

Michael R. Milligan, Ph.D.

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Education and Training

Ph.D., Economics, University of Colorado, Boulder

M.A., Economics, University of Colorado, Denver

B.A., Mathematics, Albion College, Albion, MI

Professional Experience

Dr. Michael Milligan recently retired as Principal Researcher at the National Renewable Energy Laboratory, and he is now an independent power system consultant. He has more than 35 years' experience in analysis and modeling the bulk power system, and nearly 30 years focusing on the impacts of wind and solar generation integration into the bulk system. He is the author/coauthor of more than 225 journal articles, conference papers, technical reports, and book chapters on topics that include the physical impacts of variable generation on power system operations, reserves, economics, and resource adequacy (links at milligangridsolutions.com). He has also published articles and book chapters on variable generation and energy markets, the impacts of variability pooling and wide-area energy management, conditional firm transmission potential in the West, the application of genetic algorithms and fuzzy logic to wind power plant location optimization, and short-term wind forecasting. He has given papers and presentations in China, Japan, India, Portugal, Spain, Italy, France, Ireland, England, Scotland, Germany, Netherlands, Malaysia, Canada, Denmark, Sweden, Norway, and Finland, and has developed methods that are used for many aspects of integration analysis.

As a consultant, Michael has undertaken a wide range of projects that include (a) advising a wind plant owner/operator on ancillary services tariffs, (b) submitting comments to FERC on reliability and resilience, and wholesale markets (c) writing papers for publications, (d) providing workshops on grid reliability at state commissions, FERC, NERC, RTOs, and other stakeholders. He has provided expert review for technical publications by the International Energy Agency, advised stakeholders in Alaska regarding the impacts of control area consolidation on the Railbelt system, and has advised many stakeholder groups on utility economics and reliability as part of ISO/RTO transmission planning processes, especially related to renewable integration on the bulk power system. He has submitted expert testimony in several state public utility commission proceedings, focusing on resource adequacy and planning, ancillary services, and renewable integration issues. His clients include RTOs, trade groups, and educational organizations. He is a member of GridLab's expert team, and also serves as an ad hoc technical advisor to the Western Interstate Energy Board.

Dr. Milligan has provided expert testimony in public utility proceedings and workshops around the United States. For many years when he was at NREL, he collaborated with the Western Interstate Energy Board, was a member of the Western Governors' Association's Clean and Diverse Energy Advisory Committee (CDEAC), and he was the primary author of the wind

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integration and scenario chapters. He led and contributed to multiple projects analyzing the potential benefits of the then-proposed Energy Imbalance Market in the West, including reserves and ramping analysis and electricity production simulation. This work was influential in the formation of the EIM, which is now operating and expanding in the Western Interconnection—parts of California, Nevada, Arizona, Utah, Wyoming, Idaho, Oregon, and Washington are participating. Since its launch in 2014 the EIM has enhanced grid reliability and reduced costs by more than \$3 Billion for the market participants. The EIM improves the ability of the bulk power system to effectively manage the increasing levels of wind and solar power, now and in the future.

Michael has advised the 21st Century Clean Power Partnership (<http://www.21stcenturypower.org/projects.cfm>), a multilateral effort of the Clean Energy Ministerial, operated by the Joint Institute for Sustainable Energy Analysis. In this role, he has provided guidance to governments and utilities in China, India, South Africa and others on methods to improve the ability of their power systems to efficiently integrate renewable energy. He recently served as a principal technical advisor to a large-scale renewable energy integration study in India. His work was influential in influencing the Indian Grid Operator (POSOCO) to embark on a Pilot Project on 5-Minute Scheduling in India that is currently underway.

Dr. Milligan is an internationally recognized expert in loss-of-load probability analysis and resource adequacy. He led the North American Electric Reliability Corporation (NERC) Task Force for Capacity Value of Variable Generation and co-led the Institute of Electrical and Electronics Engineers (IEEE) Wind Power Coordinating Committee Capacity Value Task Force. He advises regional transmission organizations and utilities on resource adequacy methods and has advised many power system industry task forces and working groups. He was a charter member of the NERC Integrating Variable Generation Task Force and Essential Reliability Services Task Force (now Working Group) and the Western Electricity Coordinating Council's (WECC's) Variable Generation Subcommittee; and has served on multiple WECC committees and has been a key contributor to multiple NERC and WECC reports.

Michael led the Bulk Electric Power System Task Force for NREL's groundbreaking Renewable Electricity Futures study (http://www.nrel.gov/analysis/re_futures/). On behalf of the U.S. Department of Energy, he led the Power System Integration and Transmission task forces for the Wind Vision (<https://energy.gov/eere/wind/wind-vision>) and the Hydro Power Vision (<https://energy.gov/eere/water/new-vision-united-states-hydropower>) studies.

