load and wind energy at each moment in time.

Probabilistic results with multiple outputs allow the decision maker (system operator or planner) to make an explicit decision about risk. These results may be a single-action output (as described above) or a mapping of output action to risk. A single action can be produced in a probabilistic setting by choosing an explicit risk level. A common example of this is in the resource adequacy domain, where a common LOLE target is 1 day in 10 years, and a generation portfolio that can achieve this level of reliability is deemed adequate. In other applications the risk level could indicate that the action is optimal with a calculated distribution of outcomes or that the action will produce the desired outcome with a certain risk. For example, a dispatch could be created that will satisfy demand with a 95 percent, 99 percent, or 99.9999 percent probability. This is an example of how a given risk level can be translated into some form of confidence interval, specifying that the dispatch would be effective in maintaining

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[33] This example uses a Gaussian, or normal distribution, for simplicity. Note that the appropriate distribution for a given problem may not be normal. Examples can be found in Hodge, Lew, and Milligan (2013) Short-term Load Forecasting Error Distributions and Implications for Renewable Integration Studies, available at http://www.nrel.gov/docs/fy13osti/57340.pdf, and Hodge, Orwig, and Milligan (2012) Examining Information Entropy Approaches as Wind Power Forecasting Performance Metrics, available at http://www.nrel.gov/docs/fy12osti/53515.pdf.

[34] GE Energy, 2010: Western Wind and Solar Integration Study. Golden, CO: National Renewable Energy Laboratory, New York, May, 536pp. http://www.nrel.gov/wind/systemsintegration/wwsis.html

system balance (and interchange schedules) with a given probability. An example of this can be found in an NREL VG study,[35] which develops a series of ramping envelopes up to 12 hours in duration and at different probability levels, as shown later in this report.

Alternatively, probabilistic results can be created that inform a decision but do not specify an action. For example, using sampling and simulation, a relationship between wind output, flexibility reserve levels, and non-served energy could be developed. For a given wind output level and reserve level, the probabilistic result would indicate the likelihood of non-served energy. This result does not indicate the correct decision but allows the decision maker to explicitly decide an acceptable level of risk. Of course, a decision rule could be developed that captures the decision maker's risk tolerance.

Probabilistic models can also be used to demonstrate trade-offs in a multi-objective framework. Pareto curves, or efficient frontiers, inform the decision maker of the best solution he or she can construct for a performance metric without sacrificing value from another performance metric. Pareto curves are developed in a space of two or more objectives that conflict; i.e., when one improves, the others worsen. Pareto curves may be made with either deterministic objectives, probabilistic objectives, or a combination of both. For example, an efficient frontier could be constructed where cost is on one axis and probability of non-served energy is on the other. The efficient frontier then indicates the lowest possible cost for given reliability levels or, alternatively, what reliability level can be achieved for each cost point.

This efficient frontiers approach has been applied in industry. Hydro Quebec used it to study balancing reserves when hypothetically adding 3,000 MW of wind power to the system. In the Hydro Quebec case, the trade-off was between increased balancing reserves and decreased risk of non-served load.[36] As shown in Figure 1, at a nominal amount of balancing reserves (BR_{nom}), the system exists at 17 percent risk level (point one). When wind in a high-generation scenario is added to the system (point two), the same level of balancing reserves produces a 25 percent risk of non-served energy. To return to the 17 percent risk rating, the balancing reserves must be increased by ΔBR to 650 MW (point three). Both with and without wind generation, the system operator is able to trade off increased balancing reserves and decreased risk.

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[35] J. King, B. Kirby, M. Milligan, S Beuning, "Flexibility Reserve Reductions from an Energy Imbalance Market with High Levels of Wind Energy in the Western Interconnection", NREL/TP-5500-52330, October 2011, http://www.nrel.gov/docs/fy12osti/52330.pdf

[36] M. Milligan, et al., "Operating reserves and wind power integration, an international comparison," 9th Annual International Workshop on Large-Scale Integration of Wind Power into Power Systems, Quebec, Canada, October 2009.

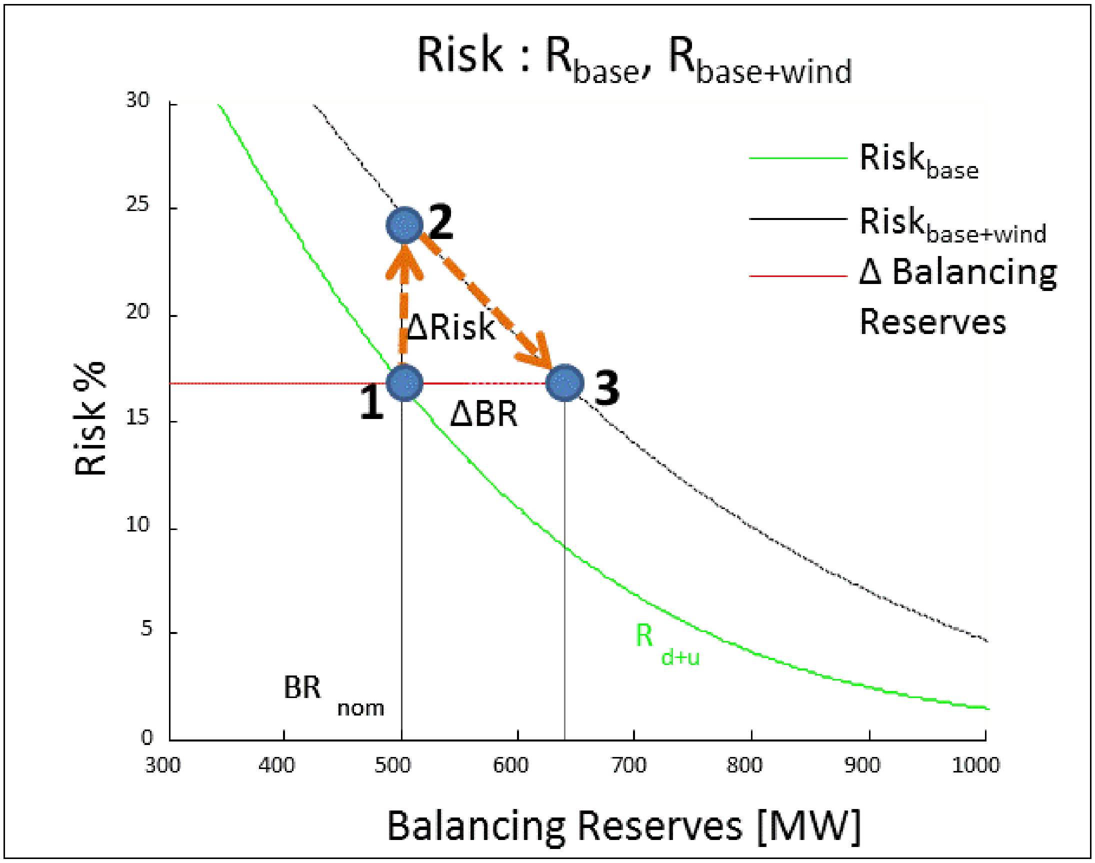

Figure 1: **Balancing reserve and risk trade-off diagram from Hydro Quebec (adapted from Milligan et al 2009)**

Basic Computational Approaches

Several different computational approaches are used within probabilistic methods. This section briefly outlines some of the most common computational approaches applied for power system analyses.

Convolution

Convolution is a method appropriate when one obtains a probabilistic description of a random variable that is the sum or difference of other random variables for which probability descriptions are known. There are several computational approaches, including recursion, Fourier transform, method of cumulants, and segmentation.

Markov Models, Including Frequency and Duration

A Markov process is a random process; i.e., a probabilistic representation of transitions between defined states in which a system or component may reside. A Markov process is said to be “memoryless” because the present state “summarizes” the entire history of the process; i.e., all of the information contained in the values taken by the random variables of the past are contained in the random variable of the present.[37] In general, a Markov process may have any number of states, and the component or system may reside in any one of them (but not in more than one of them simultaneously). The key to Markov representation is to express the probability of transitioning from one state to each other possible state. If these so-called transition probabilities can be obtained, then the probability of finding the system in any particular state in the future may be obtained based on the knowledge of the state in which it presently resides. It is also possible to compute the long-term state frequency and duration. The state frequency is the expected number of stays in (or arrivals into, or departures from) a particular unit of time; the state duration is the expected amount of time per stay of the random process in a particular state.

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[37] Although not discussed here, processes that do have “memory,” such as auto-regressive integrated moving average (ARIMA) processes, do exist.

