Visualization of the Eastern Renewable Generation Integration Study

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***Abstract*—The Eastern Renewable Generation Integration Study (ERGIS), explores the operational impacts of the widespread adoption of wind and solar photovoltaic (PV) resources in the U.S. Eastern Interconnection and Québec Interconnection (collectively, EI). In order to understand some of the economic and reliability challenges of managing hundreds of gigawatts of wind and PV generation, we developed state of the art tools, data, and models for simulating power system operations using hourly unit commitment and 5-minute economic dispatch over an entire year. Using NRELs high-performance computing capabilities and new methodologies to model operations, we found that the EI could balance the variability and uncertainty of high penetrations of wind and PV at a 5-minute level under a variety of conditions. A large-scale display and a combination of multiple coordinated views and small multiples were used to visually analyze the four large highly multivariate scenarios with high spatial and temporal resolutions.**

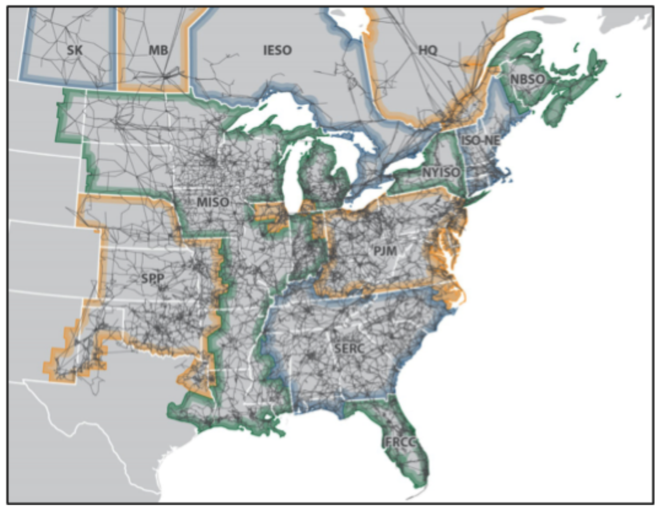

Figure 1. Base transmission network of the Eastern Interconnection modeled by ERGIS.

1. Introduction

The U.S. Eastern Interconnection and Québec Interconnection (collectively, EI) is the largest power system in North America (see Figure 1) and one of the most complex power systems in the world. Wind and solar photovoltaic (PV) generation are the fastest growing electricity resources in the United States. The Eastern Renewable Generation Integration Study (ERGIS), a scenario-based study of multiple potential wind and PV futures – up to 30% on an annual energy basis with instantaneous penetrations over 50% – was designed to understand the operational impacts of wind and PV on the transmission system and thermal and hydro generators [1]. Renewable generation sources, like wind and PV, add significant variability and uncertainty to a system that requires that demand and generation be balanced. Using high-performance computing capabilities [2], ERGIS advanced the state-of-the-art by conducting the most detailed and complex simulations of power system operations ever run. The project explores variable and uncertain conditions caused by wind and solar forecast errors, seasonal and diurnal patterns, and weather and system operating constraints. Building off and extending prior research [3], [4], [5], this study models the operational impacts of high renewable penetrations at a 5-minute resolution. The study finds it is technically feasible for the EI to operate when variable generation regularly exceeds 200 GW, and meets 30% of annual load, translating to more than a 30% reduction in power system operating costs and CO2 emissions.

Four power system future scenarios were simulated. A low variable generation (lowVG) represented a future with no new wind or PV generation installations and minimal transmission expansion. A moderate-penetration scenario (RTx10) with intra-regional transmission expansion and approximately 10% variable generation penetration designed to align to meet state renewable portfolio standards. A high-penetration scenario (RTx30) with identical transmission expansion to RTx10 with approximately 30% combined wind and PV generation within each region. And a high-penetration scenario (ITx30) with interregional transmission expansion that included several high-voltage direct current lines and 30% combined wind and PV, utilizing the best wind and solar resources in the EI.

