GRID
MODERNIZATION INITIATIVE
U.S. Department of Energy

Category 1 (Foundational/Regional) Project Final Report

Report Completion Date:

Section 1: Project Information

Project Information	
Control #: Title:	1.4.26 Development and Deployment of Multi-Scale Production Cost Models
Project Title:	Development and Deployment of Multi-Scale Production Cost Models
Project PI Name and Lab Affiliation: Project Co-PI (plus-one) and Lab Affiliation:	Jessica Lau, NREL Jean-Paul Watson, LLNL (at SNL during project execution)
DOE Project Manager(s):	Jian Fu, Kerry Cheung
Period of Performance:	April 2016 – March 2019
Date Closed:	March 31, 2019 (extension requested December 31, 2019)

Section 2: Project Assessment and Checklist

Project Assessment and Checklist	Y/N	Confirmation Date	Comments
Have all quarterly reports been submitted?	**Y**		
Have all milestones have been delivered?	Y		
Are all products finalized (e.g. technical reports, journal articles)?	N		**SNL's Prescient PCM tool is pending open source release.**
Have all project products been finalized and presented/submitted to DOE Project Manager(s) and/or GMI Leadership?	N		**Per above.**
Have all potential sensitivities been identified and addressed with DOE Project Managers and/or GMI Leadership?	Y		
Has the project team received feedback from Project Stakeholders (e.g. advisory group)?	Y		
Are there any open or pending costs?	N		

Section 3: Outcomes, Deliverables, Publications

Provide the following: **In addition to titles, provide links to any websites or other repositories where deliverables and/or other information will be available after the project has been completed* **Publications available for public release, URLs, etc. listed here should be uploaded to GMLC Open Point*

1. **List of Outcomes:**

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The *Development and Deployment of Multi-Scale Production Cost Models* project developed advanced computational methods to reduce the execution time required to analyze future power system scenarios via production cost models (PCMs), while simultaneously considering higher-fidelity system representations and integrating on common software platforms. The project team consists of NREL, SNL, LLNL, ANL, and PNNL. PCMs are what power system planners use to design and analyze proposed future system configurations, by simulating a range of system scenarios. The project team has significantly advanced the state-of-the-art in PCM simulations, enabling studies that would otherwise be infeasible or impractical due to the system size (e.g., regional and national) and time scales (year-long simulations at 5-minute resolution) involved. These advances have been accomplished by developing advanced computational methods and deploying tools through industry outreach. Numerous peer-reviewed journal articles have been published under the project. Some software components have been released as open source, with others pending, to support broader community engagement and enable further development and deployment.

In the first project year, each lab team developed and validated their specific methodology and quantified execution time reduction or fidelity improvements to better reflect real system operations. Over the final two project years, the team collaborated to integrate the individually developed methods and codes into common software platforms and study systems. Overall, the project developed advanced computational method and applied these methods to analyze large-scale PCM test systems, while simultaneously integrating software onto common platforms and engaging with industry stakeholders.

- Methods: Developed new algorithms, including different decompositions methods, to reduce solve time and increase model accuracy. Developed advanced models of unit commitment, to address a key computational bottleneck in PCM simulations. The developed computational advances benefit both deterministic and stochastic power grid analyses.
- System Representations: Created multiple reference production cost model system representations to enable rigorous testing, and to ensure scalability and applicability of developed methods.
- Software: Validated lab-developed PCM software platform (Prescient and EGRET) with two commercial PCM software products (PLEXOS and PSO). Integrated all computing methods on the common lab software platform, which is important because commercial software products typically do not allow for user to develop new computing algorithms.
- Engagement: Multiple Technical Review Committees (TRCs) held with industry vendors, users, and academia to review and deploy the developed methods, systems, and software. The project team helped MISO (system operator) implement five capabilities developed in this project in their Planning, Day-Ahead Markets, and R&D departments. The open-source (EGRET) release of all methods developed in this project enable others to improve their tools and collaboration.