Enumeration

In the pure enumeration approach, one simulates all possible events and classifies each according to some particular outcome. The probability of a given outcome is the summed probabilities of the events for which the outcome occurred. The pure enumeration approach can be computationally expensive, so when it is applied (e.g., for power system contingency analysis), the number of contingencies is typically restricted in some way, to provide bounds on the desired outcome of probabilities.

Monte Carlo

In Monte Carlo simulation, a functional evaluation is performed under parameter uncertainty. The parameter uncertainty is modeled by representing each uncertain parameter with a numerical distribution. Then a value for each uncertain parameter is drawn from each distribution, and for each draw, the function is evaluated. This is repeated many times, so that the many functional evaluations themselves form a distribution from which statistics (e.g., mean, variance, etc.) may be computed.

Model Execution

Probabilistic methods can be effectively included in power system modeling. Once an operator or planner has decided on appropriate formulation and risk metrics, the problem needs to be solved. Some of the modeling techniques utilize optimization methods, but the problems themselves are not inherently optimization problems. One example is production simulation, which uses cost minimization, an optimization method used to simulate the power system operation over a given time period. Monte Carlo simulation, for example, uses probabilistic information about a random variable (RV), or multiple RVs, to generate multiple scenarios. It is often possible to parallelize the analysis, particularly if Sequential Monte Carlo is used. Solving this class of problems may therefore be made computationally less demanding if multiple processors can be devoted to them. Other approaches include convolution, which is often used in LOLP applications.

Other problems are inherently oriented to optimization; for example, providing an optimal transmission build-out subject to the objective function and various constraints. Problems such as this are the most difficult from an optimization perspective. They are multi-period, stochastic, integer, and often nonlinear. As mentioned above, even if a problem may be formulated in a commercial solver, a solution may not be attainable within a reasonable time because of the complexity and size of the problem. This is especially true when actual utility problems (rather than academic-scale problems) are attempted. Thus, approximations may be necessary. In cases that cannot benefit from some type of parallelization or other computational improvement and are therefore computationally challenging, there are a variety of simplifications and off-line simulations that can be done beforehand to incorporate probability without requiring exhaustive modeling of every possible solution.

One option when there is a mismatch between solution-time and real-time scales is off-line preprocessing. Off-line preprocessing shifts the required computational time to prior to the decision point. This allows 1) running multiple optimizations before the decision must be made, and 2) using the closest set of inputs and running models in increasing complexity to refine inputs. If off-line preprocessing is insufficient, the problem may also be simplified to reduce its size. Reducing the size of the problem can be achieved by switching from a full probability distribution representation of uncertainty to scenarios, or reducing the number of scenarios considered. If the uncertainty is not the main source of computational time, constraints may be relaxed (e.g., allowing for construction of fractional transmission lines and then rounding to the nearest line size). The solution to the relaxed problem must be validated as it may not be realistic.

Finally, if the problem cannot be solved using traditional techniques, meta-heuristics may be used. Unlike traditional optimization techniques, meta-heuristic solution algorithms are neutral to the type of problem considered. This neutrality allows them to be applied to probabilistic and other traditionally difficult problems. Meta-heuristics include genetic algorithms, simulated annealing, Tabu search, ant colony, and many other biologically inspired search algorithms. The advantage of these algorithms is that they can produce solutions quickly and often provide solutions to problems where traditional solvers cannot. The inherent disadvantage, however, is that there is no guarantee to the quality of the solution produced—the solution may be good, but it may not be possible to prove it is the best optimal solution.

Application Areas

VG adds to the complexity of long- and short-term power systems planning; however, planning the BPS for the future has always been subject to various risk factors that are suitable to the application of probabilistic methods. These factors include:

- fuel price and fuel delivery capacity uncertainty,[38] which may become more important with high reliance on natural gas[39] and higher uncertainty levels that accompany increased penetrations of wind/solar energy;
- unforeseen economic stagnation (or growth) that reduces (or increases) the demand and, hence, the need for new facilities;
- regulatory risk;
- uncertainty regarding future operating rules, emission limits, etc.;
- meteorological conditions impacting hydro generation and, more recently, wind and solar generation output uncertainty and variability;
- retirement plans for existing resources;
- transmission development in neighboring systems;
- construction delays; and
- risks of new technologies.

The generation and transmission systems should be robust across multiple possible scenarios. This leads to the need for more robust planning processes for both generation and resource adequacy and flexibility, along with network (transmission and distribution) system planning and design. Operationally, VG also brings increased levels of uncertainty that can benefit from the application of probabilistic methods.

In this chapter, applications in the supply planning area are dealt with under the heading of generation expansion models that include resource adequacy and flexibility. This is followed by network planning (both transmission and distribution), and operations planning, including forecasting, reserve estimation, and stochastic unit commitment.

Generation Expansion Models

The portfolio of future generation must perform over a wide range of conditions, because the future mix of generation and load conditions can’t be known with certainty. In terms of uncertainty around future costs, it should be noted that the levelized cost of energy from VG is more certain than the levelized cost of other forms of generation, so VG reduces cost uncertainty in this case. This point highlights the uncertainty at different time scales—VG is uncertain at short timescales (minutes to days) and less so at long time scales of months and years.[40] Resource planning—whether performed by regulated utilities or conducted via market mechanisms—must provide a fleet of generation that is itself robust to alternative levels of development, including varying amounts of VG. One or more generation build-out scenarios that provide sufficient capacity and sufficient flexibility are needed so that the future power system can be operated reliably and economically.

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[38] Roques, Fabien A. & Newbery, David M. & Nuttall, William J., 2008. “Fuel mix diversification incentives in liberalized electricity markets: A Mean-Variance Portfolio theory approach,” Energy Economics, Elsevier, vol. 30(4), pages 1831-1849, July

[39] NERC, *2012 Long-Term Reliability Assessment*, http://www.seia.org/sites/default/files/resources/2012_LTRA_FINAL.pdf, November 2012

[40] Holttinen, H.; Kiviluoma, J.; Estanqueiro, A.; Gómez-Lázaro, E.; Rawn, B.; Dobschinski, J., Meibom, P.; Lannoye, E.; Aigner, T.; Wan Y.H.; Milligan, M.; “Variability of load and net load in case of large scale distributed wind power” http://repositorio.lneg.pt/bitstream/10400.9/1518/1/Task%2025%20Variability%20paper%20final.pdf

Resource Adequacy

A key issue when planning for future generation is to determine how much generation is needed by a future date to serve the expected future load while maintaining a desired reliability level. A related issue is whether an over-building or under-building of generation can be alleviated by additional market transactions with neighboring systems (exports and imports). Traditional approaches have targeted the estimated future peak load plus a planning reserve margin. More robust approaches incorporate LOLP or related methods, which provide for an estimate of the reliability of the power supply. VG does not fundamentally change the problem that must be solved; however, it does influence the relationship between the planning reserve margin (expressed as a percentage of peak load) and resource adequacy. The NERC IVGTF 1.2 Task Force recommends a probabilistic approach based on effective load-carrying capability (ELCC) to estimate resource adequacy.[41] This is consistent with the recommendations of a recent IEEE task force paper on the subject of capacity value and credit calculations.[42]

Multiple years of data are critical to achieve the objective of a resource adequacy assessment. Limited data on extremes may mean that it is not possible to quantify any relevant statistical relationship even with multiple years of data. Therefore, efforts are underway to better understand the tails of the relevant probability distributions for VG production, unit outages, and other factors. This is important because LOLP and related metrics provide a measure of some aspect of the tail of the probability distribution of insufficient resources to meet load. Milligan, et al.[43] analyzed three years of data and compared annual ELCC for wind. At some sites, there was little variation in the capacity value; however, one site varied from 27 percent to 42 percent of maximum capacity. An earlier analysis also included the evaluation of solar and other types of renewable resources.[44] A study in Ireland showed that four years of data provides reasonable assurance that the wind capacity value, measured by ELCC, is a stable measure given enough data.[45] Dent and Zachary found that limited historic experience of high demands coincident with poor wind resource leads to large uncertainties in the results of capacity value calculations.[46] Studies of the capacity credit of solar energy are moving forward but there is much work to be done.[47] An industry case study on probabilistic resource adequacy assessment (including wind) of the Mid-Continent Area Power Pool (MAPP) for the 10-year planning horizon from 2009–2018 was recently reported.[48]

Flexibility

There are two interrelated aspects to flexibility. Resources themselves (generators, responsive loads, and storage), for example, are flexible if they can change states quickly (e.g., start/stop, ramp, have low minimum loads, and

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[41] NERC (2011a). Integration of Variable Generation Task 1.2, "Methods to Model and Calculate Capacity Contributions of Variable Generation for Resource Adequacy Planning" North American Electric Reliability Corporation, 2011, http://www.nerc.com/files/ivgtf1-2.pdf

