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Final Scientific/Technical Report
Pacific Northwest National Laboratory
Supporting ARPA-E Power Grid Optimization

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Lead Recipient:	Pacific Northwest National Laboratory
Project Team Members	Dr. Stephen Elbert, Dr. Jesse Holzer, Dr. Arun Veeramany, Dr. Chris DeMarco, Dr. Hans Mittelmann, Dr. Thomas Overbye
Project Title:	Supporting ARPA-E Power Grid Optimization
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4. Public Executive Summary

Pacific Northwest National Laboratory (PNNL), Arizona State University (ASU), Georgia Institute of Technology (Georgia Tech), Los Alamos National Laboratory (LANL), National Renewable Energy Laboratory (NREL), Texas A&M University (TAMU), The University of Texas at Austin (UT), and the University of Wisconsin-Madison (UW-M) supported the ARPA-E Grid Optimization (GO) Competition by providing a common problem formulation, data format, datasets, evaluation mechanism, scoring, rules, and results that resulted in the awarding of $9.24 million dollars to teams from academia, industry, and national labs for solving three sets of increasingly difficult non-linear, security-constrained Alternating Current Optimal Powerflow (ACOPF) optimization problems in order to increase the efficiency of the US Electric Grid. It is estimated that a 1% increase in efficiency can save $1 billion. Current industry practices typically use a linear DC model (DC-OPF) to solve the OPF problem within the time constraints of the operation schedule. The GO Competition challenges the best power engineers, mathematicians, and computer scientists to make possible operational decisions based on accurate physical models.

To accomplish this, the GO Competition created a series of Challenges and funded teams to produce the best solver. Challenge 1 was to solve the security constrained ACOPF problem. Challenge 2 extended that by adding adjustable transformer tap ratios, phase shifting transformers, switchable shunts, price-responsive demand, ramp rate constrained generators and loads, and fast-start unit commitment (UC). Furthermore, Challenge 2 was a maximization problem while Challenge 1 was a minimization problem. While Challenge 3 was being developed, the entrants were invited to find better solutions to the Challenge 2 synthetic datasets with no restrictions on time, hardware, or algorithms. The Challenge 2 solutions turned out to be very good. Challenge 3 expanded the Challenge 2 problem further by using multiperiod dynamic markets, including advisory models for extreme weather events, day-ahead markets, and the real-time markets with an extended look-ahead. These problems included active bid-in demand and topology optimization. Together the Challenges used nearly 30 million CPU hours.

Since each team was working on the same problem, using the same data, and running on the same hardware, fair comparisons could be drawn as to the best solver. The datasets were varied enough, however, that the best solver for one dataset was not necessarily the best for another, so cumulative scores were used. The process was managed through the PNNL maintained website https://GOCompetition.energy.gov, where Entrants could find information about the problem, the data, the rules, submit their solver for evaluation, and see the scores of all the competing teams on a Leaderboard. Interest was world-wide but only American teams were eligible for prizes. The Competition has produced 34 journal articles, 118 papers, and has been cited over 500 times in literature, including 12 dissertations (4 from foreign countries: Columbia (2), Germany, and Italy) and 3 from the DOE ExaScale project. Software developed by Pearl Street Technologies for Challenges 1 and 2 is now deployed by Southwest Power Pool (SPP) and Midcontinent Independent Service Operator (MISO). Other teams have received inquiries from venture capitalists. Google DeepMind has thanked the Competition for making the datasets developed for the Competition public. They are using it to train machine learning models. The larger datasets have billions of unknowns to be solved for, but only a small percent matter in the final solution. Knowing what unknowns are important can dramatically speedup the solution.

Running from 9/1/2015 to 6/30/2024, the Competition is the longest running project in ARPA-E history as of the date of this report.

5. Acknowledgements

The GO Competition would not have been possible without the exceptional support of ARPA-E (especially Program Directors Tim Heidel, Kory Hedman, and Richard O'Neill, and (former and present) TechSETAs Ashley Arigoni, David Guarrera, Ray Duthu, and HyungSeon Oh, and T2M Advisor Eric Desrosiers) and the Competition predecessor GRID DATA participants who continued with the Competition, especially the many students and faculty now at UW-Madison (Bernie Lesieutre, Scott Greene), TAMU (Farnaz Safdarian, Adam Birchfield), Georgia Tech (Pascal Van Hentenryck, Wai Keung Terrence Mak), and NREL (Tarek Elgindy, Nongchao Guo, Elaine Hale, Bryan Palmintier). The LANL team, Carleton Coffrin, Robert Parker, and Manuel Garcia, were essential in providing the Benchmark solver that assessed the difficulty of the datasets. Other critical members of the PNNL team included Feng Pan, Olga Kuchar, Shan Osborn, and Andy Piatt. The PNNL Research Computing team, especially Tim Carlson, was invaluable. Finally, a sincere round of appreciation to the corporate sponsors that provided in-kind software that made the evaluations possible: AIMMS, AMPL, GAMS, Gurobi Optimization, IBM (CPLEX), Mosek, Panua Technologies, and Siemens.

6. Accomplishments and Objectives

This award allowed the team, consisting of Pacific Northwest National Laboratory (PNNL), the University of Wisconsin—Madison (UW-M), Arizona State University (ASU), University of Michigan (UM), Texas A&M University (TAMU) and National Rural Electric Cooperative Association (NRECA) to support ARPA-E throughout the four phases of its Power Grid Optimization Competition: design, execution, evaluation, and transition. The name of the project has since changed to Supporting ARPA-E Grid Optimization Competition (Competition). The team at UM moved to Georgia Tech and was later funded separately. NRECA, which did not receive any funds, dropped out when Tim Heidel, the initial ARPA-E Program Director left NRECA after leaving ARPA-E. Los Alamos National Laboratory was funded separately to develop the Benchmark program instead of competing as a FOA winner in Challenge 1. The National Renewable Energy Laboratory, also one of the GRID DATA participants, was funded to provide data for Challenge 3. ARPA-E also funded the University of Texas at Austin to support the Competition.

A number of tasks and milestones were laid out in Attachment 1 of the Work Authorization with Pacific Northwest National Laboratory (PNNL), Revision Number 15, the Statement of Project Objectives and Schedule of Technical Milestones and Deliverables, section B. The actual performance against the stated milestones is summarized here:

Table 1. Key Milestones and Deliverables.

Tasks	Milestones and Deliverables
Task 1-Phase 0-Design and Deploy the competition platform (for Challenge 1)	T1: Phase 0-Design and Deploy the competition platform **Actual Performance:** (10/31/2018) Plans for the GO Competition was formally announced at the ARPA-E Energy Innovation Summit in February 2017 and the website went live 6/15/2017 with information on the problem, data, and how to register and make submissions to the Sandbox. The first registration took place 8/2/2017 and the first submission was on 9/27/2017 by a registered user using Java. On 12/31/2017 there were 4 registered users. On 2/8/2018 motivation information was posted on the website. On 4/3/2018 background information about the Competition was posted.

	On 7/23/2018 ARPA-E announced the Grid Optimization (GO) Competition and followed on 7/24/2018 ARPA-E with a Funding Opportunity announcement (FOA) (DE-FOA-0001952)of up to $5 million for the research and development of algorithms to modernize the electic grid. On 8/15/2018 the Official Rules document was published on 8/28/2018 the initial Problem Formulation document and Scoring document. On 10/31/2018 Secretary of Energy Rick Perry announced ARPA-E's first ever Grid Optimization (GO) Competition along with the FOA winners. Entrant registration began 11/1/2018.
1.1 Design and finalize competition problems and formulations	T1.1: Design and finalize competition problems and formulations **Actual Performance:** (11/1/2018) Slides with a detailed explanation of the Phase 0 problem formulation were posted 4/19/17; updated 6/22/2017. The Problem Formulation document was initially posted 8/28/2018 and updated 11/1/2018, 11/14/2018, 11/30/2018, 3/29/2019 and 4/9/2019.
1.1.1 Collect and integrate feedbacks from RFI to SCOPF problem description and formulation.	M1.1.1 Collect and integrate feedbacks from RFI to SCOPF problem description and formulation. **Actual Performance:** (6/30/2017) E-mail from Guarrera 5/26/2017: "Jesse—Tim and I looked over your Phase 0 modeling section and think it looks great. However, we both think that perhaps it could benefit from some more contextual narrative that connects the equations. We tried to do this (with some limited success) in the modeling section in the RFI. Can you take a crack at putting a similar narrative together (feel free to use or not use as much of the RFI text as you desire)." E-mail from Jesse 6/22/2017 with formulation document.
1.1.2 Implement and test competition problems.	M1.1.2 Implement and test competition problems. Create benchmark algorithms **Actual Performance:** (6/30/2017) Quarterly report for July – September 2016 states: "A complete (solution) example based

Create benchmark algorithms	on the IEEE 14-bus system was created. This example reads the standard (PSS@E) input file, converts the information to GAMS format and creates a GAMS executable that can be placed on GitHub. The submission process is then initiated by a user. During the submission process the evaluation platform downloads the evaluation package from GitHub, and runs the GAMS package which produces output in the format required for evaluation. This output is moved to a folder where it is evaluated and scored with the score going back to the front-end for display to the user and the leader board." Quarterly report for April – June 2017 states: "the solver says it found a feasible point for each case. All solver issues resolved." 4/19/17.
1.1.3 Prepare instructions for the problems	M1.1.3 Prepare instructions for the problems **Actual Performance:** (4/28/2017) Slides with a detailed explanation of the Phase 0 problem formulation were posted 4/19/2017. The evaluation page was updated 4/19/2017 to remove the time and objective function value from the local output specification time and the objective function value from the local output specification.
1.2 Prepare datasets	T1.2 Prepare datasets **Actual Performance:** (10/31/2019) Challenge 1 datasets were posted as follows: Original Dataset 1 (Sandbox) 10/30/2018 updated 3/22/2019 – 5 network models (TAMU 500-bus 422 contingencies, SDET 793-buses with 100 contingencies, TAMU 2000-bus with 3300 contingencies, SDET 2312 buses with 1014 contingencies, and UW-Mad 7977 buses with 2428 contingencies) with 10 scenarios each (100 total scenarios, one set for each Division) Original Dataset 2 (Sandbox) 1/8/2019 updated 3/25/2019 – 4 network models (same as OD1 except no7977-bus case) each with 20 scenarios (except the 2312-bus case that had 10) each (140 total scenarios) Trial Event 1 4/15/2019 – 13 network models; TAMU 500-bus

	349-422 contingencies (40 scenarios); TAMU 500-bus 784-786 contingencies (60 scenarios); SDET (PNNL) 793-bus 86-97 contingencies (50 scenarios); TAMU 2000-bus 3139-3189 contingencies (18 scenarios); TAMU 2000-bus 2594-2618 contingencies (18 scenarios); SDET (PNNL) 2312-bus 942-1014 contingencies (122 scenarios); SDET (PNNL) 2312-bus 1008-1015 contingencies (8 scenarios); UW-M 3288-bus 4563-4650 contingencies (50 scenarios); UW-M 4601-bus 7075-7094 contingencies (100 scenarios); SDET (PNNL) 4918-bus 5058-5085 contingencies (70 scenarios); UW-M 9591-bus 4377 contingencies (30 scenarios); TAMU 10000-bus 9519-9622 contingencies (50 scenarios); 718 scenarios for each Division, 1436 total. Trial Event 2 7/19/2019 – 14 networks of 10 scenarios each; TAMU 500-, 2000-, 10000-, and 30000-bus; SDET (PNNL) 793-, 2312-, 3022-, and 4918-bus; UW-M 2755-, 4020-, 4619-, 8000-, 11612-, and 19402-bus; 140 scenarios for each Division, 280 total. Trial Event 3 9/13/2019 – 6 networks of 5 scenarios each; TAMU 10000-bus, 6603-9004 contingencies, and 30000-bus 10810 contingencies; SDET (PNNL) 4918-bus 5052-5074 contingencies; UW-M 8466-bus, 11157 cont., 8686-bus 11627 cont, 8688-bus 11620-11629 cont., 8733-bus 11864 cont.; 11612-bus 8747 cont., 11615-bus 8653 cont.; 18877-bus 13157 cont., 18889-bus 13167 cont., 19399-bus 13391 cont., 19402-bus 13391 and 13392 cont.; 30 scenarios for each Division, 60 total. Final Event 10/31/2019 – 17 networks of 20 scenarios each; TAMU 500-bus 693-761 cont., 2000-bus 2421-2535 cont., 10000-bus 8893-9677 cont., 30000-bus 10810-219960 cont.; SDET (PNNL) 793-bus 85-100 cont., 2312-bus 782-1035 cont., 3022-bus 1889-1970 cont., 4918-bus 5072-5980 cont.; UW-M 2742-bus 2151-2163 cont., 3970-, 4601-bus 2491-2528 cont., 4020-bus 3003-3033 cont., 4619-bus 3026-3061 cont., 4836-, 4837-bus 3429-4335 cont., 8718-, 8754-, 9591-bus 5001-5003 cont., 10480-bus 8553-8557 cont., 18877-, 18889-, 18916-, 19399-, 19402-bus 13157-13392 cont., and 24464-, 24465-bus 3200-3703 cont.; 340 scenarios for each Division, 680 total.