By using high performance computing (HPC) and advanced visualization techniques, we show that wind and PV

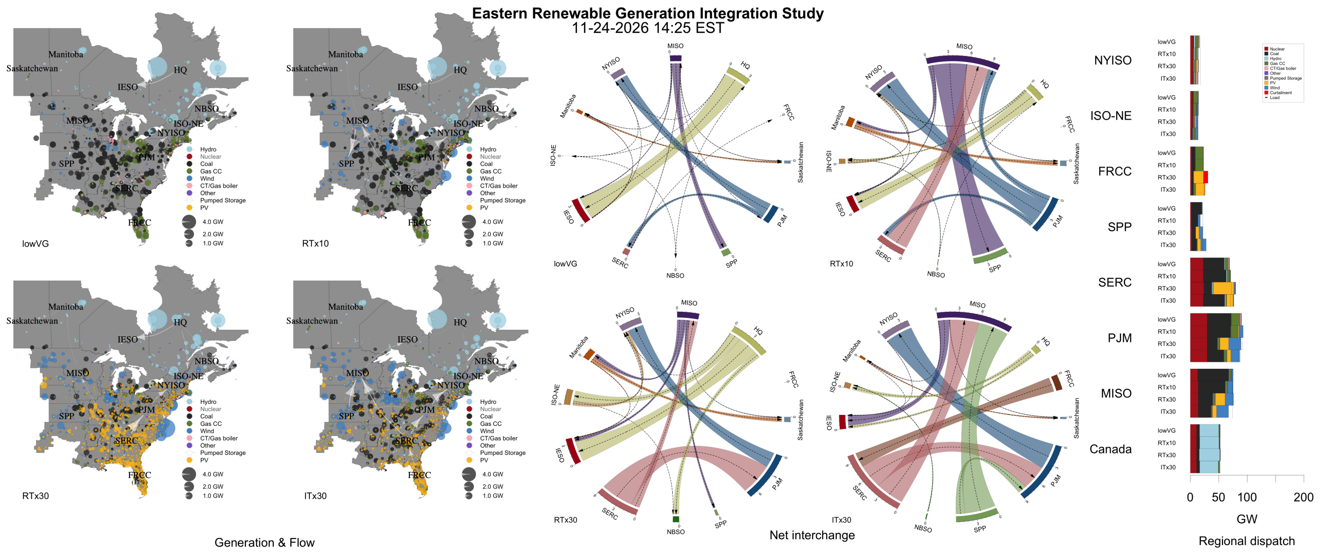

Figure 2. Single frame designed to be viewed on large-scale display wall, showing three coordinated views of four energy future scenarios.

are viable options for significantly reducing carbon dioxide emissions from the electricity sector. We also show that large-scale coordination across the US and Canada may be necessary to enable the most economical transition to a cleaner electricity future. Without HPC and the advanced visualization capabilities developed for this project, it would not have been possible to study the system in this level of detail. Furthermore, the complexity of the power system model and volume of data made the static statistical plotting techniques, traditionally used to visualize transmission studies, inadequate.

2. Modeling & Simulation

The ERGIS study joins a growing list of variable generation integration studies that have examined part or all of the EI. One of the goals of ERGIS was to add enhanced simulation methods to increase confidence in the ability to integrate increased amounts of variable generation onto the electrical transmission system. We compared our assumptions to five previous studies of the EI [3], [5], [6], [7], [8]. In aggregate, the improvements in the ERGIS study represent an increase in temporal, geographic, and technical fidelity. First, ERGIS expands the range of resources analyzed by simulating large-scale adoption of PV in addition to wind in the EI. This increases the number of generators on the system considerably from previous studies, with corresponding increases the complexity of the unit commitment and economic dispatch models. Next, the study narrows the temporal resolution to five minutes to understand the sub-hourly impact of these resources on system operations. This time resolution reflects the dispatch interval of existing regional transmission organizations and independent system operators. ERGIS also increases the spatial resolution of the model to include all synchronous components of the EI, increasing the number of transmission facilities and generators in the model significantly.

The model was executed using PLEXOS, including over 5,600 generating units, 60,000 transmission nodes, and 70,000 transmission lines and transformers. As formulated by PLEXOS, each day-ahead optimization problem has about 73,000 integer variables, 1.2 million continuous variables, and 23 million non-zeros in the constraint matrix. Because of the size of the problem, runtimes would be intractable if the model were run consecutively from January 1 through December 31 of the study year.