[42] Keane, A.; Milligan, M.; Dent, C.J.; Hasche, B.; D'Annunzio, C.; Dragoon, K.; Holttinen, H.; Samaan, N.; Soder, L.; O'Malley, M., "Capacity Value of Wind Power," Power Systems, IEEE Transactions, May 2011, doi: 10.1109/TPWRS.2010.2062543 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5565546&isnumber=5753358

[43] Milligan, M.; Shiu, H.; Kirby, B.; Jackson, K. (2006). Multi-Year Analysis of Renewable Energy Impacts in California: Results from the Renewable Portfolio Standards Integration Cost Analysis; Preprint. 40 pp.; NREL Report No. CP-500-40058. Available at http://www.nrel.gov/docs/fy06osti/40058.pdf

[44] B. Kirby, M. Milligan, Y. Makarov, D. Hawkins, K. Jackson, H. Shiu, 2003, California RPS Integration Cost Analysis-Phase I: One Year Analysis of Existing Resources, California Energy Commission, December. Available at http://www.consultkirby.com/files/RPS_Int_Cost_PhaseI_Final.pdf

[45] Hasche, B., Keane, A. and O'Malley, M.J. "Capacity value of wind power: calculation and data requirements: The Irish power system case," IEEE Transactions on Power Systems, Vol. 26, pp. 420 - 430, 2011.

[46] Dent, C.; Zachary, S.; "Capacity Value of Additional Generation: Probability Theory and Sampling Uncertainty" Probabilistic Methods Applied to Power Systems (PMAPS), 2012 IEEE 12th International Conference

[47] Duignan, R. Chris J. Dent, Andrew Mills, Member Nader Samaan, IEEE and Michael Milligan, "Capacity Value of Solar Power" IEEE PES, San Diego, July 2012

[48] Bagen, B.; Koegel, P.; Couillard, M.; Stradley, K.; Giggee, B.; Jensen, A.; Iverson, J.; Haringa, G.E., "Probabilistic resource adequacy assessment of large interconnected systems," Probabilistic Methods Applied to Power Systems (PMAPS), 2010 IEEE 11th International Conference on , pp.252-258, 14-17 June 2010, doi: 10.1109/PMAPS.2010.5528519 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5528519&isnumber=5526245

follow Automatic Generation Control (AGC) signals quickly and accurately). Future system plans (including generation, transmission, storage, and responsive load) are flexible if they can deliver the required energy reliably, economically, and environmentally under the full range of expected and possible future conditions. Increasing levels of variable generation may increase the need for both types of flexibility. A flexible plan will likely include flexible resources but may also include a significant quantity of inflexible resources if it provides greater reliability, lower costs, or environmental benefits while still providing sufficient flexibility to meet future needs.

Flexibility needs for future time periods (years) can be assessed, and some form of market mechanism or regulatory requirement (or combination) is required to ensure investment in this flexibility. This problem is in the planning domain, involving the design and building of a system that is sufficiently flexible. The objective is to build the best possible (or at least sufficiently flexible, considering both economics and reliability) system that has the needed flexibility. Once the flexibility has been planned, designed, and built, it must be made available to the system operator via the commitment and dispatch process. This is the operational domain, and its objective is to make the best possible use of existing resources. These are two different problems; however, it is clear that if the system is not planned well, it may not be flexible enough to operate efficiently. Thus, efficient planning, design, and building of the needed flexibility is a necessary—but not sufficient—condition for achieving flexibility in operations. It is not a sufficient condition, because there may be conditions that make it difficult or impossible for the existing flexibility to be accessed when needed. These constraints may include lack of information, lack of institutional market structures, or other factors.

In systems with large amounts of VG, increased flexibility needs include:

- more and faster ramping;
- lower minimum generation;
- faster start-up times;
- smaller minimum up/down times;
- faster and more accurate following of AGC signals;
- appropriate market design; and
- access to required transmission.

Generation, storage, and demand response can all provide these flexibility attributes. IVGTF Task 1.4[49] addressed this issue in detail, and another study, "Market to Facilitate Wind and Solar Energy Integration into the Bulk Power System Supply," [50] addresses some potential market challenges.

In the long term, the amount, type, and location of VG that will be installed is often unknown. As is the case for resource adequacy, there is likely a need for flexibility adequacy that essentially establishes the level of ramping or other flexibility that will be sufficient given this uncertainty level.[51] In the operational domain, the concern is that the precise level, timing, and duration of the ramping need and availability of the flexible resources are all uncertain. This is because VG performance is based on weather conditions that can't be precisely known. Load

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[49] NERC (2010b). Integration of Variable Generation Task 1.4, "Flexibility Requirements and Metrics for Variable Generation: Implications for System Planning Studies" North American Electric Reliability Corporation, 2010, http://www.nerc.com/files/IVGTF_Task_1_4_Final.pdf

[50] Milligan, M.; Holttinen, H.; Soder, L.; Clark, C.; Pineda, I.; "Markets to Facilitate Wind and Solar Energy Integration into the Bulk Power Supply: an IEA Task 25 Collaboration." Presented at the *11th Annual International Workshop on Large-Scale Integration of Wind Power into Power Systems as Well as on Transmission Networks for Offshore Wind Power Plants Conference, Lisbon, Portugal, November 13–15, 2012. Preprint available at* http://www.nrel.gov/docs/fy12osti/56212.pdf

[51] NERC, Integration of Variable Generation Task 1.4, "Flexibility Requirements and Metrics for Variable Generation: Implications for System Planning Studies" North American Electric Reliability Corporation, 2010, http://www.nerc.com/files/IVGTF_Task_1_4_Final.pdf

ramping tends to be somewhat predictable, whereas VG ramps are less predictable.[52] Their statistical characterization can be formulated and combined with the load characterization for an estimate of the net load-ramping characteristics, assuming some knowledge about the installed capacity, type, and location of the variable generation.[53] Figure 2 illustrates the distribution of the magnitude of increasing and decreasing net load (load - wind) ramps as a function of the duration of the ramp. Ramp envelopes describing the percentile range of the ramps highlight the extreme values in the distribution. The graph is based on one year of data that consists of 10-minute load and wind data. Each ramp envelope shows ramp durations of alternative magnitudes and duration at a given probability level. Graphs and analysis such as this only help establish the need for ramping capability. Additional analysis, modeling, and/or tools are needed to assess the generation fleet's capability to provide this ramping.

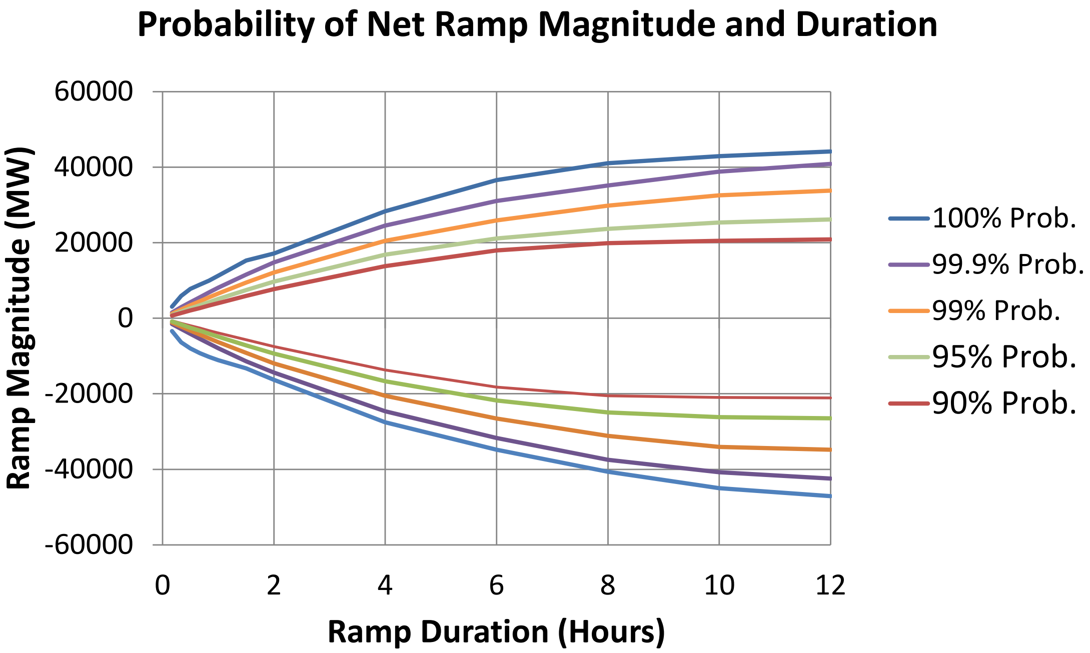

Figure 2: Alternative ramp envelopes for different confidence intervals[54]