Dr. Milligan has advised many power system industry and utility commissions, including the Mid-Continent Independent System Operator; New York Independent System Operator; Independent System Operator of New England, California Independent System Operator; Xcel Energy (Minnesota and Colorado); Portland General Electric; Arizona Public Service; PacifiCorp; Grant County Public Utility District; Nebraska Public Power District; Western Electricity Coordinating Council; Western Interstate Energy Board; North American Electric Reliability

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Corporation; British Columbia Hydro; Hydro Quebec; Alberta Electric System Operator; commissions in New Mexico, Michigan, Washington, Oregon, Utah, California, Alaska, Minnesota, and Colorado; and the Public Utility Commissioners' (PUC) Energy Imbalance Market (EIM) group in the West. He has also provided technical reviews for several National Renewable Energy Laboratory (NREL) studies, including the Western Wind and Solar Integration Study, the Eastern Wind Integration and Transmission Study, and the Nebraska Statewide Wind Integration Study. Many of these studies are available at www.esig.energy.

Dr. Milligan has presented at hundreds of technical conferences, stakeholder meetings, and webinars. Audiences range from experts in the power system industry to groups with little background in power system operations, design, or markets. He has regularly presented at the Utility Variable-Generation Integration Group (UVIG, now ESIG), including as a keynote speaker on variable-generation integration state of the art, and is on the faculty for the UVIG Short Course on Variable Generation Integration, offered bi-annually. His sustained participation on the International Energy Agency Task 25 for large-scale wind integration (https://www.ieawind.org/task_25.html) helped launch a continuing series of international technical papers on integration issues. International collaborations include papers and projects with VTT Finland, Royal Institute of Technology Sweden, DTU Delft Netherlands, University College Dublin, University of Castilla-La Mancha Spain, LNEG Portugal, Energinet.dk Denmark, ECAR Ireland, Sintef Norway, and Kansai University Japan. He was an invited panelist in 2012 to the Royal Irish Academy in Dublin and an invited keynote speaker at the 2011 Power System Computation Conference in Stockholm. He has hosted visiting researchers from Germany, Ireland, Spain, Australia, and France, and has served on Ph.D. dissertation committees and mentored Ph.D. students at MIT, Stanford, University of Colorado, University College Dublin, Northern Arizona University, University of Delaware, and University of California Berkeley.

In response to the Federal Energy Regulatory Commission (FERC) Notice of Inquiry, he provided comments based on research results to FERC. Based in part on this input, FERC eventually issued Order 764, which directs the conditions under which a transmission provider can assess integration charges for variable generation. His work on cost-causation and integration charges has also influenced the development of integration rates and resulted in an international paper with IEA collaborators and has influenced regulatory agencies to drop integration costs from integrated resource plans.

Awards

- *Lifetime Achievement Award for sustained contributions to wind and solar power system integration studies*, awarded by the Energy Systems Integration Group (formerly UVIG): 2018.
- *Technical Achievement Award for sustained advances in renewable energy integration methods*. Utility Variable-Generation Integration Group (UVIG): 2012.
- *H.M. Hubbard Award for two decades of outstanding research contributions and leadership in research and technology*, National Renewable Energy Laboratory: 2010.

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- *President's Award* (team, 2010), National Renewable Energy Laboratory,
- *National Wind Technology Center Technical achievement awards* in 2008 and 2009, National Renewable Energy Laboratory (team).
- *Best paper awards*, including papers at the 12th and 13th International Workshops on Large-Scale Integration of Wind Power.

Employment History

- 2017 – present: Independent Power System Consultant
- 2015-2016: Ph.D. advisor, University of California, Berkeley
- 2014 – 2020: Adjunct Professor and Ph.D. Advisor, Northern Arizona University
- 2013 – 2014 Ph.D. advisor, MIT, Cambridge, MA
- 2013 – 2015: Adjunct Professor, University of Denver
- 2009 – 2013: Ph.D. advisor (3), University College, Dublin
- 2008 – 2009: Ph.D. advisor, University of Maryland
- 2008 – 2017: Principal Researcher, Power Systems Engineering Center, NREL
- 2006 – 2007: Ph.D. advisor, University of Colorado, Boulder
- 1992 – 2008 Consultant, Power System Integration, NREL
- 1982 – 2008: Professor, Economics (1998–2008); Professor, Computer Science and Mathematics (1995–1998); Professor (1982–1995) and Chair (1990–1992), Computer and Information Science Department, Front Range College
- 1975 – 1982: Power system planner, Tri-State G& T. Developed software for load forecasting and resource analysis. Developed long-range planning models and documents for power and energy requirements, resource utilization, and long-term planning

Technical Articles, Reports, Book Chapters, FERC Filings

1. Goggin, M., Milligan, M. (2019), Quantifying the Consumer Benefits of the Market Reforms in the Report: *Customer Focused and Clean*. Available at <https://windsolaralliance.org/wp-content/uploads/2019/10/WSA-Consumer-Benefits-Quantification-FINAL-9.27.19.pdf>.