1.2.1 Coordinate GRID DATA teams to lay out a plan and mechanism for data exchange, data request, and feedback on data validation. Finalize data format for the competition.	M1.2.1 Coordinate GRID DATA teams to lay out a plan and mechanism for data exchange, data request, and feedback on data validation. Finalize data format for the competition. **Actual Performance:** (12/31/2017) GRID DATA Kickoff Meeting, March 30-31, 2016, in Denver. Meeting at the GRID DATA Technical Review January 26-27, 2017, in San Diego. Meeting at the 2017 FERC Software Conference 6/28/2017 in Washington, DC, (Thomas Overbye (TAMU), Chris DeMarco (UW-M), Pascal Van Hentenryck (GaTech), Venkat Krishnan (NREL), Ruishing Diao (PNNL). GRID DATA – GO Competition Integration meeting held 9/22/2017 in Chicago. Data teams represented by Pascal Van Hentenryck, Thomas Overbye, and Chris DeMarco.
1.2.2 Develop a data curation and validate procedure and implement a format conversion method.	M1.2.2 Develop a data curation and validate procedure and implement a format conversion method. **Actual Performance:** (5/31/2018) Data providers upload their datasets in the PSS@E format to PNNL GLOBUS repository where they are validated and moved to appropriate directory for evaluation.
1.2.3 Prepare instructional material and description for datasets	M1.2.3 Prepare instructional material and description for datasets **Actual Performance:** (8/28/2018) The datasets, including formatting information, are described in Appendix A of the Problem Formulation document.
1.3 Evaluation and Scoring	T1.3 Evaluation and Scoring **Actual Performance:** (10/31/2018) The original Challenge 1 Evaluation page was posted 5/23/2018 on the website and the current version is from 11/6/2019. A detailed descripton is in Appendix F of the Problem Formulation. The original Scoring page was posted 7/3/2018, the current version is from 7/26/2019 and the Scoring Docuiment is from 8/28/2018.

1.3.1 Finalize evaluation and scoring methods based on RFI feedback. Update the current implementation of evaluation and scoring procedures.	M1.3.1 Finalize evaluation and scoring methods based on RFI feedback. Update the current implementation of evaluation and scoring procedures. **Actual Performance:** (4/30/2017) Quarterly report for April – June 2017 states: "On the evaluation page, remove time and objective function value from the local output specification, completed 3/20/2017; on the evaluation page, put some language asking competitors to get in contact with our team if they are seeing significant mismatches between their time/objective function values and those given by the evaluation platform, completed 3/20/2017; Expand the language in the evaluation platform environment section to make clear that there is access to only one node, and that nothing else will have access to that node during runtime; ask for feedback—if teams feel there is anything in the platform that can hurt performance, they should let us know, completed 3/23/2017; update scoring section, completed 3/29/2017".
1.3.2 Perform tests on evaluation and validate the evaluation procedure and implementation.	M1.3.2 Perform tests on evaluation and validate the evaluation procedure and implementation. **Actual Performance:** (9/30/2017) A basic evaluation process was developed 9/30/2016. The procedure was validated by the Mountain Bees Team from the University of Utah with a submission on 9/27/2017
1.3.3 Perform tests on scoring procedures and implementation. Perform scoring tuning (adjusting parameters in light of experience) procedures and cross-validate with all team members. Compare different scoring methods.	M1.3.3 Perform tests on scoring procedures and implementation. Perform scoring tuning (adjusting parameters in light of experience) procedures and cross-validate with all team members. Compare different scoring methods. **Actual Performance:** (8/28/2018) Several scoring procedures and implementations were considered 9/30/2016. After much discussion and test two methods were chosen. The first formed a geometric mean of the scenarios belonging to each network model and then the geometric mean of all the network models formed a score for each team. The second method used performance profile scoring. A scoring document was published

	7/26/2018 and updated 8/28/2018
1.4 Maintain and update the computing facility hardware and software	T1.4 Maintain and update the computing facility hardware and software **Actual Performance: (**10/31/2018) The original Evaluation Platform page on the website was posted 1/30/2018 and describes the hardware resources available to Entrants. For Challenge 1 and 2 this was the Constance machine, which was replaced by Deception for Challenge 3. The Available Solvers page describes the various commercial and open source solvers (AMPL, CPLEX, CVX, GAMS, Gurobi, Ipopt, MOSEK, and PARDISO) and the versions available to the Entrants, was originally posted 9/14/2018. There is also a link to the solver benchmarks maintained by Competition collaborator Hans Mittelmann at ASU. The Languages page, originally posted 1/30/2018, contains information on how to access the various compilers and run-time libraries available. Challenge 1 used 8.9 million CPU hours on Constance.
1.4.1 Complete the development of the scripts for automatically executing competition algorithms. Update the hardware and software according to feedback from RFI	M1.4.1 Complete the development of the scripts for automatically executing competition algorithms. Update the hardware and software according to feedback from RFI **Actual Performance:** (10/31/2017) Scripts for automatically executing competition scripts were developed and tested for the GAMS case. This task is now executed by a service account. A resource allocation bug that would periodically shut down the process was identified and resolved. 9/30/2016
1.4.2 Test the computation platform for submission, evaluation, and scoring. Assure backend and frontend linkages.	M1.4.2 Test the computation platform for submission, evaluation, and scoring. Assure backend and frontend linkages. **Actual Performance:** (10/31/2017) The submission procedure was tested by the Mountain Bees Team from the University of Utah with a submission on 9/27/2017. This demonstrated that the backend and frontend linkages worked, and that the platform could successfully evaluate and score the submission

1.4.3 Update and test required software tools and libraries	M1.4.3 Update and test required software tools and libraries **Actual Performance:** (10/31/2017) The continued success of Entrant submissions demonstrates that the required software tools and libraries are in place and functioning.
1.5 Maintain and update the competition website	T1.5 Maintain and update the competition website **Actual Performance:** (6/15/2017) The website GOCompetition.energy.gov was in place (behind firewall) 4/20/2017 and passed an internal review 4/27/17. Phase 0 "went live" 6/15/2017 7:30 pm PDT in the presence of Dave Guerrera and Patrick McGrath from ARPA-E. Information updates since then have been frequent as new information became available. Security related updates happen quarterly.
1.5.1 Update mechanisms for downloading datasets and submitting algorithms and resolve functionality issues	M1.5.1 Update mechanisms for downloading datasets and submitting algorithms and resolve functionality issues **Actual Performance:** (9/30/2017) Two datasets were posted with an updated downloading mechanism 6/2/2017. Methods to submit C/C++ codes and binary executables were documented under languages and deployed 8/7/2017. The recently completed Java submission procedure was tested by the Mountain Bees Team from the University of Utah with a submission on 9/27/2017 using the IEEE 14-bus single scenario dataset. This was the very first external submission to the GO Competition. The submission failed because the code had been developed in a Windows environment using Windows file syntax rather than Java standard syntax and the team attempted to use their own CPLEX libraries. The GO Competition Team was able to manually force the code to run and be evaluated showing they had PV and PQ feasibility violations. The team was informed of the problems and additional guidance was added to the Java section of the web site. On 10/02/2017 the team resubmitted their code and successfully received a score with no time or feasibility violations, although their objective function was not as good as that achieved by the GAMS reference code. This is not surprising since GAMS uses a nonlinear solver (Knitro) and the Mountain Bees

	presumably used a piece-wise linear approach, since CPLEX does not have a nonlinear solver.
1.5.2 Update and enhance the score for web display and for reflecting multiple scoring metrics and scores from multiple datasets	M1.5.2 Update and enhance the score for web display and for reflecting multiple scoring metrics and scores from multiple datasets **Actual Performance:** (11/30/2017) When a submission is made, it is logged on Personal Submission Results section of the Entrants home page, indicating the date and time of the submission. A link to the output of the submission is provided along with summary information, *e.g.*, the name of the GitHub repository, the run status, language used, the network model Division and scenario being evaluated and the score the evaluation produced.
1.5.3 Provide references and tutorials	M1.5.3 Provide references and tutorials **Actual Performance:** (6/14/2017) On any Competition website page is a banner with dropdown menus for Background (links to Inspiration, Timeline, Prizes, About, and Cited By), References (links to Getting Started, Solvers, Languages, Evaluation Platform, GitHub, Docker, How-to Register, How-to Create a Team, How-to Make a Submission, and Rules) and Competitions (Sandbox, Challenge 1, Challenge 2, Challenge 2: Monarch of the Mountain, Challenge 3). Other direct link items on the banner are Home, Support, FAQs, Forum, News and Definitions. The PNNL Administrator has a Approvals link on the banner and ARPA-E personnel have an ARPA-E dropdown link (Approvals, E-mail List, User Information, Team Information, Submission Information, (web) Analytics, Future-Frequency Stability, Future-OPF-SC-CA). These last two only work when an authorized user is logged in to the website. A series of webinars were held before the first Event of Challenge 1. Webinar #1: Challenge 1 Overview and Registration, 2/4/2019 (recording, slides) Webinar #2: Platform Interaction and Entry Submission , 2/21/2019 (recording, slides) Webinar #3: File Formatting and Solution Evaluation, 3/1/2019