Operational tools can be applied to this problem in a planning context, but existing tools do not generally assess the ramping capability in a probabilistic way, or otherwise account for the risk of not being able to access ramping capability when it is needed. An exception is the model of Lannoye, et al., which calculates a probabilistic metric called the Insufficient Ramping Resource Expectation (IRRE), which is analogous to LOLE.[55] The basic difference is that LOLE is based on installed capacity, whereas IRRE is based on the ability of that capacity to ramp (essentially the first derivative of capacity with respect to time), accounting for forced outages. This metric thus captures part

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[52] Mills, Andrew. (2010). Understanding Variability and Uncertainty of Photovoltaics for Integration with the Electric Power System. Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory. LBNL Paper LBNL-2855E. Retrieved from: http://escholarship.org/uc/item/58z9s527

[53] Bouffard, F.; Ortega-Vazquez, M., "The value of operational flexibility in power systems with significant wind power generation," Power and Energy Society General Meeting, 2011 IEEE, pp.1-5, 24-29 July 2011 doi: 10.1109/PES.2011.6039031 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6039031&isnumber=6038815

[54] J. King, B. Kirby, M. Milligan, S. Beuning, 2011, *Flexibility Reserve Reductions from an Energy Imbalance Market with High Levels of Wind Energy in the Western Interconnection*, NREL/TP-5500-52330, November, http://www.nrel.gov/docs/fy12osti/52330.pdf

[55] Lannoye, E., Flynn, D., O'Malley, M., "Evaluation of Power System Flexibility" IEEE Transactions on Power Systems, Vol. 27, pp. 922 – 931, 2012

of the probabilistic nature of the problem of providing ramp capability when it is needed. Other approaches and methods to quantify flexibility are starting to appear in the literature.[56, 57]

A fuller treatment of flexibility would involve the accounting for the stochastic nature of the ramp itself. The probabilistic aspect of the calculation involves a stochastic treatment of the generation fleet's ability to provide the needed ramping capability when it is actually needed.

Recently, some ISOs in North America have begun looking at the need for including ramping products in their markets to ensure sufficient ramping capability is available to respond to variability and uncertainty. For example, the California ISO (CAISO) has proposed a "Flexible Ramping" product that would be co-optimized with energy and ancillary services in their day-ahead and real-time processes.[58] This would ensure that sufficient ramping is available in each interval to manage a range of ramps defined by a confidence interval of up and down net load ramps based on an analysis of historical data. A similar approach is being proposed in the Midcontinent ISO (MISO).[59] Ramping capability is currently considered in day-ahead security-constrained unit commitment (SCUC) processes, ensuring enough ramping capability is made available to meet statistically determined ramping requirements for every time interval (Gribik, 2012).[60] This will be extended to MISO's day-ahead security-constrained economic dispatch (SCED) and real-time SCED. Generators providing ramping in both CAISO and MISO would be compensated based on the marginal price of the ramping service, similar to existing energy and ancillary service markets. Including ramping requirements in this way ensures ramps can be met in an economically efficient way while improving reliability.

Network planning

Increased levels of VG normally require substantial investment in transmission and distribution networks. The best large-scale VG resources (in particular wind) tend to be far from major load centers and transmission solutions that are robust. Possible locations of the VG deployment will need to be identified. Solar, in particular photovoltaic (PV) systems, are well suited as distributed generation (DG) and will drive the need for improved or new distribution networks. The VG technology itself is continuing to evolve, and network solutions will need to account for potential future developments.

Research results are appearing that indicate that with increased VG and the need for flexibility, expansion models will have to account for the sequential nature of power system operations, such as the starts of conventional generators, and this will require far more computing power.[61, 62] Combined with the additional computational power that is required for probabilistic methods, it can lead to computationally intensive problems with long run times. Even so, there appears to be significant value in moving toward long-term time series analysis or other sequential methods.

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[56] Ma, J., Silva, V., Belhomme, R., Kirschen, D. Evaluating and Planning Flexibility in Sustainable Power. IEEE Transactions on Sustainable Energy, in press, 2012

[57] Menemenlis, N.; Huneault, M.; Robitaille, A., "Thoughts on power system flexibility quantification for the short-term horizon," Power and Energy Society General Meeting, 2011 IEEE , pp.1-8, 24-29 July 2011 doi: 10.1109/PES.2011.6039617 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6039617&isnumber=6038815

[58] Xu, L. and Tretheway, D. Flexible Ramping Products, California ISO, Available online: http://www.caiso.com/Documents/DraftFinalProposal-FlexibleRampingProduct.pdf

[59] Navid, N., Rosenwald G. and Chatterjee, D. MISO Markets, Midwest Independent System Operator, Available online: https://www.midwestiso.org/Library/Repository/Communication%20Material/Key%20Presentations%20and%20Whitepapers/Ramp%20Capability%20for%20Load%20Following%20in%20MISO%20Markets%20White%20Paper.pdf

[60] Gribik, P., Chatterjee, D., Nivad, N. "New Products and Models to Manage Uncertainty," presented at IEEE Power and Energy Society General Meeting, July 2012

[61] Shortt, A., Kiviluoma, J. and O'Malley, M., "Accommodating Variability in Generation Planning," IEEE Transactions on Power Systems, in press, 2012

[62] V. Krishnan, E. Ibanez, T. Das, Y. Gu, and J. McCalley, "Modeling Operational Effects of Variable Generation within National Long-term Infrastructure Planning Software," to appear in IEEE Transactions on Power Systems.

Transmission Networks

Probabilistic methods for steady-state transmission planning have recently been proposed.[63, 64, 65] Over the past few decades, the French system operator has developed its own probabilistic methods to assess the static and dynamic security of real transmission systems under uncertainty.[66] An article[67] from *Wiley Interdisciplinary Reviews, Energy and Environment Press,* reviewed transmission planning for wind energy and mentioned probabilistic methods.

The variable nature of wind and solar resources with a relatively low capacity factor necessitates reassessment of the classic N-1 deterministic planning criteria of transmission networks.[68] Interestingly, Karki, et al. point out that probabilistic techniques require data that may not be available and propose a model to simulate this data. Traditionally, deterministic N-1 has led to underutilization of the investment in transmission,[69] and VG—with its relatively low capacity factors—can make this worse. VG is often viewed as an energy resource, so from the point of view of transmission planning, building transmission capacity to accommodate the full rated amount of all VG simultaneously is likely to be too expensive. The trade-off between under- and over-building transmissions can be assessed with probabilistic methods.

While wind and solar variability is significantly smoothed by aggregation over larger geographic areas, the remaining level of correlation can still have a significant impact on the optimal design of transmission systems.[70] This correlation can also be used to reduce the amount of dimensionality of planning studies while maintaining the spatial correlations.[71] Commercial considerations, particularly with regard to VG curtailment risk due to a lack of transmission, are spurring the development of probabilistic methods. For example, an article[72] from *IEEE Transactions on Sustainable Energy* discussed a method to quantify curtailment and also investigated the uncertainty in these estimates and the influence of other interdependencies.

The Electric Power Research Institute (EPRI) has been working on a methodology for probabilistically modeling the uncertainty related to the output of variable generation (such as wind and solar power and coincidental loads)

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[63] Choi, J.; Tran, T.; El-Keib, A.A.; Thomas, R.; Oh, H.; Billinton, R., "A Method for Transmission System Expansion Planning Considering Probabilistic Reliability Criteria," Power Systems, IEEE Transactions, vol.20, no.3, pp. 1606- 1615, Aug. 2005, doi: 10.1109/TPWRS.2005.852142 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1490615&isnumber=32048

[64] Choi, J.; Mount, T.D.; Thomas, R.J.; Billinton, R., "Probabilistic reliability criterion for planning transmission system expansions," Generation, Transmission and Distribution, IEE Proceedings, vol.153, no.6, pp.719-727, November 2006, doi: 10.1049/ip-gtd:20050205 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4015896&isnumber=4015882

[65] Xu, Xiaokang; Edmonds, Michael J. S., "Probabilistic Reliability Methods and Tools for Transmission Planning and System Analysis," Probabilistic Methods Applied to Power Systems, 2006. PMAPS 2006. International Conference , pp.1-6, 11-15 June 2006, doi: 10.1109/PMAPS.2006.360254 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4202266&isnumber=4202205