To address the extreme computational challenge presented by large unit commitment and economic dispatch models, previous work at NREL developed methods to decompose these types of annual simulations into shorter time partitions while preserving the accuracy of simulation results [2]. The effort resulted in a method for time-domain decomposition and parallel simulation of production cost models. ERGIS used the time domain partitioning method to parallelize unit commitment and economic dispatch simulations using NRELs HPC system, Peregrine [9] into 73 independent simulation horizons. The parallelization provided an approximately 30x speedup, enabling annual simulations that were projected to take in excess of 545 days to be completed in roughly 19 days.

3. Visualization

We used a large-scale display with a combination of multiple coordinated views [10] and small multiples [11] to visually analyze the four large, highly multivariate scenarios. We employed three types of visualization as multiple coordinated views: a geographic diagram, a chord diagram, and dispatch charts. These three views were duplicated for each of the scenarios as a set of small multiples (see Figure 2).

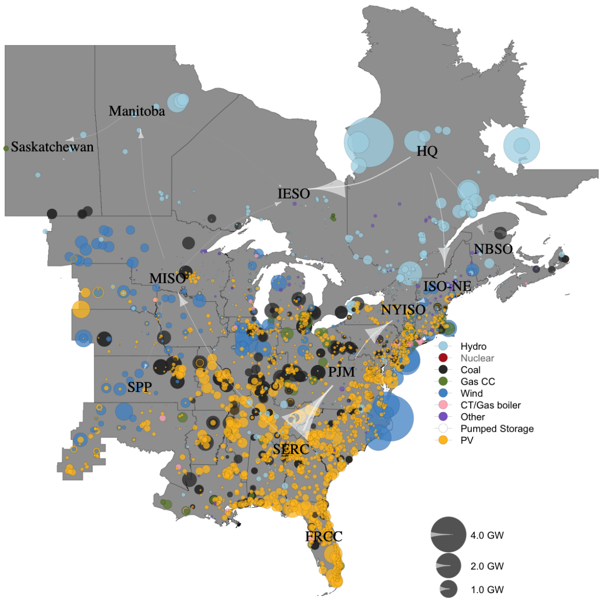

Figure 3. Geographic view provides qualitative view of the generation distribution and net regional interchanges.

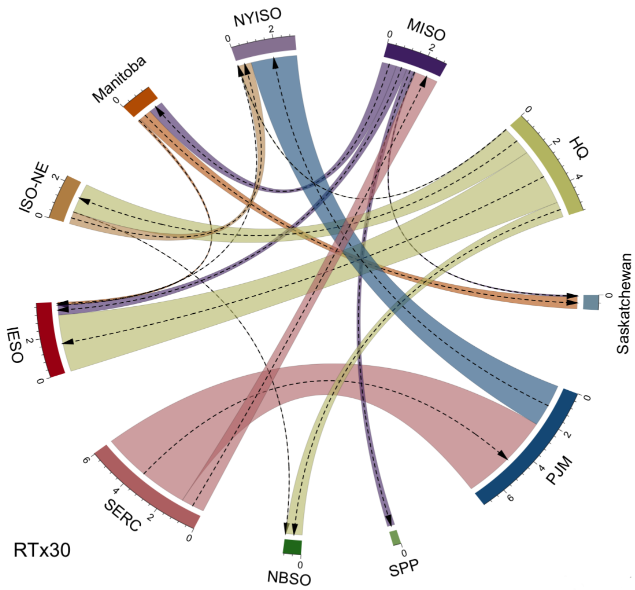

Figure 4. Chord view provides a quantitative visualization of the net interchange between regions, e.g., this image shows 5GW moving from SERC to PJM and 2.5GW moving from PJM to NYISO.

A large-scale power-wall display provided the visual real estate for all twelve views to be visualized simultaneously, allowing analysts to step through time to contemplate the dynamics of the system and the differences between scenarios.