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3. Reply Comments of Michael Milligan, Ph.D.: Grid Resilience in Regional Transmission Organizations and Independent System Operators. Docket AD18-7-000. Available at <http://www.milligangridsolutions.com/milligan%20ferc%20comments%20AD%2018-7-000%20from%20FERC%20web.pdf>. 2018.
4. Reply Comments of Michael Milligan, Ph.D. Grid Reliability and Resiliency Pricing, Docket No. RM18-1-000. Available at <http://www.milligangridsolutions.com/Milligan-Comments-FERC%20from%20ferc%20web.pdf>. 2017
5. Milligan, M.; Frew, B.; Clark, K; Bloom, A. (2017). Marginal Cost Pricing in a World without Perfect Competition: Implications for Electricity Markets with High Shares of Low Marginal Cost Resources. NREL Technical Report NREL/TP-6A20-69076. December. Available at <https://www.nrel.gov/docs/fy18osti/69076.pdf>.
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7. Palchek, David; Cochran, Jaquelin; Ehlen, Ali; McBennet, Brandon, Milligan, Michael; Chernyakhovskiy, Ilya; Deshmukh, Ranjit; Abhyankar, Nikit; Soonee, Sushil Kumar; Narasimhan, S.R.; Joshi, Mohit; Sreedharan, Priya. Greening the Grid: Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid, Vol 1 – National Study. National Renewable Energy Laboratory, 2017. <https://www.nrel.gov/docs/fy17osti/68530.pdf>
8. Aaron Bloom, Bethany Frew, Aaron Townsend, Erik Ela, Todd Levin, Audun Botterud: **Electricity Markets, Renewable Generation and Software Agents: Traditional and Emerging Market Designs**. Springer, 2018. <https://www.springer.com/us/book/9783319742618>
9. Frew, B.; Milligan, M.; Brinkman, G.; Bloom, A.; Clark, K; Denholm, P: Revenue Sufficiency and Reliability in a Zero Marginal Cost Future. Proceedings of the 15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants. Vienna, Austria. Nov 15-17, 2016.

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10. Frew, B.; Gallo, G.; Brinkman, G.; Milligan, M.; Clark, K.; Bloom, A. Impact of Market Behavior, Fleet Composition, and Ancillary Services on Revenue Sufficiency. NREL Technical Report NREL/TP-dD00-66076 (2016).
<http://www.nrel.gov/docs/fy16osti/66076.pdf>.
11. (Multiple Authors), M. Milligan, Hydropower Vision: A New Chapter for America's 1st Renewable Electricity Source. United States Department of Energy. Available at
<http://energy.gov/eere/water/articles/hydropower-vision-new-chapter-america-s-1st-renewable-electricity-source>.
12. Peña, I.; Milligan, M.; Ela, E.; Bloom, A.; Botterud, A.; Townsend, A.; Levin T. **Market designs for revenue sufficiency and flexibility provision for the integration of renewable energy.**
13. Holttinen, H.; et al (2016). Design and operation of power systems with large amounts of wind power: Final summary report, IEA Wind Task 25, Phase three 2012-2014.
<http://www.vtt.fi/inf/pdf/technology/2016/T268.pdf>
14. Michael Milligan; Bethany A Frew; Aaron Bloom; Erik Ela; Audun Botterud; Aaron Townsend; Todd Levin: **Wholesale Electricity Market Design with Increasing Levels of Renewable Generation: Part 1 Revenue Sufficiency and Long-Term Reliability.** 2016. Electricity Journal, 29, pp 26-38.
15. Erik Ela; Michael Milligan; Aaron Bloom; Audun Botterud; Aaron Townsend; Todd Levin; Bethany A Frew: **Wholesale Electricity Market Design with Increasing Levels of Renewable Generation: Part 2 Incentivizing Flexibility in System Operations.** 2016. Electricity Journal, 29, pp 51-60.
16. Bird, Lori & Lew, Debra & Milligan, Michael & Carlini, E. Maria & Estanqueiro, Ana & Flynn, Damian & Gomez-Lazaro, Emilio & Holttinen, Hannele & Menemenlis, Nickie & Orths, Antje & Eriksen, Peter Børr, 2016. "Wind and solar energy curtailment: A review of international experience," Renewable and Sustainable Energy Reviews, Elsevier, vol. 65(C), pages 577-586.
<https://www.sciencedirect.com/science/article/pii/S1364032116303161?via%3Dihub>
17. Aidan Tuohy, Eamonn Lannoye, Jody Dillon, Chris Dent, Amy Wilson, S. Zachary, E. Ibanez, M. Milligan: **Capacity Adequacy and Variable Generation: Improved Probabilistic Methods for Representing Variable Generation in Resource Adequacy Assessment.** Electric Power Research Institute in collaboration with National Renewable Energy Laboratory; Heriot-Watt University, Edinburgh, UK; Durham University, Durham, UK; Ecar

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20. Milligan, M.; Few, B.; Zhou, E.; Arent, D.: **Advancing System Flexibility for High Penetration Renewable Integration. Part of the China Grids Program for a Low-Carbon Future**, supported by the Children’s Investment Fund Foundation. NREL technical report NREL/TP-6A20-64864, Oct. 2015. <https://www.nrel.gov/docs/fy16osti/64864.pdf>
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32. E. Ibanez, M. Milligan (NREL, USA) (WIW14-1063), **Comparing Resource Adequacy Metrics**. 13th International Workshop on Large-Scale Integration of Wind Power into Power Systems. Berlin, Germany. Nov 11-13, 2014.

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