U.S. Department of Energy
Advanced Research Projects Agency – Energy

Request for Information (RFI)
DE-FOA-0001683
On
Grid Optimization Competition Design

A. OBJECTIVE

ARPA-E seeks input on the design of a competition (carried out in multiple phases) to accelerate the development and comprehensive evaluation of new solution methods for grid optimization. Specifically, ARPA-E seeks to provide a platform for the identification of transformational and disruptive methods for solving power system optimization problems including Security Constrained Optimal Power Flow (OPF) and Security Constrained Unit Commitment (UC). Algorithms that perform well in the proposed competition will enable increased grid flexibility, reliability and safety, while also significantly increasing economic and energy security, energy efficiency and substantially reducing the costs of integrating variable renewable generation technologies into the electric power system in the United States.

With this RFI, ARPA-E is soliciting opinions regarding various details of the competition design—including the baseline problem specifications, competition rules, eligibility for participation, scoring metrics, criteria for winning, prize structure and online competition computational platform design details. ARPA-E is anticipating total prize money in this competition of $3,500,000, subject to the availability of appropriated funds. Designing a competition that identifies and validates the most promising new grid optimization solution methods in a fair and transparent manner is critically important.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below, and note in particular: the information you provide will be used by ARPA-E solely for competition and program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA) OR INITIATION OF A COMPETITION. NO FOA OR COMPETITION EXISTS AT THIS TIME. Respondents shall not include any information in their response to this RFI that might be considered proprietary or confidential.**

B. PURPOSE AND NEED FOR INFORMATION

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of a future competition related to grid optimization algorithm development.[1] ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI on a non-

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[1] The America COMPETES Reauthorization Act of 2010, Public Law 111–358, enacted January 4, 2011, authorizes Federal agencies to issue competitions to stimulate innovations in technology, education, and science.

attribution basis. This RFI provides the broad research community and industry stakeholders with an opportunity to contribute views and opinions regarding the design of multiple phases of a grid optimization algorithm focused competition. Based on the input provided in response to this RFI and other considerations, ARPA-E may decide to launch a substantial prize competition and/or decide to release a separate "Proposal Track" FOA related to this competition (to support algorithm development). If a separate FOA is published related to the competition, it will be issued under a new FOA number. No FOA or competition exists at this time. ARPA-E reserves the right to not issue a FOA in this area and not initiate a prize competition in this area.

C. REQUEST FOR INFORMATION GUIDELINES

ARPA-E is not accepting applications for financial assistance or financial incentives, or competition entries under this RFI. Responses to this RFI will not be viewed as any commitment by the respondent to develop ideas discussed or enter any future competition. ARPA-E may decide at a later date to issue a FOA or initiate a prize competition based on consideration of the input received from this RFI. No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E reserves the right to contact a respondent to request clarification or other information relevant to this RFI. All responses provided will be taken into consideration, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that might be considered proprietary or confidential.**

Responses to this RFI should be submitted in PDF or Word format to the email address ARPA-E-RFI@hq.doe.gov by **5:00 PM Eastern Time on November 22, 2016**. ARPA-E will not review or consider comments submitted by other means. Emails should conform to the following guidelines:

- Please insert "Responses for Grid Optimization Competition RFI" in the subject line of your email, and include your name, title, organization, type of organization (e.g. .. university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise in the body of your email.
- Responses to this RFI are limited to no more than 50 pages in length (12 point font size). Though, shorter, concise responses are encouraged.
- Responders are strongly encouraged to include preliminary results, data, and figures that support their perspectives but shall not include any information that might be considered proprietary or confidential.
- Responses to this RFI may be shared with organizations supporting ARPA-E's efforts in designing the competition including national laboratory partners and academic subcontractors.[2]

[2] ARPA-E would like to thank Dr. Feng Pan and Dr. Stephen Elbert at Pacific Northwest National Laboratory, Prof. Christopher DeMarco at the University of Wisconsin-Madison, and Prof. Hans Mittelmann at Arizona State University for their important contributions to this RFI and the proposed competition design.

D. BACKGROUND

Reliable operation of electric power systems requires the real-time matching of instantaneous electricity generation and demand. Achieving a continuous match between supply and demand requires utilities, grid operators, and other stakeholders to use a variety of sophisticated optimization algorithms operating across a wide range of timescales. A number of emerging trends, including the integration of high penetrations of renewable electricity generation, changing electricity demand patterns, and the improving cost effectiveness of distributed energy resources (including storage), will substantially alter the operation and control of electric grids over the next several decades. This expected growth in system complexity will require the development of substantially improved software optimization and control tools to assist grid operators, and deliver the societal benefits of improved grid performance.