The geographic diagram provides a qualitative view of the study domain representing individual generator output and interregional transmission flows (see Figure 3). The output of every generator is plotted for every five minutes as semi-transparent bubbles centered at the generators actual location with areas proportional to their associated output, and colored by generation type (e.g., coal, natural gas combined cycle, and photovoltaic). This approach was adopted from a visualization created for the Renewable Electricity Futures Study [12]. The generator bubble glyphs were sorted by generation size, drawing smaller generation over larger generation to better illustrate the generation distribution in dense areas. A single frame provides an overall understanding of the geographic distribution of generation, and when animated, the dynamics of that distribution. The dynamics include both the changing output and cycling of the generators. Arrows overlay the generation bubbles, representing regional transmission flows and provide a sense of the direction and magnitude of power flow.

The chord diagrams [13] provide a more quantitative view of the net interchange between each of the regions (see Figure 4). Chord diagrams were designed and are primarily used for comparative genomics [14], but their ability to show directed relationships among groups of objects makes them well suited to show interchange between regions. We represent each region as an arc on the perimeter of a circle; the length of the arc is proportional to that regions total interchange in GW. Directional ribbons are drawn between two regions to represent the direction and magnitude of the interchange. To the extent practicable, regions that share a common border were positioned on opposite sides of the circle to separate the flow ribbons. The colors of the chords match their source. The width of each chord end-point reflects the interchange magnitude; wider chords represent greater interchange. Finally, the aggregate generator output for each region and scenario is displayed as bar charts or grouped stacked bar charts. We developed the visualizations in the R programming language and used the visualizations in multiple ways. We created stills of individual time steps for each scenario, compiling these into desktop movies for analysis and communication. We created high-resolution stills for each time step representing all four scenarios and sized for NREL's 14 MPixel display wall (see Figure 5). Using this display, analysts could step forward and backward in time to compare the generation and flows. Finally, we visualized the individual scenarios as interactive web applications using the R shiny package [15].

4. Discussion

Efficient operation of the power system requires operators to commit and dispatch the system under a variety of challenging conditions. We analyzed the results of the simulations to identify potentially challenging conditions for the EI in the RTx30 and ITx30 scenarios. By visualizing the results as shown in Figure 5, we were able to make cross scenario comparisons that were not previously possible in the literature. For example, the normalization of the chord view to the largest transmission build in the study provided an understanding of the substantial differences in

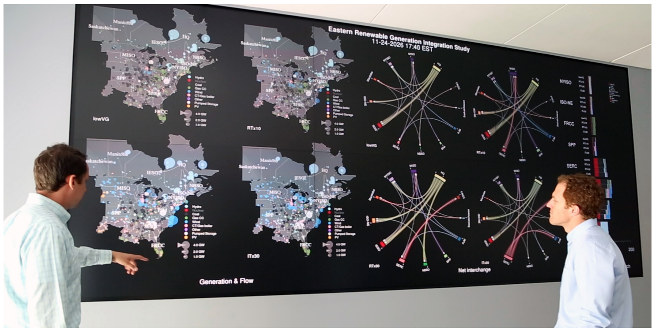

Figure 5. ERGIS Visualization as viewed and analyzed on a large-scale 14 MPixel display wall, showing three coordinated views of four energy future scenarios.

interchange capability across the scenarios. Additionally, statistical analysis of forecast errors and net load ramps identified a period of particularly challenging conditions. Using this visualization, we were able to make comparisons across the scenarios with respect to how the variability and uncertainty are managed across the system, under these challenging conditions. Finally, the geographic view enabled us to understand the breadth of coordination utilized to balance electricity supply and demand at least cost to the system. Previous attempts to visualize net interchange between the regions focused on one region, and its immediate neighbors. Through the use of this set of tools, we were able to understand how generation availability could impact not only regions that shared a common border but could impact operations across many regions, from Florida to Québec.

These additional insights matter for system operators and regulators. ERGIS showed the total EI operating costs decreased by \$30-31 billion and carbon dioxide emissions decreased by 31-33% in the high wind and PV penetration scenarios (RTx30 and ITx30). The visualization described here told the story of how these reductions in costs and emissions were achieved. The visualization increased the credibility of the results and identified pathways forwards for operators and regulators to achieve high penetrations of wind and PV. Using HPC, we were able to analyze the EI at an unprecedented fidelity. This resulted in spatially and temporally complex results which could not be adequately analyzed using traditional visualization techniques. By animating these results and analyzing them on our 14 MPixel display wall we were not only able to see results buried within the data, but we were also able to communicate these results to key audiences [16].