[66] Henry, S. J. Pompee, L. DeVatine, M. Bulot, K. Bell; "New Trends For The Assessment Of Power System Security Under Uncertainty" Assess, CIGRE 2004 http://areeweb.polito.it/eventi/irep2004/Session%20D3/D3_5.pdf

[67] Smith, C.J., Osborn, D., Zavadil, R., Lasher, W., Gómez-Lázaro, E., Estanqueiro, A., Trötsche, Statnett T., Tande, J., Korpås, M., Van Hulle, F., Holttinen, H., Orths, A., Burke, D., O'Malley, M., Dobschinski, J., Rawn, B., Gibescu, M., Dale, L. "Transmission Planning for Wind Energy: Status and Prospects," Wiley Interdisciplinary Reviews: Energy and Environment, in press, 2012

[68] O'Neill, R.P.; Hedman, K.W.; Krall, E.A.; Papavasiliou, A. Oren, S. "Economic analysis of the N-1 reliable unit commitment and transmission switching problem using duality concepts" Energy Syst; DOI 10.1007/s12667-009-0005-6; December 2009 http://www.ieor.berkeley.edu/~oren/pubs/Economic_Analysis_N1_2009.pdf

[69] Karki, R.; Hu, P.; Billinton, R., "Adequacy criteria and methods for wind power transmission planning," Power & Energy Society General Meeting, 2009. PES '09. IEEE , vol., no., pp.1-7, 26-30 July 2009 doi: 10.1109/PES.2009.5275810 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5275810&isnumber=5260217

[70] Burke, D.J., O'Malley, M.J. (2011b). A Study of Optimal Nonfirm Wind Capacity Connection to Congested Transmission Systems. IEEE Transactions on Sustainable Energy, vol.2, no.2, pp.167-176, April 2011 doi: 10.1109/TSTE.2010.2094214 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5643190&isnumber=5735622

[71] Burke, D.J. and O'Malley, M.J. (2011a). A Study of Principal Component Analysis Applied to Spatially Distributed Wind Power. IEEE Transactions on Power Systems, vol.26, no.4, pp.2084-2092, doi: 10.1109/TPWRS.2011.2120632 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5738711&isnumber=6048014

[72] Burke, D.J. and O'Malley M.J. (2011c). "Factors influencing wind energy curtailment," IEEE Transactions on Sustainable Energy, vol. 2, pp. 185-193

since 2010. The objective of this modeling approach is to provide appropriate input to reliability analysis programs and other traditional software used in power system transmission planning. The output from the model is especially well suited for developing input to probabilistic programs such as EPRI's Transmission Contingency and Reliability Evaluation (TransCARE) in that it allows the uncertainty associated with the availability of variable generation to be properly captured in system-wide reliability analysis.

The Eastern Wind Integration and Transmission Study (EWITS) used the ELCC metric to calculate the capacity contribution from wind energy, both with and without a hypothetical transmission build-out.[73, 74] This work showed that wind capacity value is a function of transmission, among other factors. But more fundamentally, it is clear that the level of capacity required to achieve a specific target LOLE is driven in part by the transmission system. To investigate this further, Ibanez and Milligan developed a model of the Western Interconnection.[75] They asked the following question: "What is the ELCC with 'perfect transmission' (unlimited interconnection) in the West, compared to that of the system as currently planned and operated?" They discovered that when individual BAs develop their own generation requirements based on a target of 1 day in10 years LOLE, approximately 60 GW of additional generation is needed, which is above and beyond the case in which adequacy targets are developed with perfect transmission. This impact is caused by both the transmission expansion and full coordination among the various BAs that resulted from the transmission infrastructure. The key implication of this work is that transmission design and generation needs are inextricably linked, and the need for tools that account for this link will only increase with more VG.

A practical industry example of scenario-based transmission planning can be found in MISO. MISO has an extensive Transmission Expansion Planning (MTEP) process under which they have adopted many probabilistic methods. The process is continually evolving; and in particular, it has changed to account for the rapid increase in wind energy.[76] Therefore, it is an interesting example of state-of-the-art probabilistic planning methods with increasing levels of variable generation. MISO is adopting probabilistic methods to account for all uncertainties, but wind is not the most significant. Wind energy production ranks third in component contribution to the variability of net load behind load and non-scheduled interchange. Load, non-scheduled interchange, and wind are the major sources of net load variability.

The MISO value-based (Economic and Reliability) planning process was developed to produce transmission expansion plans for very large power systems. The results of multiple scenarios or futures that have unique generation forecasts and unique transmission system conceptual designs are tested for robustness against the transmission conceptual designs of other futures. Weighted probabilistic analysis is performed for the purpose of selecting a single robust transmission system expansion that could best meet the future's requirements. The MISO transmission planning process is characterized by an extensive stakeholder process that is used to develop scenario weights, rather than weighting them equally, which was the practice until 2013. These weights are used to value different plans across all scenarios to find the most robust one with respect to the different possible futures and multiple objectives, including cost minimization, reliability, renewable energy mandates, and resource adequacy. The conversion of stakeholder beliefs of what the future involves requires a survey and the conversion of the results using a Rasch model[77] into numerical weights.

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[73] EnerNex Corporation, 2010: Eastern Wind Integration and Transmission study (EWITS), prepared for the National Renewable Energy Laboratory, January 2010, http://www.nrel.gov/docs/fy11osti/47078.pdf

[74] NERC (2011a). Integration of Variable Generation Task 1.2, "Methods to Model and Calculate Capacity Contributions of Variable Generation for Resource Adequacy Planning" North American Electric Reliability Corporation, 2011, http://www.nerc.com/files/ivgtf1-2.pdf

[75] Ibanez, E.; Milligan, M., "Impact of Transmission on Resource Adequacy in Systems with Wind and Solar Power," IEEE Power and Energy Society General Meeting, 2012. San Diego, CA

[76] https://www.midwestiso.org/Planning/TransmissionExpansionPlanning/Pages/TransmissionExpansionPlanning.aspx

[77] http://www.rasch.org

With 65,000 buses and 9,000 generators, the MISO system is very large, and the computational challenge it poses for a Monte Carlo approach is significant. MISO must model neighboring systems as well as the MISO system to obtain accurate study results as a result of market interactions.

NREL models and MISO experience show that full wind energy production is not greater than 91 percent of the installed capacity. MISO wind generation is located in an area of 680 x 640 miles. The chance that wind would be sufficient for maximum generation everywhere is unlikely. Full wind output is modeled at 70 percent load shoulder distributions for reliability studies. Wind energy has a 14 percent capacity credit as established by the Equivalent Load Carrying Capability method using the GE MARS probabilistic loss of load probability program. The power transfer capability of the robust transmission plan is used for Resource Adequacy calculations and the wind capacity factor analysis when using the LOLP program. This trade-off between transmission investment and curtailed wind is consistent with the fundamental goal of the MTEP to provide access to the lowest-cost electric energy for the consumer by addressing local and regional reliability needs.[78] This is a similar approach to the one adopted in the Texas Competitive Renewable Energy Zones (CREZ) described below.

In some parts of the United States, locations for potential VG development have been identified so that transmission planning could move forward prior to renewable development. The CREZ in Texas allowed ERCOT to plan for (and start building) transmission sized for future high-renewable build-out levels, in some cases prior to renewable build-out.[79, 80] Although zone-renewable build-out is not guaranteed, knowing the likely zones of future VG development reduces the risk of building transmission to the wrong locations or not building transmission until the VG is developed, thereby stranding some or all of the renewable energy until the line is built.

WECC's Long-Term Planning Tools Task Force is developing a Study Case Development Tool (SCDT) and a Network Expansion Tool (NXT) to study long-term scenarios and develop transmission plans.[81] The Geographical Information System (GIS)-based tools optimize generation and transmission build-out and incorporate consideration of a wide range of input, including policy targets, environmental limitations, and government mandates. They use information from the WREZ project (modeled on ERCOT's CREZ), which independently developed "likely" locations where large capacities of VG would be developed. Using information on load hubs, renewable energy hubs, existing transmission, and existing/future generation attributes, the attributes of future generation mixes are calculated and generation and transmission are optimized. There is a requirement that the probabilities of horizon end states must be determined and communicated clearly to users. The purpose of the WREZ is, in part, to narrow the universe of potential building locations for VG, which in turn reduces the uncertainty of building transmission to undeveloped VG locations.[82]

In fall 2013, the Eastern Interconnection States' Planning Council (EISPC) initiated efforts to examine whether existing deterministic transmission planning processes and tools are adequate for future needs or whether they should be augmented with probabilistic methods. To this end, the EISPC engaged EPRI to develop a probabilistic transmission planning white paper and to conduct a limited number of probabilistic transmission planning case studies with selected planning authorities. The EISPC white paper will serve as a primer on how to incorporate probabilistic assessment methods into existing transmission processes and survey existing tools and methods. The EISPC case studies will apply existing probabilistic planning tools to portions of the existing planning processes at Tennessee Valley Authority (TVA), MISO, and Southwest Power Pool (SPP).