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2. List of Deliverables:

No.	Milestone Name/Description	End Date
1	Task 1: Deliver the ERGIS database to Energy Exemplar for public hosting and sharing across project team.	August 30, 2016
2	Task 4: Complete literature review on general MIP warm-starting techniques and field knowledge on expediting deterministic sequential UCs.	August 30, 2016
3	Task 5: Identify ERGIS sub-region for stochastic analysis and convert database into use with PRESCIENT stochastic production cost model.	August 30, 2016
4	Task 6: Identify stochastic decomposition scheme to develop/extend, and coordinate with SNL to utilize same stochastic production cost model for LLNL algorithms	August 30, 2016
5	Task 1: Coordinate and host at least 1 TRC meetings with other GMLC projects, i.e. Midwest Regional Partnership, and North American Renewable Generation Integration Study. Meetings should have at least 10 non-lab participants.	October 31, 2016
6	Task 2: Improve functionality of existing NREL temporal decomposition methods through improved software tools for running PLEXOS in Linux	October 31, 2016
7	Task 3: Submit a document for DOE review that quantifies differences in production cost model results under zonal vs. nodal transmission assumptions.	October 31, 2016
8	Task 4: Identify warm-starting techniques that are ready to implement in sequential deterministic UCs; implement and test the performance of the preliminary warm-starting techniques on small-scale test system. 2) Develop and implement a temporal decomposition method based on well-known techniques (e.g., Lagrangian relaxation); collect and analyze the performance of the preliminary results from the method on small-scale test systems.	October 31, 2016
9	Task 5: Integrate relevant WIND and SIND data from NREL into PRESCIENT, and demonstrate ability to generate stochastic renewables production scenarios.	October 31, 2016

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No.	Milestone Name/Description	End Date
10	Task 6: 1) Participate in technical review committee meeting and coordinate stochastic renewable generation scenarios with SNL. 2) Test stochastic decomposition schemes for real-world but smaller scale instances than the ERGIS scenarios.	October 31, 2016
11	Task 2: Enable external access to Peregrine HPC to enable workshop participants to execute test runs using NREL temporal decomposition and data management tools developed by research team by hosting at least 1 deployment workshop.	February 28, 2016
12	Task 4: Document the findings from the initial development and testing of warm-start and temporal decomposition methods in two conference/journal papers.	February 28, 2016
13	Task 6: 1) Participate in advanced PCM workshop, and document initial work in technical reports. 2) Create stochastic PCM models derived from SNL models for LLNL decomposition schemes.	February 28, 2016
14	Task 1: Coordinate and host at least 1 TRC meetings with other GMLC projects, i.e. Midwest Regional Partnership, and North American Renewable Generation Integration Study. Meetings should have at least 10 non-lab participants.	July 31, 2017
15	Task 3: Identify and test at least two approaches to geographic decomposition and present results to the TRC. Increase the accuracy and relevancy of transmission and generation modeling by increasing model resolution while decreasing solve time.	July 31, 2017
16	Task 4: Identify bottlenecks and improve performance of the initial warm-start and temporal decomposition methods studied in FY16; implement the most promising additional algorithms accordingly.	July 31, 2017
17	Task 5: Complete initial comparison of stochastic and deterministic production cost models on identified ERGIS sub-region.	July 31, 2017
18	Task 6: Complete initial experiments on ERGIS derived stochastic PCM models, to guide further enhancements	July 31, 2017

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No.	Milestone Name/Description	End Date
19	Task 1: Coordinate and host at least 1 TRC meetings with other GMLC projects, i.e. Midwest Regional Partnership, and North American Renewable Generation Integration Study. Meetings should have at least 10 non-lab participants.	November 31, 2017
20	Task 2: Discuss workshop activities and simulation outcomes at TRC meeting. Identify and prioritize at least 3 access and software enhancements.	November 31, 2017
21	Task 3: Combine NREL temporal decomposition methods with geographic decomposition methods and present results to the TRC.	November 31, 2017
22	Task 4: Test the improved warm-start and decomposition methods on larger-scale systems; report the performance of the improved methods.	November 31, 2017
23	Task 5: Demonstrate initial scalability of stochastic commitment solvers in PRESCIENT on identified ERGIS sub-region. Within 5x of deterministic production cost model simulation times.	November 31, 2017
24	Task 6: Test enhanced stochastic decomposition schemes on ERGIS models and present at TRC meeting	November 31, 2017
25	Task 1: Coordinate and host at least 1 TRC meetings with other GMLC projects, i.e. Midwest Regional Partnership, and North American Renewable Generation Integration Study. Meetings should have at least 10 non-lab participants.	February 28, 2017
26	Task 2: Improve functionality of existing NREL temporal decomposition and geographic decomposition methods through improved software tools for running PLEXOS in Linux	February 28, 2017
27	Task 3: Test combinations of decomposition techniques from Tasks 3, 4, 5, and 6.	May 31, 2018
28	Task 4: Scale up the computational experiments to real-world systems (e.g. sub-region of ERGIS or WECC); document the first set of large-scale test results, with focus on computational performance.	May 31, 2018