Acknowledgments

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References

[1] A. Bloom, A. Townsend, D. Palchak, J. Novacheck, J. King, C. Barrows, E. Ibanez, M. O'Connell, G. Jordan, B. Roberts, C. Draxl, and K. Gruchalla., "Eastern Renewable Generation Integration Study," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL/TP-6A20-64472, 2016.

[2] C. Barrows, M. Hummon, W. Jones, and E. Hale, "Time Domain Partitioning of Electricity Production Cost Simulations," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. TP-6A20-60969, 2014.

[3] EnerNex Corporation, "Eastern Wind Integration and Transmission Study," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL/SR-5500-47078, 2011.

[4] D. Lew, G. Brinkman, E. I. A. A. Florita, M. Heaney, B. Hodge, M. Hummon, G. Stark, J. King, S. Lefton, N. Kumar, D. Agan, G. Jordan, and S. Venkataraman, "Western Wind and Solar Integration Study Phase 2," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL/TP-5500-55588, 2013.

[5] GE Energy Consulting., "Minnesota Renewable Energy Integration and Transmission Study (Final Report)," Tech. Rep., 2014. [Online]. Available: https://mn.gov/commerce/energy/images/final-mrits-report-2014.pdf

[6] GE Energy Consulting, "PJM Renewable Integration Study Executive Summary Report, Revision 05," Tech. Rep., 2014. [Online]. Available: http://www.pjm.com/~/media/committees-groups/subcommittees/irs/postings/pris-executive-summary.ashx

[7] J. Bakke, Z. Zhou, and S. Mudgal, "Manitoba Hydro Wind Synergy Study: Final Report," MISO, Tech. Rep., 2013.

[8] Eastern Interconnection Planning Collaborative, "Phase 2 Report: Interregional Transmission Development and Analysis for Three Stakeholder Selected Scenarios," Tech. Rep. DOE Award Project DE-OE0000343, 2012. [Online]. Available: http://www.eipconline.com/uploads/20130103_Phase2Report_Part2_Final.pdf

[9] NREL, "NREL High Performance Computing," http://hpc.nrel.gov/users/systems/peregrine, 2015.

[10] M. Q. W. Baldonado, A. Woodruff, and A. Kuchinsky, "Guidelines for using multiple views in information visualization (avi '00)," in *Proceedings of the Working Conference on Advanced Visual Interfaces*. New York, NY, USA: ACM, 2000, pp. 110–119. [Online]. Available: http://doi.acm.org/10.1145/345513.345271

[11] E. R. Tufte, *The Visual Display of Quantitative Information*. Cheshire, CT, USA: Graphics Press, 1986.

[12] M. M. Hand, S. Baldwin, E. DeMeo, J. M. Reilly, T. Mai, D. Arent, G. Porro, M. Meshek, and D. Sandor., "Renewable Electricity Futures Study. Volume 1: Exploration of High-Penetration Renewable Electricity Futures," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL/TP-6A20-52409-1, 2013.

[13] H. Zhang, P. Meltzer, and S. Davis, "Rcircos: an r package for circos 2d track plots," *BMC Bioinformatics*, vol. 14, no. 1, pp. 1–5, 2013. [Online]. Available: http://dx.doi.org/10.1186/1471-2105-14-244

[14] M. I. Krzywinski, J. E. Schein, I. Birol, J. Connors, R. Gascoyne, D. Horsman, S. J. Jones, and M. A. Marra, "Circos: An information aesthetic for comparative genomics," *Genome Research*, 2009.

[15] W. Chang, J. Cheng, J. Allaire, Y. Xie, and J. McPherson, "shiny: Web application framework for r. r package version 0.13.0." http://CRAN.R-project.org/package=shiny, 2016.

[16] NREL, "The eastern renewable generation integration study: Redefining what's possible for renewable energy," http://www.youtube.com/watch?v=jx9_4GNkbIQ, 2016.