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[78] https://www.midwestiso.org/Planning/TransmissionExpansionPlanning/Pages/BenefitsofMTEP.aspx

[79] B. Kirby, 2007, Evaluating Transmission Costs and Wind Benefits in Texas: Examining the ERCOT CREZ Transmission Study, The Wind Coalition and Electric Transmission Texas, LLC, Texas PUC Docket NO. 33672, April, www.consultkirby.com

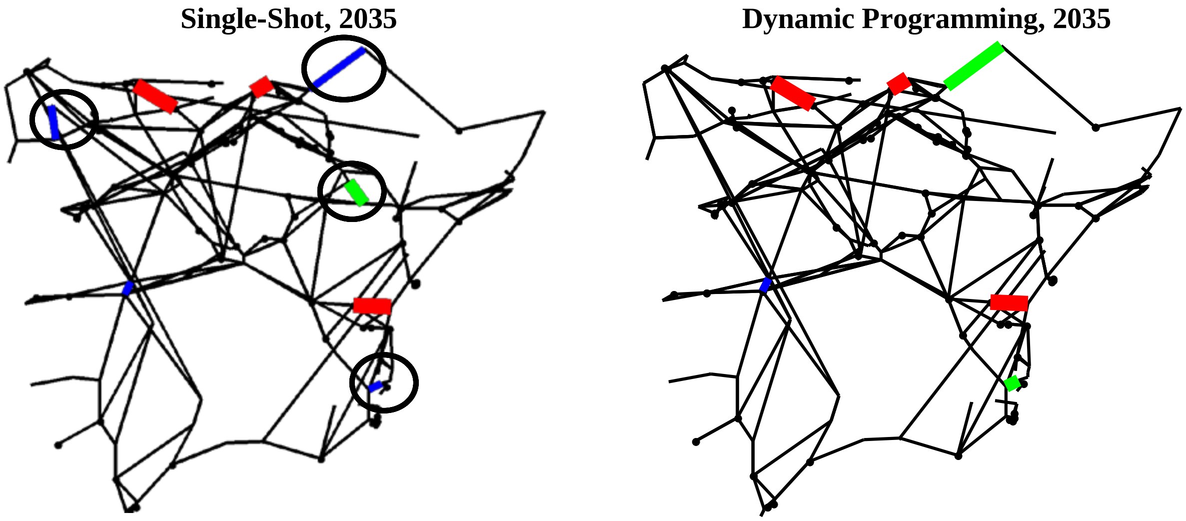
[80] Smith, C.J., Osborn, D., Zavadil, R., Lasher, W., Gómez-Lázaro, E., Estanqueiro, A., Trötsche, Statnett T., Tande, J., Korpås, M., Van Hulle, F., Holttinen, H., Orths, A., Burke, D., O'Malley, M., Dobschinski, J., Rawn, B., Gibescu, M., Dale, L. "Transmission Planning for Wind Energy: Status and Prospects," Wiley Interdisciplinary Reviews: Energy and Environment, in press, 2012

[81] WECC, 2012, https://www.wecc.biz/committees/BOD/TEPPC/TAS/LTPTTF/default.aspx

[82] Nickell, B.; Long-term Planning Tool Demonstration, Presented at the CREPC and SPSC Joint Meeting, April 4, 2012

It is also worth noting that remedial action schemes (RASs) are becoming more prevalent in transmission planning. Here again, probabilistic methods can help make their design more robust.[83, 84]

Because it is time-consuming to build transmission in the United States, transmission solutions must ensure system robustness to handle challenges of VG integration. Thus, "single-shot" transmission planning may be overly optimized for one specific set of assumed conditions and may miss more robust solutions provided by probabilistic methods that consider multiple future scenarios. For example, as shown in Figure 3, Spain single-shot plan for 2035 has different corridors and different capacities than a dynamic programming model that was optimized over 30 years with investment decisions every ten years. In this model, 50 percent of the lines constructed in the single-shot model are inconsistent with the dynamic programming model with two 400 MW lines not constructed and one 400 MW line changed to a 750 MW line. Differences between the plans are circled in black on the single-shot map.



2035	Single-Shot	Dynamic Programming
400 MW	4	1
750 MW	1	2
1500 MW	3	3

Figure 3: Single-Shot and Dynamic Programming Transmission Plans for Spain[85]

For a number of years, the system planning standard in Great Britain has consisted of two components: a deterministic demand security component, and a cost-benefit analysis component. The planning standard aimed at balancing the cost of additional reinforcement against reduced cost of finite network capacity constraining the generation schedule. These cost-benefit analyses are carried out through calculation of expected (in the mathematical sense) constraint costs by non-sequential Monte Carlo simulation, with stochastic modeling of

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[83] Wen, J.; Arons, P.; Liu, W.-H.E. , "The role of Remedial Action Schemes in renewable generation integrations," Innovative Smart Grid Technologies (ISGT), 2010 , vol., no., pp.1-6, 19-21 Jan. 2010, doi: 10.1109/ISGT.2010.5434770 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5434770&isnumber=5434721

[84] Burke, D.J., O'Malley, M.J. (2011b). A Study of Optimal Nonfirm Wind Capacity Connection to Congested Transmission Systems. IEEE Transactions on Sustainable Energy, vol.2, no.2, pp.167-176, April 2011; doi: 10.1109/TSTE.2010.2094214 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5643190&isnumber=5735622

[85] Donohoo, P. "Integrating Dynamics and Generator Location Uncertainty for Robust Electric Transmission Planning." INFORMS Annual Meeting. November 13, 2011. Charlotte, North Carolina, USA

generation-forced outages and available wind capacity, and the distribution of demand represented by a limited number of discrete levels. Future research and development prospects include improved wind power resource data for training the statistical wind resource model. Additional studies consider fluctuations of the constraint costs around the expected (mean) value output using current modeling approaches.[86, 87] The role of risk modeling in transmission planning with wind in Great Britain is described in the Britain transmission planning and operational standards study.[88]

Distribution Networks

Connecting variable generation close to the load, such as with distributed solar PV or other distributed generation (DG), is a trend that brings with it many challenges that can benefit from probabilistic methods. Distribution networks were not designed for any significant level of local generation, and coupled with the stochastic nature of the distributed energy resources and the desire to optimize the network utilization, this leads to many challenging research questions. The NERC IVGTF Task 1.8 documents the Reliability Impacts of Distributed Resources to identify the potential impacts of DER, potential mitigating strategies, review existing NERC Registry Criteria specific to DER applications and to propose potential future approaches to ensure continued reliability in systems with large amounts of DER.[89]

The IPEC report *Probabilistic Voltage Solution Method for Distribution Systems with Wind Electric Generators*[90] explored probabilistic load flow methods for distribution networks that take account of the stochastic nature of wind. Another report used a Monte Carlo-based probabilistic load flow for similar purposes[91]. Su proposes a probabilistic load flow method that incorporates the uncertainties associated with DG output, load demand, network configurations, and the operation of voltage control devices.[92] Accounting for the reactive power capability of DG units should lead to improved voltage levels in the distribution system, which would ultimately provide increased benefits in terms of improved system operation. However, incorporating the reactive power capability of DG together with system uncertainties can potentially increase the complexity of optimization tools for planning. Jayaweera *et al.*, are developing probabilistic methods to quantify expected losses, voltage rise effects and wind integration capacity with distributed control of reactive power.[93] Similarly, in Zou *et al.*, a distribution system planning model is proposed which determines the optimal allocation for DG while minimizing

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[86] National Grid 2012 "Amendment Report GSR009: Review of Required Boundary Transfer Capability with Significant Volumes of Intermittent Generation," available at http://www.nationalgrid.com/uk/Electricity/Codes/gbsqsscode/LiveAmendments/

[87] National Grid 2012 "National Electricity Transmission System Security and Quality of Supply Standard Version 2.3," available at http://www.nationalgrid.com/uk/Electricity/Codes/gbsqsscode/DocLibrary/

[88] Dent, C.J.; Bell, K.R.W.; Richards, A.W.; Zachary, S.; Eager, D.; Harrison, G.P.; Bialek, J.W.; , "The role of risk modelling in the Great Britain transmission planning and operational standards," Probabilistic Methods Applied to Power Systems (PMAPS), 2010 IEEE 11th International Conference on , pp.325-330, 14-17 June 2010, doi: 10.1109/PMAPS.2010.5528890 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5528890&isnumber=5526245