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No.	Milestone Name/Description	End Date
29	Task 5: Integrate warm-starting capability into stochastic solvers in PRESCIENT. Demonstrate at least 20% reduction in run times	May 31, 2018
30	Task 6: Integrate further improvements to stochastic decomposition method, and demonstrate improvement in computational performance	May 31, 2018
31	Task 2: Conduct final deployment workshop to enable participants to execute test runs using (1) geographic decomposition, (2) temporal decomposition, (3) MIP warm-starting, and (4) stochastic optimization.	August 31, 2018
32	Task 4: Complete large-scale real-world experiments; document algorithms, experimental results, computational performance in technical report and other publications; make related algorithms publicly available as open source code.	November 30, 2018
33	Task 5: Conduct analysis of number of scenarios required for stability in stochastic production cost model runs.	November 30, 2018
34	Task 6: Complete ERGIS derived experiments, conduct analysis, document algorithms in technical reports and release as open-source code.	November 30, 2018

3. List of Publications:

A. Staid, J. Watson, R. Wets, and D. Woodruff. "Generating short-term probabilistic wind power scenarios via nonparametric forecast error density estimators." Wind Energy 20, no. 12 (2017): 1911-1925. https://onlinelibrary.wiley.com/doi/abs/10.1002/we.2129

A. Xaiver, F. Qiu, F. Wang, and P. Thimmapuram, "Transmission Constraint Filtering in Large-Scale Security-Constrained Unit Commitment." IEEE Transactions on Power Systems, May 2019. https://ieeexplore.ieee.org/document/8613085

B. Knueven, J. Ostrowski and J. Watson, "Exploiting Identical Generators in Unit Commitment," in IEEE Transactions on Power Systems, vol. 33, no. 4, pp. 4496-4507, July 2018. doi: 10.1109/TPWRS.2017.2783850
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8207780&isnumber=8387923

B. Knueven, J. Ostrowski, and J. Watson. “A Novel Matching Formulation for Startup Costs in Unit Commitment.” Mathematical Programming Computation, Feb 2020 https://link.springer.com/article/10.1007%2Fs12532-020-00176-5

B. Rachunok, D. Woodruff, D. Yang, A. Staid, and J. Watson. “Stochastic Unit Commitment Performance Considering Monte Carlo Wind Power Scenarios.” 2018 PMAPS Conference Proceedings (2018).

C. Barrows, B. McBennett, J. Novacheck, D. Sigler, J. Lau, and A. Bloom. “A Multi-Operator Approach to Production Cost Modeling at Scale.” IEEE Transactions on Power Systems, May 2019. https://ieeexplore.ieee.org/document/8721563/

C. Barrows, A. Bloom, A. Ehlen, J. Ikaheimo, J. Jorgenson, D. Krishnamurthy, J. Lau, B. McBennett, M. O’Connell, E. Preston, A. Staid, G. Stephen, and J. Watson. “The IEEE Reliability Test System: A Proposed 2019 Update.” IEEE Transactions on Power Systems, Jul 2019. https://ieeexplore.ieee.org/document/8753693

D. Woodruff, J. Deride, A. Staid, J. Watson, G. Slevogt, and C. Silva-Monroy. "Constructing probabilistic scenarios for wide-area solar power generation." Solar Energy 160 (2018): 153-167. https://www.sciencedirect.com/science/article/pii/S0038092X17310605

K. Kim, A. Botterud and F. Qiu, "Temporal Decomposition for Improved Unit Commitment in Power System Production Cost Modeling," in IEEE Transactions on Power Systems, vol. 33, no. 5, pp. 5276-5287, Sept. 2018. doi: 10.1109/TPWRS.2018.2816463
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8316946&isnumber=8444484