Many new grid optimization methods have been proposed in the research community in recent years.[3,4,5,6] In addition, many claims have been made regarding the possible practical benefits that these new algorithms might offer utilities and grid system operators. Today, it is extremely difficult to compare strengths and weaknesses of different proposed approaches. The vast majority of reports only test new algorithms on relatively small-scale models that often must be heavily modified to satisfy the modeling requirements for each algorithm. Computational experiments are also typically conducted on a wide range of computational systems (ranging from commodity laptops to large-scale clusters with many thousands of nodes). Variations in modeling assumptions further complicate the comparability of algorithm testing results (for example, what types of contingency constraints are included and/or how normal vs. emergency ratings are considered). Even small changes in how specific constraints are modeled or which constraints are considered can have significant implications for algorithm performance and solution quality. A new paradigm for the testing and evaluation of emerging grid optimization algorithms is needed to accelerate the adoption of these transformational techniques by industry.

This competition seeks to lay the foundation for that change. In particular, ARPA-E is considering filling this gap through the establishment of a prize competition, executed in multiple phases, using a common computational platform for the fair and consistent evaluation of new algorithms. The existence of this platform will accelerate the use and widespread adoption of new power system optimization and control approaches. As currently envisioned, success will require competitors to demonstrate the applicability and strength of new algorithms across a wide range of system operating conditions.

Initially, the competition is expected to focus on the central optimization challenge underlying a wide range of grid planning and operations tools: the security constrained Optimal Power Flow (OPF) problem. Simply stated, the OPF problem is that of finding the optimal dispatch settings

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[3] S. Frank, I. Steponavice, and S. Rebennack, "Optimal power flow: a bibliographic survey I," Energy Systems, vol. 3, no. 3, pp. 221-258, April 2012, doi: 10.1007/s12667-012-0056-y

[4] S. Frank, I. Steponavice, and S. Rebennack, "Optimal power flow: a bibliographic survey II," Energy Systems, vol. 3, no. 3, pp. 259-289, April 2012, doi: 10.1007/s12667-012-0057-x

[5] F. Capitanescu, J.L Martinez Ramos, P. Panciatici, D. Kirschen, A. Marano Marcolini, L. Platbrood, and L. Wehenkel, "State-of-the-art, challenges, and future trends in security constrained optimal power flow," Electric Power Systems Research, vol. 81, no. 8, pp. 1731-1741, August 2011, doi: 10.1016/j.epsr.2011.04.003

[6] F. Capitanescu, "Critical review of recent advances and further developments needed in AC optimal power flow," Electric Power Systems Research, vol. 136, pp. 57-68, July 2016, doi: 10.1016/j.epsr.2016.02.008

for power generation, flexible customer demand, energy storage, and grid control equipment that maximize one or more grid objectives.[7,8,9] In order to be deployable, the recommended settings must satisfy all physical constraints of electric power infrastructure and applicable operating standards (including, for example, minimum/maximum voltages at each bus, minimum/maximum power generation from all generators, thermal transmission constraints, and constraints related to the security of the system when contingencies occur). For a more complete history and formal problem formulation, we refer the reader to a history authored by the Federal Energy Regulatory Commission (FERC).[10]

The core OPF solution methods predominantly used in industry today were designed in an era when computers were far less capable and more costly than they are currently and formal general purpose optimization solvers were in their infancy. Grid operators, power system software vendors, and the research community were required to make a range of simplifying assumptions, most commonly a set of linearizing assumptions which ignore voltage and reactive power optimization, referred to as "DC-OPF."[11] Many proprietary variations on these algorithms have been developed over the past several decades by industry vendors. Despite improvements in DC-OPF formulations and solvers, there are no tools currently in widespread use in industry that use the full AC power flow equations (without linearizing assumptions) and simultaneously co-optimize both real and reactive power generation (known as "AC-OPF").

The OPF tools in use today often result in conservative solutions that additionally must be iteratively checked for physical feasibility before implementation. The development and demonstration at scale of OPF solution methods providing physically feasible solutions and capable of optimizing both real and reactive power generation and demand within the time limits required for practical application remains an open, unsolved problem. Achieving these capabilities are expected to become increasingly critical in the future as electricity systems evolve, especially as OPF becomes increasingly important in the context of electric distribution systems.

Improved OPF algorithms could yield significant benefits. For example, recent studies have suggested that enhanced OPF algorithms could offer as much as 5–10% reductions in total U.S. electricity cost due to the alleviation of grid congestion (corresponding to $6–$19B saved depending on energy prices).[12] In addition, the full realization of the potential benefits of

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[7] J. Carpentier, "Contribution to the economic dispatch problem," Bulletin de la Société Française des Électriciens, ser. 8, vol. 3, pp. 431- 447, 1962

[8] H.W. Dommel and W.F. Tinney, "Optimal power flow solutions," IEEE Transactions on Power Apparatus and Systems, vol. 87, no. 10, pp. 1866-1876, October 1968

[9] There are a variety of specific applications for OPF. The specific objective function and most important constraints can vary widely. In many applications, where demand is considered fixed, the objective is considered to be minimization of total generation cost. In the context of electric distribution systems, this problem has historically often focused on minimization of system losses.