	(recording, slides)
1.5.4 Enhance the website, e.g., adding competitor profiles (geographic, organization, educational background), ARPA-E branding, user access to forums, displaying scores, providing mechanism for supporting team participation, and integrate feedbacks from the RFI.	M1.5.4 Enhance the website, e.g., adding competitor profiles (geographic, organization, educational background), ARPA-E branding, user access to forums, displaying scores, providing mechanism for supporting team participation, and integrate feedbacks from the RFI. **Actual Performance:** (12/31/2017) To participate in the Competition everyone must register. Required information includes a Username, E-mail address, Name, Display name, Age Certification (over 18 or not), Citizenship(s), Country, Address, City, State, Zip code (State and Postal code is country dependent) and Organization. Voluntary information includes Time Zone, Phone Number, Mobile Phone Number, Position, and Programming Languages. A Team name is supplied when a Team is joined (all approved participants must belong to a team). The Terms and Conditions of use box must be checked, and the individual must respond to an email with information on setting a password before the registration is complete. The administrator must approve the registration before the password e-mail is sent. To form a team, a participant must click the Create Team on their Account page and the name must be approved by the Administrator. After that, the leader may add others to the team by editing their account page. The leader also needs to fill out a Team Form and have all team members fill out Individual Forms and upload them to the website for approval by ARPA-E. Once approved Team members have access to the submission mechanism. Registration is needed for submissions and to participate in any of the Forums, but is not needed to view any Competition pages or download information and datasets. Administrators have access to a summary User Information page that lists first and last name, account information, organization, e-mail, team, programming languages, date registered, and date of last login. This information may be sorted by last name, organization, e-mail, team, programming language, and access (first or last) and searched by last name, team name, or

	organization name. Similar information is available for Teams, but access is for first and last submission (ID and date/time). Another table lists all submission information. At the end of the Competition there were 17,308 submissions on the list.
1.5.5 Moderate and provide input to the discussion forum	M1.5.5 Moderate and provide input to the discussion forum **Actual Performance:** (12/31/2017) A total of 31 posts were received and responded to. Over 19,000 views on some topics. This has not been a heavily used feature, which is understandable given the small size of the community. E-mail is the main source of questions and the responses are posted as FAQs so all can see.
1.5.6 Fix problems and update website with feedback from users	M1.5.6 Fix problems and update website with feedback from users **Actual Performance:** (12/31/2017) The website GOCompetition.energy.gov was in place (behind firewall) 4/20/2017 and passed an internal review 4/27/17. Email from Guarrera on May 26, 2017, regarding this pre-release website: 1) The main markup text has all changes accepted except Steve's recent changes (which I believe are already on the website) and Myself and Tim's (which are not) excluding the evaluation, rules, scoring and datasets section; 2) No feedback on the dataset section, it looks good; 3) I've combined the rules document that we have been building along with the rules you had currently posted on the website and put in the attached rules document. Please review and if there are no issues, make this the rules section on the website; 4) Separate feedback on the scoring and evaluation sections attached. The Phase 0 website "went live" 6/15/2017 7:30 pm PDT in the presence of Dave Guerrera and Patrick McGrath from ARPA-E. The first registration took place 8/2/2017 and the first submission was on 9/27/2017 by a registered user using Java. On 12/31/2017 there were 4 registered users.

1.6 Assist ARPA-E program office and conduct outreach	T1.6 Assist ARPA-E program office and conduct outreach **Actual Performance:** (6/30/2024) Four successful prize-awarding Challenges were staged: Challenge 1, Challenge 2, Challenge 2: Monarch of the Mountain, and Challenge 3. On February 18, 2020, an Outreach Event was held at the Renaissance New Orleans Arts Warehouse District Hotel to introduce the winners of the GO Competition Challenge 1. The agenda included talks by Lane Genatowski, Director of ARPA-E, Key Industry Speakers, and a Panel discussion with selected entrant teams: LLNL, Lehigh, Georgia Tech and CU-Boulder. Ten teams shared $3.4 million in prizes, but teams that were also FOA winners were required to spend the funds on Challenge 2. After Challenge 2, A virtual Outreach Event was held October 5-6, 2021. After Challenge 3, An Outreach Event (GO Competition Performers and GO Competition Construction) was held October 15, 2023, at the INFORMS Annual Meeting in Phoenix, Arizona. (same as task 2.4)
1.6.1 Support RFI effort and decide stakeholder committee	M1.6.1 Support RFI effort and decide stakeholder committee **Actual Performance:** (10/31/2017) To directly involve the community, a Request for Information (RFI), on the design of the Competition was developed with PNNL help (meeting 4/28/2016, drafts 2/12/2016, 2/16/2016, 8/2/2016, 8/26/2016, and 8/30/2016) and was released October 11, 2016. On November 7, 2016, ARPA-E held a 90-minute webinar to discuss the RFI. Responses closed November 22, 2016. Batch 1 of the responses was sent to PNNL 11/28/2017 and Batch 2 on 12/5/2017. A 3-hour WebEx meeting was held 12/8/2016 to discuss the results. Heidel sent out an issue tracking spreadsheet 12/16/2016. The feedback was further discussed at the GRID DATA Annual Meeting January 26-27, 2017, in San Diego. The GO Competition was formally announced at the ARPA-E Energy Innovation Summit in February 2017. Regular 1-hour meetings with Heidel, McGrath, Desrosiers, and Guarrera were held Thursdays from Febuary 16, 2017, to March 9, 2017. By the on-site Review of March 8, 2017, most of the issues had been resolved.

1.6.2 Promote the competition through attending professional meetings	M1.6.2 Promote the competition through attending professional meetings **Actual Performance:** (12/31/2017) At the 2015 FERC Technical Conference on Increasing Market and Planning Efficiency through Improved Software held at the FERC building in Washington, DC, June 22-24, 2015, Elbert gave a talk on "Using High Performance Computing to Solve Unit Commitment Problem." Elbert and Kuchar had posters at the GRID DATA Kickoff Meeting March 30-31, 2016 in Denver. At the 2016 FERC Technical Conference on Increasing Market and Planning Efficiency through Improved Software was held at the FERC building in Washington, DC, June 27-29, 2016, Heidel, Pan, Elbert, DeMarco, and Mittlemann gave the talk "Optimal Power Flow Competition Design Considerations." Elbert and Kuchar again had posters at the GRID DATA Annual Technical Review Meeting in San Diego, CA, January 26-27, 2017. At the 2017 FERC Technical Conference on Increasing Market and Planning Efficiency through Improved Software held at the FERC building in Washington, DC, June 26-28, 2017, Elbert gave the GRID DATA related talk "DR POWER: a Data Repository for Power system Open models With Evolving Resources."
Task 2-Phase 1-First round of prized competition **2.1 Design and finalize competition problems and formulations**	T2 Task 2-Phase 1-First round of prized competition (Challenge 1) **Actual Performance:** (2/18/2020) Registrations began 11/1/2018 and the final event closed 10/31/2019. Challenge 1 prizes were awarded February 18, 2020, at the Renaissance New Orleans Arts Warehouse District Hotel. Agenda T2.1 Design and finalize competition problems and formulations **Actual Performance:** (4/12/2019) Initial draft of Challenge 1 Problem Formulation was released 8/28/2018 and updated 11/1/2018, 11/14/2018, 11/30/2018, 3/29/2019. The Final version was released 4/12/2019.

2.1.1 Finalize competition problems and formulations for Phase 1 competition. Update the problems as the competition progresses	M2.1.1 Finalize competition problems and formulations for Phase 1 competition. Update the problems as the competition progresses **Actual Performance:** (4/12/2019) Initial draft of Challenge 1 Problem Formulation was released 8/28/2018 and updated 11/1/2018, 11/14/2018, 11/30/2018, and 3/29/2019. Final version was released 4/12/2019.
2.1.2 Prepare instructions for the problems and shorten learning curve by providing supports to contestants on problem explanation and OPF background	M2.1.2 Prepare instructions for the problems and shorten learning curve by providing supports to contestants on problem explanation and OPF background **Actual Performance:** (8/28/2018) The Problem Formulation is an 82-page document with 210 equations with sections on Background, Symbol Reference, Model Formulation, Input Data Format, Data Construction Solution Output, and Solution Evaluation initially released 8/28/2018 and updated regularly until 4/12/2019 to resolve questions and comments from contestants.
2.1.3 Implement and test competition problems. Create benchmark algorithms	M2.1.3 Implement and test competition problems. Create benchmark algorithms **Actual Performance:** (10/30/2018) The Original Data Set 1 (50 scenarios from 5 networks) was released for download 10/30/2018 after a Benchmark run showing feasible solutions.
2.1.4 Prepare competition problems for Phase 2	M2.1.4 Prepare competition problems for Phase 2 (Challenge 2) **Actual Performance:** (7/20/2020) The initial release of the Challenge 2 Problem Formulation was 7/20/2020.

2.2 Prepare datasets	T2.2 Prepare datasets **Actual Performance:** (10/31/2019) The Challenge 1 Dataset page on the website has all the information about the data used in the Sandbox or Events for Challenge 1.
2.2.1 Coordinate with GRID DATA teams on test case designs and schedules and availability.	2.2.1 Coordinate with GRID DATA teams on test case designs and schedules and availability. **Actual Performance:** (10/31/19) Weekly calls with the data providers were held throughout the runup to Challenge 1 and thereafter.
2.2.1 Dataset Delivery **Note: similar Milestones have been merged to simplify performance comment**	**T2.2.1 Dataset Delivery** **Actual Performance:** (10/31/2019) A total of 4,797 synthetic scenarios were developed for Challenge 1 (the milestones called for 4200), but only 1348 were used in the Sandbox or Events. This was sufficient for a fair evaluation. The Final Event closed 10/31/2019.
2.2.1.2 UIUC 500 buses 75 scenarios 200 contingencies data 2.2.1.7 UIUC 500 buses 75 scenarios 200 contingencies data 2.2.1.17 UIUC 500 buses 75 scenarios 200 contingencies data 2.2.1.29 UIUC 500 buses 75 scenarios 200 contingencies data set	M2.2.1.2, M2.2.1.7, M2.2.1.17, M2.2.1.29 **TAMU 500 buses** 300 scenarios 200 contingencies **Actual Performance:** (9/30/2019) 451 validated 500-bus scenarios with at least 200 contingencies: Network_01R-10, 10 scenarios Network_01R-20, 20 scenarios Network_01R-040, 40 scenarios Network_02R-060, 60 scenarios Network_02R-074_t1500_20190601-1, 74 scenarios, 6/1/2019 Network_02R-074_t1500_20190601-2, 74 scenarios, 6/1/2019 Network_02-173-tgo500_20190828, 173 scenarios, 8/28/2019
2.2.1.3 UIUC 2000 buses 75 scenarios 1000 contingencies data set	M2.2.1.3, M2.2.1.8, M2.2.1.18, M2.2.1.30 **TAMU 2000 buses** 300 scenarios 1000 contingencies **Actual Performance:** (9/30/2019) 325 validated 2000-bus scenarios with at least 1000 contingencies: Network_05R-10, 10 scenarios

2.2.1.8 UIUC 2000 buses 75 scenarios 1000 contingencies data set 2.2.1.18 UIUC 2000 buses 75 scenarios 1000 contingencies data set 2.2.1.30 UIUC 2000 buses 75 scenarios 1000 contingencies data set	Network_05R-10, 10 scenarios Network_05R-018, 18 scenarios Network_06R-050, 50 scenarios Network_06R-113_t102k_20190401, 113 scenarios, 4/1/2019 Network_06-124-tgo2000_20190828, 124 scenarios, 8/28/2019
2.2.1.9 UIUC 10000 buses 150 scenarios 3000-8000 contingencies data set 2.2.1.19 UIUC 10000 buses 150 scenarios 3000-8000 contingencies data set 2.2.1.31 UIUC 10000 buses 150 scenarios 3000-8000 contingencies data set	M2.2.1.9, M2.2.1.19, M2.2.1.31 **TAMU 10000 buses** 450 scenarios 8000 contingencies **Actual Performance:** (10/31/2019) 256 validated 10000-bus scenarios with at least 8000 contingencies: Network_13R-050, 50 scenarios Network_13R-088_t110k_20190401, 88 scenarios, 4/1/2019 Network_13R-015_t110k_20190601, 15 scenarios, 6/1/2019 Network_13-103-tgo10K_20191010, 103 scenarios, 10/10/2019
2.2.1.10 UIUC 30000 buses 150 scenarios 5000-10000 contingencies data set 2.2.1.20 UIUC 30000 buses 150 scenarios 5000-10000 contingencies data set 2.2.1.32 UIUC 30000 buses 150 scenarios 5000-10000 contingencies data set	M2.2.1.10, M2.2.1.20, M2.2.1.32 **TAMU 30000 buses** 450 scenarios 5000-10000 contingencies **Actual Performance:** (10/31/2019) 117 validated 30000-bus scenarios with at least 5000 contingencies: Network_30R-044_t130k_20190401, 44 scenarios, 4/1/2019 Network_30R-025_t130k_20190601, 25 scenarios, 6/1/2019 Network_30-048-t130K_20191003, 48 scenarios, 10/3/2019 The milestones called for 1500 scenarios from 4 network sizes from TAMU and only 1149 scenarios were produced. This was considered adequate given the complexity of the networks produced.