[89] NERC (2011b). Integration of Variable Generation Task 1.8, "Potential Bulk System Reliability Impacts of Distributed Resources" North American Electric Reliability Corporation, 2011, http://www.nerc.com/docs/pc/ivgtf/IVGTF_TF-1-8_Reliability-Impact-Distributed-Resources_Final-Draft_2011.pdf

[90] Opathella, C.; Venkatesh, B.; Dukpa, A.; "Probabilistic voltage solution method for distribution systems with wind electric generators," IPEC, 2010 Conference Proceedings , pp.220-223, 27-29 Oct. 2010, doi: 10.1109/IPECON.2010.569710 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5697109&isnumber=5696950#

[91] Zou, K.; Agalgaonkar, A.P.; Muttaqi, K.M.; Perera, S.; Browne, N.; , "Support of distribution system using distributed wind and PV systems," Power Engineering Conference, 2009. AUPEC 2009. Australasian Universities , pp.1-6, 27-30 Sept. 2009

[92] Su, C-L., "Stochastic Evaluation of Voltages in Distribution Networks With Distributed Generation Using Detailed Distribution Operation Models," Power Systems, IEEE Transactions on , vol.25, no.2, pp.786-795, May 2010, doi: 10.1109/TPWRS.2009.2034968 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5340599&isnumber=5452108

[93] Jayaweera, D.; Islam, S.; Tinney, P.; "Analytical approaches to assess embedded wind generation effects on distribution networks," Probabilistic Methods Applied to Power Systems (PMAPS), 2010 IEEE 11th International Conference on , vol., no., pp.419-424, 14-17 June 2010 doi: 10.1109/PMAPS.2010.5528959 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5528959&isnumber=5526245

the computational effort of the algorithm.[94] The model accounts for the uncertainties inherent with DG and load demand by using probabilistic models while also incorporating the reactive power capability of the generation units.

Improvements to load demand modeling will also be necessary if DG is to be successfully incorporated in future distribution system designs. The introduction of new loads (such as electric vehicles) with demand-side management schemes will alter the traditional load profiles, particularly at the low-voltage residential level of the system. Two other studies proposed probabilistic methods for modeling distribution system load with varying levels of electric vehicle penetration.[95, 96] Emerging flexible resources, such as demand-side management resources, electric vehicles, etc., and their potential impact on the integration of VG are detailed in the NERC IVGTF Task 1.5 report.[97]

Operations Planning

Operationally, the uncertainties primarily appear in the unit commitment and dispatch time frames. IVGTF 2.4 has done a comprehensive job of reviewing the state of the art in power system operations with VG.[98] This report concentrates on studies and applications where probabilistic methods are most relevant.

From the early days of VG integration into power systems, forecasting these resources has received significant attention.[99] Of particular importance is forecasting on time scales of up to a few days ahead. A recent discussion by CAISO can be found in the joint CAISO-NERC report.[100] A comprehensive coverage of this technology can be found in the NERC IVGTF Task 2.1 report.[101] As the technology has advanced, the concept of a probabilistic forecast has gained momentum—using not just one forecast, but a multitude of forecasts, each with its own probability[102, 103] or a forecast represented as a probability distribution for each time value. For example, ERCOT has recently implemented a probabilistic wind forecasting system for ramps.[104, 105]

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[94] Zou, K.; Agalgaonkar, A.P.; Muttaqi, K.M.; Perera, S.; "Distribution System Planning With Incorporating DG Reactive Capability and System Uncertainties," Sustainable Energy, IEEE Transactions, vol.3, no.1, pp.112-123, Jan. 2012, doi: 10.1109/TSTE.2011.2166281 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6102294&isnumber=6102278

[95] Qian, K.; Zhou, C.; Allan, M.; Zhou, W.; , "Modeling of the Cost of EV Battery Wear Due to V2G Application in Power Systems," Energy Conversion, IEEE Transactions on , vol.26, no.4, pp.1041-1050, Dec. 2011 doi: 10.1109/TEC.2011.2159977 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5958591&isnumber=6083464

[96] Richardson, P.; Taylor, J.; Flynn, D.; Keane, A., "Stochastic analysis of the impact of electric vehicles on distribution networks," Proceedings of CIRED 21st International Conference on Electricity Distribution, June 2011.

[97] NERC (2010c). Integration of Variable Generation Task 1.5, "Potential Reliability Impacts of Emerging Flexible Resources" NERC, 2010, http://www.nerc.com/files/IVGTF_Task_1_5_Final.pdf

[98] NERC (2011d). Integration of Variable Generation Task 2.4, "Operating Practices, Procedures, and Tools" North American Electric Reliability Corporation, 2011, http://www.nerc.com/files/ivgtf2-4.pdf

[99] Kariniotakis, G; "European Research in Wind Power Forecasting. The objectives of the *Anemos.plus* and *SafeWind* projects," ANEMOS Workshop, June 2011, http://www.anemos-plus.eu/

[100] NERC 2013 Special Reliability Assessment: Maintaining Bulk Power System Reliability While Integrating Variable Energy Resources – CAISO Approach. Available at http://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC-CAISO_VG_Assessment_Final.pdf

[101] NERC (2010d). Integration of Variable Generation Task 2.1, "Variable Generation Power Forecasting for Operations" North American Electric Reliability Corporation, 2010, http://www.nerc.com/files/Varialbe%20Generationn%20Power%20Forecasting%20for%20Operations.pdf

[102] Pinson, P.; Madsen, H., "Probabilistic Forecasting of Wind Power at the Minute Time-Scale with Markov-Switching Autoregressive Models," Probabilistic Methods Applied to Power Systems, 2008. PMAPS '08. Proceedings of the 10th International Conference, pp.1-8, 25-29 May 2008 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4912618&isnumber=4912596

[103] This should not be confused with the closely related but distinct concept of ensemble forecasts where a number of different methods are used to produce multiple forecasts.

[104] Doggett, T. "UPDATE ON WIND TECHNOLOGY" President & CEO, ERCOT National Association of Regulatory Utility Commissioners July 23, 2012 http://www.narucmeetings.org/Presentations/Wind%20tech%20Dogget%2023%20Jul%202012.pdf

[105] "ERCOT Using New Forecasting Tool to Prepare for Wind Variability" News release, March 2010 http://www.ercot.com/news/press_releases/show/326

Probabilistic forecasts facilitate dynamically changing reserve targets[106, 107, 108] and have spurred the development of stochastic scheduling algorithms in which all the forecasts can be used to schedule the system in an optimal manner.[109,110] The relationship between the modeled stochastic characteristics of an underlying wind resource, as represented by scenario trees, can have important implications on how units are scheduled.[111] This further emphasizes the need for high-quality data. Stochastic unit commitment with correct probabilistic forecast input data can actually negate the need for explicit reserve constraints.[112,113] While probabilistic methods applied to unit commitment can be shown in a study environment to give better performance (in regard to cost or reliability) than deterministic methods,[114] significant translational work is required before they can be deployed operationally in control rooms.[115] It is also possible that they may not be deployed directly, but rather that the methods will be used to develop “smarter” deterministic criteria, or “rules of thumb” that capture most of the benefits and are more easily translatable into operable actions as discussed above.

An NREL study on the Eastern Interconnection with increased levels of wind penetration showed that the Wilmar stochastic unit commitment tool brought significant benefits.[116] However, the computational issues were significant due to the size of the system. More frequent commitment—rather than a statistical approach—was more practical and beneficial.[117]

Some of the commitment issues will change if high penetrations of VG are accompanied by flexible generation that replaces retiring base load units, as anticipated in the NERC *2012 Long-Term Reliability Assessment*.[118] In an extreme case, one could imagine a large fleet of reciprocating engines or aero derivative gas turbines with fast start-up times and efficient ramping and cycling. In such a system, unit commitment and reserves scheduling would likely be quite different than they are today.

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[112] Stuart, A and G. Strbac, “Efficient Stochastic Scheduling for Simulation of Wind-Integrated Power Systems,” IEEE Trans. Power Syst., 27(1), pp. 323 - 334, 2012.