K. Ryan, S. Ahmed, S. Dey, D. Rajan, A. Musselman, J.P. Watson, “Optimization-Driven Scenario Grouping”, INFORMS Journal on Computing, Mar 2020. https://pubsonline.informs.org/doi/abs/10.1287/ijoc.2019.0924?journalCode=ijoc

4. List of Awards or Recognition:

- Worked with MISO, a key industry stakeholder and TRC member, to implement five different developments from this project. The team implemented geographic decomposition method for PLEXOS and kaleidoscope visualization for the Planning group, made MIP unit commitment formulation improvements for the Day-Ahead

Market group, and disseminated the transmission constraint & warm-start methods for the R&D group. Overall, these efforts accelerated solve time and improved optimality gaps.

- IEEE working group recognition to consider the team's Reliability Test System (RTS-GMLC) as its next update. The current system has been published in IEEE transaction and passing through different working group discussions.

5. **List any ROIs – Software, Intellectual Property, Licensing, Patents, Etc.**
   - EGRET (Software, Open). EGRET is a library of state-of-the-art unit commitment (UC) and economic dispatch (ED) optimization models, written in Python and built on the Pyomo (www.pyomo.org) open source optimization modeling library. EGRET has been released open source under the 3-clause BSD license, and is located here: https://github.com/grid-parity-exchange/Egret
   - Prescient (Software, Intellectual Property). Prescient is a Python-based PCM simulation tool, which initially formed the basis for the technologies in EGRET. Prescient is presently an SNL proprietary code; open source release is pending.
   - Scenario Grouping for Accelerating Stochastic Programming (Software, Intellectual Property). An LLNL-developed algorithm for identifying relevant groups of scenarios to significantly accelerate the solution of stochastic unit commitment problems. Written in generic form to work with the Pyomo open source library. Code is presently LLNL proprietary.

Section 4: Final Costing

Each Lab Financial POC Completes Final Costing of GMLC Projects for their lab. PIs, Lab Leads will need to assist but not required to report financials with this final report.

Section 5: Final Thoughts/Comments

Final Thoughts	Comments
Lessons Learned	• Each lab had clear responsibilities on the project and understood how each contribution would work together. This was key for accomplishing milestones on-time and a harmonious work environment. • Industry engagement is key to developing applied research that can add value. • There were significant opportunities for accelerating PCM simulation run-times and fidelity, as demonstrated by the speedups obtained for each of the developed models and capabilities.

	Further, the improvements were additive, allowing for significant overall reductions in PCM run-times. • Stochastic PCM models – specifically considering uncertainty in unit commitment – are now computationally tractable for modest (regional) scale system studies. This is critical when analyzing future scenarios with very large renewables penetration shares (> 50%).
Opportunities for Improvement	• MISO was a major collaborator for the team in developing and implementing computational methods. Additional industry TRC members would have improved the project impact more broadly. • More licenses and use of other commercial products could broaden the testing of the team's computational methods. • Difficult to transition developed capabilities directly into vendor products, due to closed and non-extensible architectures. A lab-led effort to develop open standards for PCM and related tools would significantly enhance the ability of vendors to prototype and integrate advanced models and solvers, and for industry to assess and provide feedback on those capabilities.
Future Projects: Ideas for future work? Possible next steps and research direction?	• Enable additional scalability in single- and multi-energy sectors and decrease simulation time for energy systems modeling. o Modeling continues to grow to simulate larger systems, longer durations, and more granular variables and time period. While much as been accomplished through this project, other research

	and industry. Simulation time and fidelity level continues to be a limiting logistic to successful grid and energy systems operations and planning.
	• Developing methods and data for resilience application.
	  o Most resilience analysis is using "blue-sky" everyday models to examine extreme events. Workarounds and customization have been used to accomplish each modeling scenario or circumstance to be examined.
	  o Operations and planning tools need risk mitigation strategies and investments that can be proposed from models, like re-dispatch tool in the control room to mitigate a contingency.
	• Enable and increase approachability of high performance computing and cloud architecture for modeling
	  o Industry architecture and standards have been barriers for adoption of HPC and cloud for modeling uses. Research could help address concerns and create new standards that enable secure and reliable modeling systems
	• Conduct educational outreach and training programs in grid modeling
	  o These tools are seen as specialized models and often learnt on-the-job. Enabling more use through academic and recreation channels would ensure future talent.

Other:	