2.2.1.1 PNNL 700 buses 75 scenarios 100 contingencies data set 2.2.1.5 PNNL 700 buses 75 scenarios 100 contingencies data set 2.2.1.13 PNNL 700 buses 75 scenarios 100 contingencies data set 2.2.1.25 PNNL 700 buses 75 scenarios 100 contingencies data set	M2.2.1.1, M2.2.1.5, M2.2.1.13, M2.2.1.25 **PNNL 700 buses** 300 scenarios with at least 100 contingenciesl **Actual Performance:** (10/31/2019) 480 validated 793-bus scenarios with at least 100 contingencies: Network_03R-10, 10 scenarios Network_03R-20, 10 scenarios Network_03R-050, 50 scenarios Network_03R-200_S0700_20190625, 200 scenarios, 6/25/2019 Network_03-200_S0700_20190923, 200 scenarios 9/23/2019
2.2.1.6 PNNL 2000 buses 150 scenarios 1000 contingencies data set 2.2.1.14 PNNL 2000 buses 150 scenarios 1000 contingencies data set 2.2.1.26 PNNL 2000 buses 150 scenarios 1000 contingencies data set	M2.2.1.6, M2.2.1.14, M2.2.1.26 **PNNL 2000 buses** 450 scenarios with at least 1000 contingencies **Actual Performance:** (10/31/2019) 1004 validated 2312-bus scenarios with at least 782 contingencies: Network_07R-10, 10 scenarios Network_07R-20, 20 scenarios Network_07R-122, 122 scenarios, 942-1014 cont. Network_70R-008, 8 scenarios, 1008-1015 cont. Network_70R-422_S2000_20190625, 422 scenarios, 6/25/2019 Network_70-422_S2000_20190923, 422 scenarios, 782-1035 cont. 9/23/2019
2.2.1.15 PNNL 3000 buses 150 scenarios 2000 contingencies data set 2.2.1.27 PNNL 3000 buses 150 scenarios 2000 contingencies data set	M2.2.1.15, M2.2.1.27 **PNNL 3000 buses** 300 scenarios with at least 2000 contingencies **Actual Performance:** (10/31/2019) 816 validated 3013- or 3022-bus scenarios with at least 2000 contingencies: Network_08R-070, 70 3013-bus scenarios, 1957-1978 cont. Network_08R-373_S3000_20190625, 373 3022-bus scenarios, 6/25/2019 Network_08-373_S3000_20190923, 373 3022-bus scenarios, 1889-1970 cont., 9/23/2019

2.2.1.16 PNNL 50000 buses 150 scenarios 5000 contingencies data set 1 2.2.1.28 PNNL 5000 buses 150 scenarios 5000 contingencies data set 2	M2.2.1.15, M2.2.1.27 **PNNL 5000 buses** 300 scenarios with at least 5000 contingencies **Actual Performance:** (10/31/2019) 329 validated 4918-bus scenarios with at least 5000 contingencies: Network_09R-070, 70 scenarios, 5058-5085 cont. Network_09R-064_S5000_20190625, 64 scenarios, 5052-5074 cont., 6/25/2019 Network_09-195_S5000_20190923, 195 scenarios, 5072-5980 cont., 9/23/2019 The milestones called for 1350 scenarios over 4 network sizes from PNNL and 2629 were produced.
2.2.1.4 UW 2000 buses 75 scenarios 300 contingencies data set 2.2.1.11 UW 2000 buses 75 scenarios 300 contingencies data set 2.2.1.21 UW 2000 buses 75 scenarios 300 contingencies data set 2.2.1.33 UW 2000 buses 75 scenarios 300 contingencies data set	M2.2.1.4, M2.2.1.11, M2.2.1.21, M2.2.1.33 **UW 2000 buses** 300 scenarios 300 contingencies **Actual Performance:** (9/30/2019) 570 validated 2742- to 4837-bus scenarios with at least 300 contingencies: Network_75-040_UW-ALMS44-2743_20190829, 40 2742-bus scenarios, 2151-2163 cont., 8/29/2019 Network_76R-080_UW-ALMSV2-2755_20190709, 80 2755-bus scenarios Network_81R-050, 50 3288-bus scenarios with 4563-4650 cont. Network_82-040_UW-NEISOV9-3970_20191011, 40 3970-bus Network_83R-130_UW-TNKYL3-4020_20190709_SWREM0, 130 4020-bus scenarios with 3003-3033 cont., 7/9/2019 Network_86R-050_UW-MOLAAR-4619_20190715, 50 4619-bus scenarios, 7/15/2019 scenarios with 2491-2501 cont., 10/11/2019 Network_82-010_UW-NEISOV6-4601_20191011 (2528 contingencies), 10 4601-bus scenarios with 2528 cont., 10/11/19 Network_84R-100, 100 4601-bus scenarios with 7075-7094 cont. Network_86-040_UW-MOLAAR-4619_20191017, 40 4619-bus scenarios with 3026-3061 cont. 10/17/2019 Network_88-030_UW-HVWIILIAMN-4837_20191106, 7 4836-bus scenarios with 3429 cont. 11/6/2019 Network_88-030_UW-HVWIILIAMN-4837_20191106, 23 4837-

	bus scenarios with 4334 or 4335 cont. 11/6/2019
2.2.1.12 UW 9000 buses 150 scenarios 3000-8000 contingencies data set 2.2.1.22 UW 9000 buses 150 scenarios 3000-8000 contingencies data set 2.2.1.34 UW 9000 buses 150 scenarios 3000-8000 contingencies data set	M2.2.1.12, M2.2.1.22, M2.2.1.34 **UW 9000 buses** 450 scenarios with at 3000-8000 contingencies **Actual Performance:** (10/31/2019) 289 validated 7977- to 11615-bus scenarios with at 3000-8000 contingencies: Network_10R-10, 10 7977-bus scenarios Network_11R-056_UW-9kLA2MN-8k_20190728, 56 8466- to 8733-bus scenarios with 11157 to 11864 cont. 7/28/2019 Network_12R-030_UW_WIILIAMN, 30 9591-bus scenarios with 4377 cont. Network_12-050_UW-WIILIAMN-8718-8754-9591_20191105, 103 8718-, 8754-, or 9591-bus scenarios, with 5001 or 5003 cont., 11/5/2019 Network_14-050_UW-105TX2ND4U-10480-20191009, 50 10480-bus scenarios with 8553-8557 cont., 10/9/2019 Network_15R-010_UW-TX2ND-11612_20190715, 10 11612-bus scenarios, 7/15/2019 Network_15R-030_UW-TX2ND-11615_20190725, 30 11615-bus scenarios, 7/25/2019
2.2.1.23 UW 20000 buses 150 scenarios 5000-10000 contingencies data set 2.2.1.35 UW 20000 buses 150 scenarios 5000-10000 contingencies data set	M2.2.1.23, M2.2.1.35 **UW 20000 buses** 300 scenarios with at 5000 to 10000 cont. **Actual Performance:** (10/31/2019) 160 validated 1877- to 24465-bus scenarios with at 5000 to 10000 contingencies: Network_20R-100_UW-LA2MN-19402_20190718, 100 18877-, 18889-, 18916-, 19399-, or 19402-bus scenarios with 13157-13392 cont., 7/18/2019 Network_25-060_UW-LA2ND-24464_20191025, 3 24464-bus scenarios with 3699-3703 cont., 10/25/2019 Network_25-060_UW-LA2ND-24464_20191025, 57 24465-bus scenarios with 3200 cont., 10/25/2019

2.2.1.24 UW 60000 buses 150 scenarios 5000-10000 contingencies data set 2.2.1.36 UW 60000 buses 150 scenarios 5000-10000 contingencies data set	M2.2.1.24, M2.2.1.36 **UW 60000 buses** 300 scenarios with at 5000 to 10000 cont. **Actual Performance:** (10/31/2019) No datasets. This problem turned out to be too complex and time consuming and there were doubts that it could be solved within the allotted time so, with ARPA-E approval, the milstone was dropped. The milestones called for 1350 scenarios from 4 network sizes from UW and only 1019 scenarios were produced, but for a wider range of network sizes. This was considered sufficient given the complexity of the networks produced.
2.2.2 Run benchmark algorithm on each dataset to check feasibility and collect the performance measure (time, objective value, violation) as part of scoring function	M2.2.2 Run benchmark algorithm on each dataset to check feasibility and collect the performance measure (time, objective value, violation) as part of scoring function **Actual Performance:** (8/31/2018) The benchmark was run on all datasets to check feasibility and assess difficulty. The measure of difficulty was used to select which scenarios were used in the Final Event.
2.2.3 Convert datasets to competition format and prepare dataset for downloading	M2.2.3 Convert datasets to competition format and prepare dataset for downloading **Actual Performance:** (8/31/2018) Original Data Set 1 (50 scenarios from 5 networks) released for download 10/30/2018 Original Data Set 2 (70 scenarios from 4 networks) released for download 01/08/2019 Trial Event 1 Divison 1 (39 scenarios, 3 [easy, medium, hard] from 13 networks) released for download 5/21/2019 Trial Event 1 Division 2 (39 scenarios—same as D1) released for download 6/6/2019 Trial Event 2 (140 scenarios from 14 networks for each division)

	released for download 8/20/2019 Trial Event 3 (30 scenarios from 6 networks for each division) released 9/29/2019 Final Event (340 scenarios from 17 networks for each division) released 12/3/2019
2.2.4 Prepare instructional material and description for datasets	M2.2.4 Prepare instructional material and description for datasets **Actual Performance:** (12/31/2019) The Challenge 1 Dataset page on the website has all the information about the data used in the Sandbox or Events for Challenge 1. *The Challenge 1 Input Files and Format description is in Appendix A of the Challenge 1* Problem Formulation, while the Output Files and Format description is in Appendix E. Other information is on the Evaluation, Scoring, and Rules pages.
2.2.5 Engage GRID DATA teams to prepare test cases for Phase 2 (Challenge 2)	M2.2.5 Engage GRID DATA teams to prepare test cases for Phase 2 (Challenge 2) **Actual Performance:** (12/31/2019) Weekly teleconferences with the data providers (including Georgia Tech for Challenge 2) continue.
2.3 Evaluation and Scoring	**T2.3 Evaluation and Scoring** **Actual Performance**: (12/31/2019) The Evaluation page was posted 5/23/2018 on the website and the current version is from 11/6/2019. A detailed descripton of the Evaluation procedure is in Appendix F of the Problem Formulation. The original Scoring page was posted 7/3/2018, the current version is from 7/26/2019 and the Scoring Docuiment is from 8/28/2018.
2.3.1 Evaluating and scoring competition algorithms during the training stage. Provide	M2.3.1 Evaluating and scoring competition algorithms during the training stage. Provide feedback to competitors as appropriate **Actual Performance:** (10/31/2019) A number of FAQs were provided: Question about who judges the Competition; 10/23/2018