[113] J. Wang, A. Botterud, R. Bessa, H. Keko, L. Carvalho, D. Issicaba, J. Sumaili, V. Miranda, Wind power forecasting uncertainty and unit commitment, Applied Energy, Volume 88, Issue 11, November 2011, Pages 4014-4023, ISSN 0306-2619, 10.1016/j.apenergy.2011.04.011. http://www.sciencedirect.com/science/article/pii/S0306261911002339

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[117] E. Ela; M. Milligan; P. Meibom; R. Barth; A. Tuohy; “Advanced Unit Commitment Strategies for the U.S. Eastern Interconnection” 9th Annual International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Québec, Canada October 2010

[118] NERC, “2012 Long-Term Reliability Assessment,” http://www.seia.org/sites/default/files/resources/2012 LTRA_FINAL.pdf, November 2012

In addition to fundamental methodological work on reserves and stochastic unit commitment, there are significant practical and human elements involved. Interpretation of probabilistic methods output is very challenging, and visualization techniques may be an important tool for addressing this.[119] Whatever method is used to calculate a probabilistic reserve level, a specific set of operator actions are required, and translating from a stochastic commitment algorithm to an actionable commitment plan may not be straightforward. Markets can help with this if they are properly designed and function well by increasing system operator access to the full flexible capability of all resources. Discretion with regard to a specific operating action is also a function of human risk aversion. Overcommitting generation may result in an economic penalty to some units and to the power system as a whole; however, under-scheduling may result in insufficient generation and lost load. Faced with this choice and limited knowledge regarding the relative risks, a rational system operator will likely err on the side of overscheduling. The human element (i.e., the risk profile of the operators and how they are presented with the information) is usually different in an operations situation than in a planning context.

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Conclusions and Recommendations

Conclusions

Most activity in probabilistic methods for integrating VG in power systems is still in the research domain. The probabilistic tools and techniques being developed by the research community have not yet been widely adopted by industry. This is consistent with the recent findings of a CIGRE study on VG[120] and probabilistic methods in general.[121]

However, this is an area of very active and vibrant research. Many power system planning and operating problems are implicitly probabilistic, and while deterministic assumptions and approximations have served us reasonably well in the past, it is very likely that probabilistic methods will be required to ensure more optimal and effective solutions in the future. The growing penetrations of variable generation, with the variability and uncertainty that are an implicit characteristic of the wind and sun that fuels such generation, will further serve to make probabilistic methods useful and valuable.

There are many challenges facing the widespread deployment of probabilistic methods. Research scale tools and models are being developed and deployed on small representative test systems, but despite faster and relatively inexpensive computation platforms, they are not yet demonstrated to be practical for the full detail of real systems. There is an understandable reluctance on the part of industry to adopt probabilistic methods that initially appear to be very complex and difficult to understand, and there may be a “skills gap” within industry. Many of the traditional deterministic methods are still fit for their purposes, but with more VG they may become inadequate. However, probabilistic methods require significant amounts of data that may not exist or are difficult and expensive to acquire.

Despite the challenges, the potential benefits and the changing nature of the power system will move the industry as a whole down the path to using probabilistic methods for some applications. All generators, transmission lines, and distribution lines have probabilistic characteristics, but in the past, deterministic methods or simple rules of thumb have seemed adequate since their characteristics are often viewed as contingency concerns (either it works or it doesn’t). With a future that will increasingly be dominated by variable generation, distributed generation, demand response, and other elements of implicit variability and uncertainty, operators and system planners will still need to exploit the benefits of increasingly sophisticated probabilistic methods to ensure that our assumptions are still reasonable in the near term, and to directly help plan and operate the power system in the longer term.

Observations and Findings

Observations and findings for industry from the six classes of decision problems associated with VG:

- Reserves: The level of specific reserves needed for VG integration is broadly understood; however, specific methods have not been rigorously tested and compared. The application of stochastic methods appears promising but needs validation and acceptance if it is to be successfully used.
- Dispatch: There is emerging work on probabilistic methods to dispatch conventional generation to minimize cost and maintain reliability in the presence of high levels of VG; however, there is a gap between academic work and practice as a result of more limited experience with high levels of VG.

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[120] CIGRE 2012; Technical Brochure on Coping with Limits for Very High Penetrations of Renewable Energy, Joint Working Group C1/C2/C6.18 of Study Committee C6, August 2012, International Conference on Large High Voltage Electric Systems

[121] CIGRE 2010 “Review of the Current Status of Tools and Techniques for Risk-Based and Probabilistic Planning in Power Systems” CIGRE October 2010

- Commitment: There has been considerable interest in stochastic unit commitment. Methods and approaches vary, and most of this work resides in the academic/research domain. Collaboration to evolve and move these methods into actual practice, when appropriate, is needed.
- Maintenance: Maintenance scheduling may be more difficult in market regions where there is limited central authority to coordinate scheduled maintenance, and high levels of VG will likely have a significant influence. Methods to quantify the risk of both capacity shortfalls and flexibility shortfalls can be developed and tested in industry.
- Generation planning: New methods have been developed to begin quantifying flexibility needs and risks of insufficient flexibility within generation expansion planning algorithms. This in turn results in a VG investment balance in supporting technologies moving forward and providing the flexibility that VG—as well as BSP reliability—require. There is room for improvement in these methods, as well as a need to evolve and move these approaches from the research community to industry practice.
- Transmission planning: There is evidence that stochastic approaches to transmission planning may yield more robust solutions; combining such methods with co-optimization of generation and planning decisions is particularly appealing but computationally challenging. However, these methods are new and emerging, and additional research and deployment of such methods may be useful.

Recommendations:

- Grow appreciation for the ways in which the future power system will change. VG is a catalyst for this change in viewpoint, but it is not the only driver toward a different future system that challenges traditional assumptions and practices.
- Work to develop and demonstrate efficient probabilistic techniques and solutions that are capable of addressing full-scale industry problems.
- Improve the understanding of probabilistic methods within the industry. The research community needs to work more closely with the industry to clearly demonstrate the benefits of probabilistic methods. The industry needs to clearly communicate shortcomings in deterministic methods and areas that probabilistic methods can be most fruitful. Cooperative efforts of the research and industry communities are needed to overcome the challenges in terms of both understanding and demonstration.
- More and better data are needed to allow the research and demonstrations to be meaningful and realistic—from real power systems, from VG resources, and for future VG deployment scenarios. Collecting and maintaining large data sets can be expensive; however, stochastic methods generally require data that may not be readily available. Industry should discuss the trade-offs and costs vs. benefits of collecting data that could help inform stochastic methods and the more rigorous assessments of various risks associated with power system planning and operations with high levels of VG.
- Because the task force envisions a significant increase in the development and application of stochastic methods to help analyze the impacts of VG, the task force recommends that NERC perform a bi-annual assessment of development in this area. The IVGTF would be an appropriate home for this work.

Appendix I: NERC IVGTF Task 1-6 Roster

Name	Position	Title	Organization
Michael Milligan	Lead	Principal Researcher	National Renewable Energy Laboratory
Mark O'Mally	Member	Professor of Electrical Engineering	University College Dublin
Mark Ahlstrom	Member	CEO	WindLogics Inc.
Bagen Bagen	Member	Exploratory Studies Engineer	Manitoba Hydro
Kieran Connolly	Member	Manager, Generation Scheduling	Bonneville Power Administration
William Crews	Member	Regional Planning Assessment Engineer, Sr.	Texas Reliability Entity, Inc.
Lisa Dangelmaier	Member	Operations Superintendent	Hawaii Electric Light Company
Pearl Donohoo	Member	NSF Graduate Fellow	Massachusetts Institute of Technology
Anish Gaikwad	Member	Project Manager	Electric Power Research Institute
David Jacobson	Member	Interconnection & Grid Supply Planning Engineer	Manitoba Hydro
Sasan Jalali	Member	Electrical Engineer	Federal Energy Regulatory Commission
Warren Lasher	Member	Manager, System Assessment	Electric Reliability Council of Texas, Inc.
James McCalley	Member	Professor	Iowa State University
Jay Morrison	Member	Senior Regulatory Counsel	National Rural Electric Cooperative Association
Bradley Nickell	Member	Renewable Integration and Planning Director	Western Electricity Coordinating Council
Dale Osborn	Member	Transmission Technical Director	MISO
Mahendra Patel	Member	Senior Business Solutions Engineer	PJM Interconnection, L.L.C.
Mohammad Shahidehpour	Member	Bodine Chair Professor and Director	Illinois Institute of Technology
Daniel Brooks	Member	Manager, Power Delivery System Studies	Electric Power Research Institute
Subbaiah Pasupulati	Member	Director of Technical Studies	Oak Creek Energy Systems, Inc.
Pouyan Pourbeik	Member	Technical Executive	Electric Power Research Institute
Dariush Shirmohammadi	Member	Chief Consultant	Shir Power Engineering Consultants, Inc.
Noha Abdel-Karim	NERC Staff	Senior Engineer Reliability Assessment	North American Electric Reliability Corporation
John Moura	NERC Staff	Director of Reliability Assessments	North American Electric Reliability Corporation