feedback to competitors as appropriate	Question abouit multiple solution files; 12/11/2018 The Evaluation information was updated Nov. 1, 16, 26, 26, 27 and 29, 2018 and again 12/7/2018, 1/4/2019, 1/16/2019, 2/20/2019 and finally on 10/15/2019. The Scoring information was updated 7/26/2019. An important change in Code 2 time limits was introduced 6/10/2019 before Trial Event 2.
2.3.2 Assist competitors to become familiar with competition platform, system performance and scoring procedures	M2.3.2 Assist competitors to become familiar with competition platform, system performance and scoring procedures **Actual Performance:** (10/31/2019) A series of webinars was held Webinar 1: Challenge 1 Overview and Registration, 2/4/2019 Webinar 2: Platform Interaction and Entry Submission, 2/21/2019 Webinar 3: File Formatting and Solution Evaluation 3/1/2019 Forum discussions took place 11/24/2018, 12/5/2018, 3/4/2019, 3/8/2019, 3/22/2019, 4/3/2019, 4/10/2019, 4/15/2019, 5/10/2019, and 6/4/2019.
2.3.3 Collect feedbacks from the competitors and update evaluation and scoring as appropriate	M2.3.3 Collect feedbacks from the competitors and update evaluation and scoring as appropriate **Actual Performance:** (10/31/2019) Forum discussions took place 11/24/2018, 12/5/2018, 3/4/2019, 3/8/2019, 3/22/2019, 4/3/2019, 4/10/2019, 4/15/2019, 5/10/2019, and 6/4/2019. No updates were required.
2.3.4 Perform more thorough evaluation and scoring on top ranked algorithms after final submission	M2.3.4 Perform more thorough evaluation and scoring on top ranked algorithms after final submission **Actual Performance:** (3/31/2020) A Breakdown of rankings by network was posted 2/12/2020 and a complete list of all scores. A list of characteristics of the 12 teams that placed in the top 10 of each Final Event Division is on the Challenge 1 page.
2.3.5 Perform scoring tuning (adjusting parameters in light of experience) procedures	M2.3.5 Perform scoring tuning (adjusting parameters in light of experience) procedures and cross-validate with all team members **Actual Performance:** (10/1/2018) An important change in Code 2 time limits was introduced 6/10/2019 before Trial Event 2. For

and cross-validate with all team members	Event 1 there was no time limit for running Code 2, which did the power flow analysis for the contingencies. Althoughthis is not done in industry, as a practical matter a reasonable limit needed to be imposed since some teams were not completing the run in 90 hours. An open source code was made available to teams who did not want to develop their own.
2.3.6 Prepare evaluation and scoring for Phase 2	M2.3.6 Prepare evaluation and scoring for Phase 2 (Challenge 2) **Actual Performance:** (10/31/2021) Division 2 Evaluation information was originally posted 7/8/2020 and updated 7/10, 15, 8/21, 10/23, 30, 11/6, 13, 17, 18, 19, 22, 23, 30, 12/1, 14, 17, 22, 23/2020, 1/22,23, 2/10, 12, 22, 3/3, 8, 4/13, 5/24, and 10/25/2021
2.4 Maintain and update the computing facility hardware and software	T2.4 Maintain and update the computing facility hardware and software **Actual Performance:** (3/31/2020) Reports on the status of the hardware and software are in the quarterly reports. Both were basically stable throughout Challenge 1.
2.4.1 Running the backend platform and provide technical support	M2.4.1 Running the backend platform and provide technical support **Actual Performance:** (3/31/2020) Technical support was provided as needed, and all teams needed some—especially at the beginning. All teams at the Outreach Event 2/18/2020 expressed sincere appreciation for Arun Veramany who provided the technical support. They want to give him a prize for his dogged dedication to solving their runtime problems no matter what the time or day.
2.4.2 Update and test required software tools and libraries	M2.4.2 Update and test required software tools and libraries **Actual Performance:** 10/31/2019) The Solvers page, with the list of solvers and their versions, was updated 11/12, 28/2018, 1/28,29,30, 2/18 20, 3/4, 5, 19, and 10/28/2019. The Languages page, with a list of compilers and run-time libraries, was updated 11/26, 28/2018, 1/8, 25, 28, 2/30, 27, 3/4, 5, 6, 11, 13, 18, 19, 20,

	22, 6/3, 4, 6, 7/17, 8/29/2019.
2.4.3 Provide computing support for participants. Make additional computing resource available as needed	M2.4.3 Provide computing support for participants. Make additional computing resource available as needed **Actual Performance:** (10/31/2019) We thank Tim Carlson and the PNNL Research Computing staff for providing blocks of dedicated time to the Competition and taking the heat from other delayed projects. While doing the Final Event evaluation, the Competition was the largest computer user at PNNL. Challenge 1, using up to half the entire machine a month at a time, used 8.9 million CPU hours on Constance. We offered teams the opportunity to try machines with large (1 Terabyte) memory or GPUs, but none accepted.
2.4.4 Collect feedbacks from the competitors and update the competition platform as appropriate. Solicit additional tools and solver libraries from vendors. Requests by participants get high priority	M2.4.4 Collect feedbacks from the competitors and update the competition platform as appropriate. Solicit additional tools and solver libraries from vendors. Requests by participants get high priority **Actual Performance:** (10/31/2019) All requests for additional tools and solver libraries, such as MOSEK and PARDISO, were satisfied, as well as specific MPI implementations.
2.4.5 Prepare the backend platform for Phase 2	2.4.5 Prepare the backend platform for Phase 2 (Challenge 2) **Actual Performance:** (9/30/2020) There was not change in the backend platform between Challenge 1 and 2. The platform did change for Challenge 3.
2.5 Maintain and update the competition website	**T2.5 Maintain and update the competition website** **Actual Performance:** (6/30/2024) The website has been continuously online and updated since 6/15/2017; over seven years as of the date of this report.

2.5.1 Running the competition website and provide technical support	M2.5.1 Running the competition website and provide technical support **Actual Performance:** (10/31/2018) The website has been continuously online since 6/15/2017 except for brief security updates scheduled for periods of low activity; over seven years as of the date of this report.
2.5.2 Collect feedbacks from the competitors and update the competition website as appropriate	M2.5.2 Collect feedbacks from the competitors and update the competition website as appropriate **Actual Performance:** (10/31/2018) The FAQ page serves this purpose. Entrants can download a set of questions and answers about Challenge 1. Initial release on March 20, 2019; updated on April 3, 2019. This covers FAQs from 2/8/2018 to 10/25/2018.
2.5.3 Moderate and provide input to the discussion forum	M2.5.3 Moderate and provide input to the discussion forum **Actual Performance:** (12/31/2018) A total of 31 posts were received and responded to. Over 19,000 views on some topics.
2.5.4 Manage competition databases including datasets, and user participation and scoring. Perform SEO	M2.5.4 Manage competition databases including datasets, and user participation and scoring. Perform SEO **Actual Performance:** (12/31/2018) Competition datasets are available by Event or Sandbox for each Challenge. User logins are tracked, as are submissions. Event scores are available on the appropriate Leaderboard. Sandbox submission scores are only available to members of the same team and the Administrator. Search Engine Optimization is performed quarterly.
2.5.5 Prepare and update the website for Phase 2	M2.5.5 Prepare and update the website for Phase 2 (Challenge 2) **Actual Performance:** (12/31/2018) The website is updated whenever new information becomes available. There are web pages for all the Challenges.

2.6 Assist ARPA-E program office and conduct outreach	T2.6 Assist ARPA-E program office and conduct outreach **Actual Performance:** (2/18/2020) On February 18, 2020, an Outreach Event was held at the Renaissance New Orleans Arts Warehouse District Hotel to introduce the winners of the GO Competition Challenge 1. The agenda included talks by Lane Genatowski, Director of ARPA-E, Key Industry Speakers, and a Panel discussion with selected entrant teams: LLNL, Lehigh, Georgia Tech and CU-Boulder. Ten teams shared $3.4 million in prizes, but teams that were also FOA winners were required to spend the funds on Challenge 2. After Challenge 2, A virtual Outreach Event was held October 5-6, 2021. After Challenge 3, An Outreach Event (GO Competition Performers and GO Competition Construction) was held October 15, 2023, at the INFORMS Annual Meeting in Phoenix, Arizona.
2.6.1 Organize feedback to stakeholders and ARPA E sponsors	M2.6.1 Organize feedback to stakeholders and ARPA E sponsors **Actual Performance:** (12/31/2018) The Grid Optimization Competition Workshop held at the conclusion of the FERC Technical Conference, 6/28/2018.
2.6.2 Organize paper submission and prepare papers for publication	M2.6.2 Organize paper submission and prepare papers for publication **Actual Performance:** (6/30/2024) See section 8. Project Outputs: A. Journal Articles and B. Papers, in this report.
2.6.4 Engage social media	M2.6.4 Engage social media **Actual Performance:** (12/31/2020) GO Competition Workshop on YouTube (6/28/2018) GO Competition announced on YouTube (10/32/2018) The webinar #1 is available on YouTube (2/04/2019) The webinar #2 is available on YouTube (2/21/2019) The webinar #3 is available on YouTube (3/01/2019) Challenge 2 information is available on Twitter (7/21/2020)

7. Project Activities

7.1 *Phase 0 (Design and Deploy)*

The GO Competition seeks to improve the optimization algorithms that control the operation of the U.S. Electric Grid to reduce the expense of the U.S. energy sector while improving reliability. The 2013 FERC Technical Conference on Increasing Market and Planning Efficiency through Improved Software saw the release of 11 Optimal Power Flow and Formulation Papers by O'Neill *et al.*, and discussions of how much of the $400 billion in energy sector revenues could be saved with improved optimization algorithms. O'Neill's estimate was $10 billion. This idea eventually led to the funding of ARPA-E's GO Competition and its several Challenges, each focused on an aspect of the problem more difficult than the last. The goal is to replace the approximate linear (DC) optimization models currently used with accurate, physically correct non-linear (AC) models that can run as fast, or faster. A set of challenges was deemed the most effective way to stimulate interest and provide a fair comparison of the competing solvers. This requires a clear problem definition, a range of viable problem datasets, a consistent hardware platform, a pre-determined evaluation method to do the scoring, and a set of rules.

A development phase, from 2016 to 2017, took place while the ARPA-E GRID DATA project worked out how to develop synthetic problem datasets for the Optimal Power Flow (OPF) problem while the Competition worked on the design, execution, evaluation, and transition to actual competition. The Beta version of the Competition Website went live on June 15, 2017, at 7:30 PM PDT, the first user registration took place on August 2 followed by the first user submission on September 27.

7.2 *Challenge 1*

Challenge 1, from 2018 to 2019, focused on the basic Security Constrained AC Optimal Power Flow problem (SCOPF). The Challenge utilized sets of unique datasets generated by the ARPA-E GRID DATA program. Each dataset consisted of a collection of power system network models of different sizes with associated operating scenarios (snapshots in time defining instantaneous power demand, renewable generation, generator and line availability, etc.). Some datasets were synthetic, and others were from industry. On July 24, 2018, ARPA-E issued a funding opportunity announcement (FOA, (DE-FOA-0001952) of up to $5 million for teams to participate, since some of the most talented organizations, e.g., U.S. Federally Funded Research and Development Centers, could not compete without funding. The initial Problem Formulation was released August 28, 2018. The final April 9, 2019, version was 82 pages long with 211 equations. Secretary of Energy Rick Perry announced the 18 FOA winners on October 31, 2018.

Containers, such as Docker, were considered to improve the portability of codes, but none that could reliably support a multi-node parallel computing environment, *e.g.*, MPI, could be found.

Challenge 1 required two computational steps. Solver 1 or Code 1 solved the base SCOPF problem under a strict wall clock time limit, as would be the case in industry, and reported the base case operating point as output, which is used to compute the Objective Function value that was used as the scenario score. The feasibility of the solution was provided by the Solver 2 or Code 2, which solves the power flow problem for all contingencies based on the results from Solver 1. This is not normally done in industry, so the time limits were relaxed. In fact, there were no time limits for Trial Event 1. This proved to be a mistake, with some codes running for more than 90 hours, and a time limit of 2 seconds per contingency was imposed for all other events. Entrants were free to use their own Solver 2 or use an open-source version provided by the Competition.

The C1 Original Dataset 1, for Sandbox use, was released October 30, 2018, and updated March 22, 2019. The dataset is composed of Real-Time (Division 1, contains starting information, 10-minute time limit) and Offline (Division 2, no starting information, 45-minute time limit) parts, each with 5 network models (TAMU 500-bus 422 contingencies, SDET 793-buses with 100 contingencies, TAMU 2000-bus with 3300 contingencies, SDET 2312 buses with 1014 contingencies, and UW-Mad 7977 buses with 2428 contingencies) with 10 scenarios each (100 total scenarios). The C1 Original Dataset 2, also for Sandbox use, was released January 8, 2019, and updated March 25, 2019. Like its counterpart, the dataset is also composed of Real-Time and Offline parts, but each with 4 network models with 10 scenarios each (80 total scenarios).

After considerable discussion, it was decided to score Divisions 1 and 2 by taking the geometric mean of each network model for each team and then the geometric mean over all network models; the geometric mean somewhat diminishes the effect of outliers. Divisions 3 and 4 used the same data but ranked the teams using a performance profile method. The results were essentially the same as using an arithmetic mean and ranking by the number of best scores, which was used in subsequent Challenges. The reason for the two scoring methods is that the average score discourages aggressive approaches since any failure on an individual scenario can be devastating to a team's overall score. Ranking by the number of best scores, on the other hand, encourages aggressive approaches. Challenge 1 proceeded with 3 Trial Events followed by a Final (prize) Event.

The non-prize Trial Event 1, closed April 15, 2019, with results from the 22 participating teams announced May 21, 2019, and data (39 scenarios from 13 synthetic network models of 500A-, 500B- 793-, 2000A-, 2000B-, 2312A-, 2312B-, 3013-, 3288-, 4601-, 4918-, 9591-, 10000-buses) released May 21, 2019. This was a subset of the full 718 scenarios used in Trial Event 1. There were no industry datasets in Trial Event 1.

The non-prize Trial Event 2, closed July 19, 2019, with results from the 27 participating teams announced August 15, 2019, and data from two sets, Real-Time and Offline, of 140 scenarios from 14 synthetic network models of 500B-, 793-, 2000B-, 2312B-, 2755-, 3022-, 4020-, 4617/9-, 4918-, 8466-, 10000-, 11612/5-, 19402-, 30000-buses) released August 20, 2019. There were no industry datasets in Trial Event 2.

The non-prize Trial Event 3, closed September 13, 2019, with results from the 25 participating teams announced October 1, 2019, and data (two sets of 30 scenarios from 6 synthetic network models of 4918-, 8688-, 10000-, 11612/5-, 18877/19402-, 30000-buses) released September 27, 2019. There were no industry datasets in Trial Event 3.

The $3.4M prize Final Event 4, closed October 31, 2019, with results from the 26 participating teams announced February 12, 2020, by U.S. Secretary of Energy Dan Brouillette. The synthetic data (20 scenarios from each of 17 synthetic network models (340 total scenarios) of 500B-, 793-, 2000B-, 2312B-, 2742-, 3022-, (3970-, 4601-), 4020-, 4619-, 4836/7-, 4918-, (8718-, 8754-, 9591-), 10000-, 10480-, (18877-, 18889-, 18916-, 19339-, 19402-), 24464/5-, 30000-buses) was released December 3, 2019; some of the network models have varying numbers of buses. There were 3 industry network models, 16422-, 44175-, and 44176-buses, with 4 scenarios each that were not released.

Over 8,000 synthetic scenarios were developed for Challenge 1, as shown in Table 2, and over 2,000 were used in the four Events. The scenarios were chosen to be a mix of easy, medium, and hard problems, as determined by Carleton Coffrin and the Benchmark program.

Table 2. Challenge 1 Scenarios

Challenge 1 Network Model Source	**buses**	**Avail.**	**E1 OD**	**E2**	**E3**	**E4**	**used**	**unused**
TAMU	**totals**	**1149**	**268**	**40**	**10**	**80**	**398**	**751**
Network_01R-10; Network_01R-20	500	30	30				30	0
Network_01R-040	500	40	40				40	0
Network_02R-060	500	60	60				60	0
Network_02R-074_t1500_20190601-1	500	74		4			4	70

Challenge 1 Network Model Source	buses	Avail.	E1 OD	E2	E3	E4	used	unused
Network_02R-074_t1500_20190601-2	500	74		6			6	68
Network_02-173-tgo500_20190828	500	173				20	20	153
Network_05R-10; Network_05R-10	2000	20	20				20	0
Network_05R-018	2000	18	18				18	0
Network_06R-050	2000	50	50				50	0
Network_06R-113_t102k_20190401	2000	113		10			10	103
Network_06-124-tgo2000_20190828	2000	124				20	20	104
Network_13R-015_t110k_20190601	10000	15		2	1		3	12
Network_13R-050	10000	50	50				50	0
Network_13R-088_t110k_20190401	10000	88		8	4		12	76
Network_13-103-tgo10K_20191010	10000	103				20	20	83
Network_30R-025_t130k_20190601	30000	25		5	2		7	18
Network_30R-044_t130k_20190401	30000	44		5	3		8	36
Network_30-048-t130K_20191003	30000	48				20	20	28
SDET (PNNL)	**totals**	**2629**	**380**	**40**	**5**	**80**	**505**	**2124**
Network_03R-10; Network_03R-20	793	30	30					
Network_03R-050	793	50	50				50	0
Network_03R-200_S0700_20190625	793	200		10			10	190
Network_03-200_S0700_20190923	793	200				20	20	180
Network_07R-10; Network_07R-20	2312	30	30					
Network_07R-122	2312	122	122				122	0

Challenge 1 Network Model Source	buses	Avail.	E1 OD	E2	E3	E4	used	unused
Network_70R-008	2312	8	8				8	0
Network_70R-422_S2000_20190625	2312	422		10			10	412
Network_70-422_S2000_20190923	2312	422				20	20	402
Network_08R-070	3013	70	70				70	0
Network_08R-373_S3000_20190625	3022	373		10			10	363
Network_08-373_S3000_20190923	3022	373				20	20	353
Network_09R-070	4918	70	70				70	0
Network_09R-064_S5000_20190625	4918	64		10	5		15	49
Network_09-195_S5000_20190923	4918	195				20	20	175
UW	**totals**	**1019**	**190**	60	15	180	**445**	**574**
Network_75-040_UW-ALMS44-2743_20190829	2742	40				20	20	20
Network_76R-080_UW-ALMSV2-2755_20190709	2755	80		10			10	70
Network_81R-050	3288	50	50				50	0
Network_82-040_UW-NEISOV9-3970_20191011	3970	40				16	16	24
Network_83R-130_UW-TNKYL3-4020_20190709_SWREM0	4020	130		10		20	30	100
Network_82-010_UW-NEISOV6-4601_20191011	4601	10				4	4	6
Network_84R-100	4601	100	100				100	0
Network_86-040_UW-MOLAAR-4619_20191017	4619	40				20	20	20
Network_86R-050_UW-MOLAAR-4619_20190715	4619	50		10			10	40

Challenge 1 Network Model Source	buses	Avail.	E1 OD	E2	E3	E4	used	unused
Network_88-030_UW-HVWIILIAMN-4837_20191106	4836	7				7	7	0
Network_88-030_UW-HVWIILIAMN-4837_20191106	4837	23				13	13	10
Network_10R-10	7977	10	10					
Network_11R-056_UW-9kLA2MN-8k_20190728	8466 8686 8688 8733	56		10	5		15	41
Network_12R-030_UW_WIILIAMN	9591	30	30				30	0
Network_12-050_UW-WIILIAMN-8718-8754-9591_20191105	8718 8754 9591	103				20	20	83
Network_14-050_UW-105TX2ND4U-10480-20191009	10480	50				20	20	30
Network_15R-010_UW-TX2ND-11612_20190715	11,612	10		2	1		3	7
Network_15R-030_UW-TX2ND-11615_20190725	11,615	30		8	4		12	18
Network_20R-100_UW-LA2MN-19402_20190718	18,877 18,889 18,916 19,399 19,402	100		10	5	20	35	65
Network_25-060_UW-LA2ND-24464_20191025	24,464	3				3	3	0
Network_25-060_UW-LA2ND-24464_20191025	24,465	57				17	17	40
OD = Original Dataset, Sandbox	**totals**	**8255**	**838**	**140**	**30**	**340**	**1348**	**3449**

On February 18, 2020, an Outreach Event was held at the Renaissance New Orleans Arts Warehouse District Hotel to introduce the winners of the GO Competition Challenge 1. The agenda included talks by Lane Genatowski, Director of ARPA-E, Key Industry Speakers, and a Panel discussion with selected entrant teams: LLNL, Lehigh, Georgia Tech and CU-Boulder. Ten teams shared $3.4 million in prizes, but teams that were also FOA winners were required to spend the funds on Challenge 2. Challenge 1 used 8.9 million CPU hours**.**

The 12 teams that placed in the top 10 of one of the four Final Events had the following characteristics: 4 submitted C++ code; 4 submitted Python code (2 using Python 2.7.13 and 2 using Python 3.7.2); 3 submitted binary executables (2 using C/C++ and 1 using MATLAB); and 1 submitted Julia 1.2.0 code (this was the ARPA-E benchmark). To manage parallelism, 7 used intelmpi, 3 used openmpi, and 2 were not parallel. For Code 1, half used the maximum 6 nodes and half used just one node (24 CPUS per node). For Code 2, 10 used 6 nodes and 2 used 1 node. For solver libraries, 6 used Ipopt 3.12.13 (2 in combination with Gurobi 8.1.1; 1 in combination with CPLEX 12), 1 used CPLEX 12 without additional solver libraries; 1 used the solvers in AMPL; and 4 did not request any additional solver libraries.

Six teams used MATLAB in Challenge 1, although none finished in the top 10. Evaluating all these teams and all the scenarios in the Final Event became a bottleneck, delaying the production of the final results. The reason appeared to be that the Java thread manager MATLAB uses when parallel processing does not scale. The more tasks it was given the slower it went. We tried to communicate this to MATLAB but they were unresponsive. As a result, MATLAB was not allowed in any subsequent Challenge.

7.3 *Challenge 2*

Challenge 2, from 2020 to 2021, expanded upon the problem posed in Challenge 1 by adding adjustable transformer tap ratios, phase shifting transformers, switchable shunts, price-responsive demand, ramp rate constrained generators and loads, and fast-start unit commitment. Furthermore, Challenge 2 was a maximization problem while Challenge 1 was a minimization problem. Specifically, the economic surplus, defined as the benefit of serving load minus the cost of generation, is being maximized. It was expected that the objective value of a given solution should be positive, representing economic gain, but negative objectives from poor solutions were possible. The two Code feature of Challenge 1 was maintained. Additionally, Divisions 3 and 4 within the competition permitted on/off switching of transmission lines (Divisions 1 and 2 did not). After the initial release of the Problem Formulation on 7/20/2020, ARPA-E Director Lane Genatowski announced Challenge 2 on 9/12/2020. The final May 31, 2021, version was 97 pages long with 299 equations. The Challenge proceeded with 2 non-prize Events and 2 prize Events. Teams receiving Challenge 1 FOA awards and prize money were required to use the prize money to fund their Challenge 2 efforts. The Challenge 2 Sandbox dataset C2S6 (11/22/2020) with 38 scenarios from 12 network models (14-, 594-, 2000-, 2045-, 2380-, 2742-, 4226-, 4230-, 9459-, 9460-, 9462-, and 11152-buses) was released 11/22/2020. Previous versions C2S1

(9/1/2020), C2S2 (9/8/2020, 9/15/2020), CS3 (10/5/2020), CS4 (10/2020), CS5 (11/19/2020), and CS6 (11/20/2020) had errors.

The non-prize Event 1, closed December 4, 2020, with results from the 13 participating teams announced Jan. 8, 2021, and data (63 scenarios from 11 synthetic network models of 500-, 617-, 768-, 2020-, 2055-, 2312-, 5746-, 6469-, 8028-, 14204-, 15810-buses) released Jan. 22, 2021. The next Sandbox dataset C2S7 with 80 scenarios from 16 network models (617-, 793-, 2020-, 2312-, 4102-, 4230-, 5752-, 6473-, 8032-, 9459-, 9460-, 9462-, 12209-, 14212-, 24465-, 31777-buses) was released March 5, 2021.

The non-prize Event 2 closed May 4, 2021, with results from the 14 participating teams and data (54 scenarios from 13 synthetic network models of 617-, 2020-, 3022- 4200-, 4917-, 6100-, 7000-, 8300-, 10000-, 12209-, 17700-, 30000-, 31777-buses) released May 21.

The $600k prize Event 3 closed June 30, 2021, with data (54 scenarios from 11 synthetic network models of 2020-, 3022-, 4200-, 4917-, 6100-, 7000-, 8300-, 10000-, 12209-, 30000-, 31777-buses) released July 17, and results from the 15 participating teams announced Aug. 1; 6 teams won from $30k to $170k. The next Sandbox dataset C2S9 had four 2020-bus scenarios with a unique data feature for phase shifting transformers that is within the problem formulation but was not well-represented in the synthetic examples in the trial events. It was, however, present in some of the industry scenarios planned for the Final event.

The $1.8M prize Final Event (4) closed Aug. 12, 2021, with data (84 scenarios from 16 synthetic network models of 617-, 2020-, 2312-, 3288-, 3970-, 4200-, 4601-, 6100-, 7000-, 8300-, 8718-, 10480-, 12209-, 17700-, 19402-, 31777-buses) released Aug. 13, and results from the 16 participating teams announced 10/4/2021; 7 teams won from $30k to $600k.

Challenge 2 awarded $2.4 million in prizes to 9 teams, from $30k to $730k, while using 12.2 million CPU hours. A virtual Outreach Event was held October 5-6, 2021.

7.4 *Challenge 2: Monarch of the Mountain (Ch2-MoM)*

While Challenge 3 was being developed in 2022, the entrants were invited to see if they could produce better solutions to the 84 synthetic Challenge 2 Final Event (4) datasets with no restrictions on time, hardware, or algorithms. Submissions were opened on January 3, 2022, and the results were updated every Wednesday until 11/1/2022. Two teams were awarded a total of $440,000: $430,000 to GravityX and $10,000 to Gordian Knot. Six teams made a total of 201 submissions. GOT-BSI-OPF had 8 best results but were on the Leaderboard less time than GravityX so they received no prize. Prizes were given for the best improvement over 1% and for the longest time with the best result on the leaderboard (to discourage withholding results until the last moment as GOT-BSI-OPF appeared to do). Improved results were found for all 84 datasets with improvements running from 6.7% to 0.00039%. There were 4 scenarios with improvements >1%, all found by GravityX, and only 3 results in the 1% to 0.9% range, the rest being smaller; evidence shows that the Challenge 2 solutions were generally very good and probably nearly optimal. The Competition used 1.2 million CPU hours during the 11 months Ch2-MoM was active, but the Sandbox was active as well.

7.5 *Challenge 3*

Challenge 3, from 2022 to 2023, expanded the Challenge 2 problem further by using multiperiod dynamic markets, including advisory models for extreme weather events, day-ahead markets, and the real-time markets with an extended look-ahead. These problems included active bid-in demand and topology optimization. A new FOA was released February 16, 2022, along with the Problem Formulation, with a submission deadline of 4/5/2022. The final version was released January 22, 2024, and was 67 pages long with 328 equations.

The initial S0 Sandbox dataset was released 8/23/2022 and Sandbox Submissions were opened 12/7/2022. The 10 FOA winners announced 12/8/2022. Note that 3 of the 13 teams listed in the announcement were not FOA winners, Argonauts, GravityX, and Powersense. Challenge 3 proceeded with 2 non-prize Events and 2 prize Events like Challenge 2. The initial Challenge 3 Sandbox dataset C3S0, with 12 scenarios from 4 network models with 3-, 4-, 37-, and 73-buses was released 12/18/2022. This was followed by the C3S1 dataset with 12 scenarios from 4 network models with 600-, 1576-, 4224-, and 6049-buses on 12/22/2022.

The non-prize Event 1 closed Jan. 27, 2023, with results from the 12 participating teams announced 2/13/2023 and the data (257 scenarios from 8 synthetic network models of 3-, 14-, 37-, 73-, 600-, 1576-, 4200- and 6049-buses) released 2/14/2023. The C3S2 dataset with 6 scenarios from 2 network models with 2000- and 6717-buses was released 3/16/2023.

The non-prize Event 2 closed April 14, 2023, with results from 13 participating teams announced 4/24/2023 and data (148 scenarios from 7 synthetic network models of 73-, 617-, 1576-, 2000-, 4224-, 6049-, and 6717-buses) released 5/10/2023. The C3S3 dataset with 41 scenarios from 6 network models with 14-, 37-, 1576-, 2000-, 8316-, and 23643-buses was released 6/6/2023.

The $600k prize Event 3 closed June 16, 2023, with results from 14 participating teams announced 6/27/2023 and the data (97 scenarios from 8 synthetic network models of 73-, 617-, 1576-, 4224-, 6049-, 6717-, 8316-, and 23643-buses) released 6/29/2023. The C3S4X (switching) dataset with nine 617-bus Division 1 scenarios and four 73-bus Division 2 scenarios constructed to demonstrate the advantages of using line switching was released 8/9/2023 and the C3S4 dataset with 16 scenarios from 6 network models with 73-, 1576-, 2000-, 6049-, 6717-, and 8316-buses was released 8/21/2023.

The $2.4M prize Event 4 closed Sept. 4, 2023, with results from 15 participating teams announced 9/21/2023 and data (591 scenarios from synthetic network models of 73-, 617-, 1576-, 2000-, 4224-, 6049-, and 6717-8316-, and 23643-buses) released 10/02/2023.

Challenge 3 awarded $3.0 million in prizes to 8 teams while using 4.5 million CPU hours on a machine twice as fast as before. An Outreach Event (GO Competition Performers and GO Competition Construction) was held October 15, 2023, at the INFORMS Annual Meeting in Phoenix, Arizona

7.6 *Modifications*

The Work Authorization for the entire project had 15 revisions. The initial $800,000, awarded on 9/1/2015, funded a competition planning proposal, which received a two-month no-cost extension on 12/8/2015, to enable additional refinement, streamlining, and development beyond January 2016. On 3/16/2016 this was further extended to 6/30/2016, to provide additional time to respond to ARPA-E's Request for Information related to the ACOPF Competition and to ensure the continuity of operations associated with supporting the competition. The fourth revision, on 6/17/2016, approved $1,314,561 to enable Phase 0 (design and deploy the competition platform), extending the period of performance to 2/28/2017. This was further extended on 5/5/2017 to 9/30/2017, with no cost to provide additional time to ready the competition platform and extend subcontracts to Arizona State University and the University of Wisconsin-Madison. The sixth revision, 5/15/2017, requested by Program Director Tim Heidel, released Phase 1 (execution) funding of $581,320, to allow continued development of the Competition and extended the performance period through 9/30/2017. On 7/21/2017, PD Patrick McGrath requested an extension of the performance period through 10/31/2017 and funding of $115,001 for continued development.

The eighth revision, 10/6/2017, requested by new PD Kory Hedman, funded the project with another $2,245,749 and extended the period of performance to 1/31/2019, to allow for the integration of grid models being created by selected project teams that were part of the GRID DATA program and to formally launch the Competition. On 11/20/2017, PD Hedman approved revision 9, a schedule of delivery for datasets to be used in the competition and provided by subcontractors University of Wisconsin-Madison and Texas A&M University. PD Hedman approved revision 10 on 11/9/2018, for $1,915,000, extending the performance period to

1/31/2020, to complete Challenge 1. ARPA-E legal approved language regarding licensing of software contributed to the Competition.

Stephen Elbert took over as Principal Investigator from Feng Pan in July 2019 and Richard O'Neill became the Competition Program Director 11/25/2019 for the next 4 years.

On 11/25/2019, PD O'Neill approved an additional $480,000 and extension of the period of performance by 18 months to 4/30/2020 (revision 11), to continue supporting the Competition as Challenge 2 took shape. On 4/9/2020, PD O'Neill approved an additional $2,862,347 and an extension to 10/30/2021 (revision 12), to fully fund Challenge 2.

On 8/23/21, PD O'Neill approved an additional $2,975,142 and an extension by 20 months to 6/30/2023 (revision 13), to initiate Challenge 2: Monarch of the Mountain and Challenge 3. PD O'Neill approved a final $1,273,000 and extension to 12/31/2023 (revision 14), to cover delays in awarding the Challenge 3 FOAs and allow Challenge 3 to complete. PD O'Neill retired 11/30/2023 and there was no further PD guidance. Revision 15, on 12/13/23, approved a 6-month no cost extension to 6/30/2024, to complete the analysis of Challenge 3.

Table 3. Summary of Project ARPA-E Funding

FY	Amount	PNNL	UW-Madison	ASU	TAMU	subcontracts
2015	$ 800,000.00	$ 708,148.23	$ 62,138.77	$ 29,713.00		$ 91,851.77
2016	$ 1,321,016.00	$ 1,122,077.00	$ 119,107.00	$ 79,832.00		$ 198,939.00
2017	$ 696,321.00	$ 639,261.00		$ 57,060.00		$ 57,060.00
2018	$ 2,245,749.00	$ 1,731,312.13	$ 295,049.79	$ 61,008.74	$ 158,378.34	$ 514,436.87
2019	$ 1,915,900.00	$ 1,633,739.60		$ 65,420.74	$ 216,739.66	$ 282,160.40
2020	$ 3,342,347.00	$ 2,381,309.83	$ 412,714.00	$ 138,036.00	$ 410,287.17	$ 961,037.17
2021	$ 2,975,142.00	$ 2,019,606.01	$ 415,649.99	$ 134,436.00	$ 405,450.00	$ 955,535.99
2023	$ 1,273,000.00	$ 907,326.00	$ 188,700.00	$ 44,374.00	$ 132,600.00	$ 365,674.00
Total	$ 14,569,475.00	$ 11,142,779.80	$ 1,493,359.55	$ 609,880.48	$ 1,323,455.17	$ 3,426,695.20

8. Project Outputs

A. Journal Articles

To be listed here, one or more of the authors must be a member of the support team or an Entrant team and cite the GO Competition.

1) Agarwal, Aayushya, Priya L. Donti, J. Zico Kolter, and Larry Pileggi. "Employing adversarial robustness techniques for large-scale stochastic optimal power flow." *Electric Power Systems Research* vol. 212 (2022): 108497. doi: 10.1016/j.epsr.2022.108497

2) Agarwal, Aayushya, Amritanshu Pandey, Naeem Turner Bandele, and Larry Pileggi. "Generalized Smooth Functions for Modeling Steady-State Response of Controls in Transmission and Distribution." *Electric Power Systems Research* 213 (2022): 108657. doi: 10.1016/j.epsr.2022.108657

3) Aravena, Ignacio, Quentin Lété, Anthony Papavasiliou, and Yves Smeers. "Transmission capacity allocation in zonal electricity markets." *Operations Research* vol. 69, no. 4 (2021): 1240-1255. doi: 10.1287/opre.2020.2082

4) Aravena, Ignacio, Daniel K. Molzahn, Shixuan Zhang, Cosmin G. Petra, Frank E. Curtis, Shenyinying Tu, Andreas Wächter, Ermin Wei, Elizabeth Wong, Amin Gholami, Kaizhao Sun, Xu Andy Sun, Stephen T. Elbert, Jesse T. Holzer, Arun Veeramany. "Recent Developments in Security-Constrained AC Optimal Power Flow: Overview of Challenge 1 in the ARPA-E Grid Optimization Competition." *Operations Research* vol. 71, no. 6. Published Online:1 Sep 2023. doi: 10.1287/opre.2022.0315.

5) Baldick, Ross, Steven Low, Richard O'Neill, Daniel Ralph, and Golbon Zakeri. "Preface to Special Issue on Computational Advances in Short-Term Power System Operations." *Operations Research* Vol. 71, no. 6. Published Online: 20 Nov 2023. doi: 10.1287/opre.intro.v71.n6

6) Beck, Yasmine, Daniel Bienstock, Martin Schmidt, and Johannes Thürauf. "On a Computationally Ill-Behaved Bilevel Problem with a Continuous and Nonconvex Lower Level." *Journal of Optimization Theory and Applications* Vol. 198, pp 428-447, (2023). doi: 10.1007/s10957-023-02238-9

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8) Coffrin, Carleton, Bernard Knueven, Jesse Holzer, and Marc Vuffray. "The impacts of convex piecewise linear cost formulations on AC optimal power flow." *Electric Power Systems Research* Vol. 199, October 2021, 107191. doi: 10.1016/j.epsr.2021.107191.

9) Crozier, Constance, Kyri Baker, and Bridget Toomey. "Feasible region-based heuristics for optimal transmission switching." *Sustainable Energy, Grids and Networks* Vol. 30 (2022): 100628. https://doi.org/10.1016/j.segan.2022.100628

10) Curtis, Frank E., Daniel K. Molzahn, Shenyinying Tu, Andreas Wächter, Ermin Wei, and Elizabeth Wong. "A decomposition algorithm with fast identification of critical contingencies for large-scale security-constrained AC-OPF." *Operations Research* Vol. 71 no. 6 (2023). doi: 10.1287/opre.2023.2453

11) Donti, Priya, Aayushya Agarwal, Neeraj Vijay Bedmutha, Larry Pileggi, and J. Zico Kolter. "Adversarially robust learning for security-constrained optimal power flow." *Advances in Neural Information Processing Systems* Vol. 34 (NeurIPS 2021): 28677-28689. https://proceedings.neurips.cc/paper_files/paper/2021/hash/f0f07e680de407b0f12abf15bd520097-Abstract.html

12) Gholami, Amin, Kaizhao Sun, Shixuan Zhang, and Xu Andy Sun. "An Alternating Direction Method of Multipliers-Based Distributed Optimization Method for Solving Security-Constrained Alternating Current Optimal Power Flow." *Operations Research* Vol 71 no. 6 (2023). doi: 10.1287/opre.2023.2486

13) Gong, Lin, Yehong Peng, Chenxu Zhang, and Yong Fu. "Fully Parallel Optimization of Coordinated Electricity and Natural Gas Systems on High-Performance Computing." *IEEE Transactions on Smart Grid* Vol. 14, no. 5 (2023). doi: 10.1109/TSG.2023.3235247

14) Holzer, Jesse T., Yonghong Chen, Zhongyu Wu, Feng Pan and Arun Veeramany, "Fast Simultaneous Feasibility Test for Security Constrained Unit Commitment," in *IEEE Transactions on Power Systems*, vol. 39, no. 1, pp. 1068-1078, Jan. 2024, doi: 10.1109/TPWRS.2023.3265269.

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C. Status Reports

Quarterly reports were regularly uploaded to ePIC.

D. Media Reports

Secretary of Energy Rick Perry announced on October 31, 2018, ARPA-E's first ever Grid Optimization (GO) Competition.

Secretary of Energy Dan Brouillette announces Grid Optimization Competition Challenge 1 Winners, February 18, 2020.

ARPA-E Director Lane Genatowski announces Challenge 2 kickoff, September 12, 2020.

E. Invention Disclosures

None

F. Patent Applications/Issued Patents

None

G. Licensed Technologies

None

H. Networks/Collaborations Fostered

In addition to our collaborators at Arizona State University, Texas A&M University, and the University of Wisconsin – Madison, which were funded under subcontracts to Pacific Northwest National Laboratory, collaborations with Georgia Tech, Los Alamos National Laboratory, and the National Renewable Energy Laboratory, funded separately by ARPA-E, were essential to the success of the Project. Google's DeepMind has expressed gratitude for the datasets the Project has developed, which they are using to train their Grid related Machine Learning efforts.

I. Websites Featuring Project Work Results

https://gocompetition.energy.gov/ Project Website

https://data.openei.org/submissions/5997 ARPA-E Grid Optimization (GO) Competition Challenge 3 Synthetic Input Data and Team Results

J. Other Products (e.g. Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)

Databases

All the datasets *used* in the Competition may be found on the appropriate Dataset page.

Challenge 1: https://gocompetition.energy.gov/challenges/22/datasets

Challenge 2: https://gocompetition.energy.gov/challenges/23/datasets

Challenge 3: https://gocompetition.energy.gov/challenges/600650/datasets.

The Competition datasets are also at https://data.openei.org/ (Search GO Competition)

All the datasets developed by the Competition may be found on the PNNL GLOBUS site /pic/dtn/go; login account required.

Books

Bienstock, Daniel. "Uncertainty-Aware Power Systems Operation." Chapter 15 in *Advanced Data Analytics for Power Systems,* edited by Ali Tajer, Samir M. Perlaza, and H. Vincent. Cambridge University Press (2021). The Author was supported by multiple GO Competition FOA grants as a member of the Artelys team and cites the GO Competition.

Software

Two programs were used to

- verify the syntax and correctness of the JSON format datasets (the "checker") and,
- verify the syntax and correctness of the JSON solution files (the "evaluator").

Code for these two programs resides in two Github repositories:

- the C3DataUtilities, owned by Steve Elbert (PNNL) and
- the GO-3-data-model owned by Elaine Hale (NREL)

Webinar Series

- Webinar 1: Challenge 1 Overview and Registration
- Webinar 2: Platform Interaction and Entry Submission
- Webinar 3: File Formatting and Solution Evaluation

K. Awards, Prizes, and Recognition

Award Ceremonies were held at the conclusion of each Challenge.

Challenge 1, February 18, 2020

Renaissance New Orleans Arts Warehouse District Hotel. Agenda

Table 4. Challenge 1 Awards

Organization	Team	Leader	$k	Div 1	Div 2	Div 3	Div 4

LLNL	gollnlp	Cosmin Petra	400	1	1	1	1
Lehigh University	GO-SNIP	Frank Curtis	400	4	3	2	2
Georgia Tech	GMI-GO	Xu Sun	400	2	7	3	3
individuals	BAT	Andrew Telyatnik	-	8	2	6	5
individual	GravityX	Hassan Hijazi	400	6	6	5	4
University of Colorado - Boulder	Tartan Buffs	Kyri Baker	400	3	5	7	8
Northwestern University	NU_Columbia_Artelys	Richard Waltz	400	5	4	9	9
Pearl Street Technologies	Pearl Street Technologies	Hui Zheng	400	9	9	4	6
Mississippi State University	YongOptimization	Yong Fu	300	10	11	8	7
LANL	ARPA-E Benchmark	Carleton Coffrin	-	7	10	11	11
Global Optimal Technology, Inc.	GOT-TJU-OPF	Gilburt Chiang	200	11	12	10	10
Penn State	PennStateUP	Vinayak Shanbhag	100	17	8	13	12
		Total	**3.4M**				

Challenge 2, October 4, 2021, Virtual Event

Announcement, Agenda

Table 5. Challenge 2 Awards

Organization	Team Name	Leader	$k
Individual	GravityX	Hassan Hijazi	730
Artelys	NU_Columbia_Artelys	Richard Waltz	530
Global Optimal Technologies	GOT-BSI-OPF	Gilburt Chiang	420
Pearl Street Technologies	Pearl Street Technologies	M. Jereminov	340
University of Colorado Boulder	Electric Stampede	Kyri Baker	140
Georgia Tech	GMI-GO	Xu Sun	120
LBNL	Monday Mornings	Miguel Heleno	60
Lehigh University	GO-SNIP	Frank Curtis	30
Virginia Tech	Gordian Knot	Vassilis Kekatos	30
		Total	**2,400**

Ch2-MoM, November 1, 2022, on-line announcement.
Table 6. Challenge 2: Monarch of the Mountains Awards and Submissions

Submitting Team	Total Submissions	Best Result	Longest	>1%	Prizes
GravityX	148	74	82	4	$430,000
Gordian Knot	18	2	2		$10,000

GOT-BSI-OPF	22	8			
Monday Mornings	36				
CasePower	12				
Artelys_Columbia	1				
Total	**201**	**84**	**84**	**4**	**$440,000**

Challenge 3, October 15, 2023

INFORMS annual meeting 2023, Phoenix Convention Center, Agenda

Table 7. Challenge 3 Awards

Organization	**Team**	**Leader**	**$k**
Mississippi State University	YongOptimization	Yong Fu	645
MIT	TIM-GO	Xu Sun	595
Global Optimal Technology, Inc.	GOT-BSI-OPF	Hsiao-Dong Chiang	485
Artelys	Artelys_Columbia	Richard Waltz	390
Individual	GravityX	Hassan Hijazi	440
University of Tennessee: Knoxville	The Blackouts	James Ostrowski	200
Individual	Occams razor	Wenyuan Tang	130
University of Texas - Austin	Electric-Stampede	Javad Mohammadi	115
		Total	**3.0M**

9. Follow-On Funding

No additional funding was committed or received from other sources (e.g. private investors, government agencies, nonprofits) for the support of the Project after the effective date of ARPA-E Award, except from ARPA-E as noted Table 3. However, each of the prize winners in each Competition received additional funds from ARPA-E and some negotiated their own contracts with various Independent Service Operators (ISOs) and investors. In particular, Pearl Street Technologies, a competitor in Challenges 1 and 2, has marketed the software developed for the Project to Midwest Independent Service Operator (MISO) and Southwest Power Pool (SPP). A query from a venture capital firm, after the Challenge 2 results were announced, was directed to GravityX leader Hassan Hijazi.