[10] M. B. Cain, R. P. O'Neill, and A. Castillo, "History of optimal power flow and formulations," Federal Energy Regulatory Commission, Washington, DC, August 2013, http://www.ferc.gov/industries/electric/indus-act/market-planning/opf-papers/acopf-1-history-formulation-testing.pdf

[11] A. J. Wood, B. F. Wollenberg, and G. Sheblé, *Power generation, operation, and control*, 3rd ed. Hoboken, NJ: John Wiley & Sons, 2013

[12] M. Ilic, "Modeling of hardware and systems related transmission limits: the use of AC OPF for relaxing transmission limits to enhance reliability and efficiency," Presentation at FERC Staff Technical Conference on

renewable generation as well as recently developed electric transmission power-flow controllers, distribution automation technologies, distributed generation, energy storage, and demand-side control will require more complex grid operation optimization and dispatch algorithms. Further, as the number of controllable resources connected to electric power systems (at both transmission and distribution voltages) grows substantially, distributed or decentralized versions of OPF algorithms could become increasingly important. The importance of new "AC-OPF" methods was also recently recognized by the National Academies.[13]

There are reasons to believe that recent advances could enable significantly improved OPF software. Dramatic improvements in computational power and advancements in optimization solvers in recent years have prompted research on new approaches to grid operation and new approaches to solving OPF and other grid optimization problems.[14] Since the turn of the millennium, the performance of the most powerful supercomputers has increased by almost four orders of magnitude (while the cost per computational step has dropped by approximately the same factor).[15,16] Improvements in optimization and search methods have evolved similarly, especially those related to Mixed Integer Programming (MIP) and heuristic-based optimization methods. The relative speed of commercial general-purpose solvers such as CPLEX and GUROBI has also increased by over three orders of magnitude on fixed hardware.[17,18] Cloud computing which can be used to leverage many of these gains, has also started to gain more widespread interest within the power system engineering community.[19]

In tandem, many new approaches to solving OPF problems have been proposed in the literature in recent years; it appears increasingly likely that scalable and more accurate approaches to solving the OPF problem may be within reach. For example, fast and accurate convex relaxations have been formulated where the global minimum can be found efficiently using semi-definite and second order cone programming.[20,21,22,23] Often it can be shown that these relaxations give

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Increasing Real-Time and Day-Ahead Market Efficiency through Improved Software, Washington, DC, June 2013, http://www.ferc.gov/CalendarFiles/20140411131533-T2-B%20-%20Ilic.pdf

[13] National Academies of Sciences, Engineering, and Medicine. Analytic Research Foundations for the Next-Generation Electric Grid. Washington, DC: The National Academies Press, 2016. doi:10.17226/21919.

[14] P. Panciatici et al., "Advanced optimization methods for power systems." *Proceedings of the 18th Power System Computation Conference*, Wroclaw, Poland, August 2014, pp. 1-18, doi: 10.1109/PSCC.2014.7038504

[15] http://www.top500.org/

[16] https://intelligence.org/2014/05/12/exponential-and-non-exponential/

[17] http://www.gurobi.com

[18] T. Koch et al., "MIPLIB 2010," *Mathematical Programming Computation*, vol. 3, no. 2, pp. 103-163, June 2011, doi: 10.1007/s12532-011-0025-9

[19] J. Goldis et al., "Use of Cloud Computing in Power Market Simulations" Presentation at FERC Staff Technical Conference on Increasing Real-Time and Day-Ahead Market Efficiency through Improved Software, Washington, DC, June 2014

[20] S. Low, "Convex relaxation of optimal power flow, Part I: Formulations and equivalence," *IEEE Transactions on Control of Network Systems*, vol. 1, no. 1, pp. 15-27, March 2014, doi: 10.1109/TCNS.2014.2309732

[21] S. Low, "Convex relaxation of optimal power flow, Part II: Exactness," *IEEE Transactions on Control of Network Systems*, vol. 1, no. 2, pp. 177-189, May 2014, doi: 10.1109/TCNS.2014.2323634

[22] R. Madani, S. Sojoudi, and J. Lavaei, "Convex relaxation for optimal power flow problem: Mesh networks," *IEEE Transactions on Power Systems*, vol. 30, no. 1, pp. 199-211, May 2014, doi: 10.1109/TPWRS.2014.2322051

[23] D. Molzahn et al., "Implementation of a large-scale optimal power flow solver based on semidefinite programming," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 3987-3998, April 2013, doi: 10.1109/TPWRS.2013.2258044

global solutions to the original, non-convex problem.[24,25] Distributed and parallelizable OPF algorithms have also been proposed, for example, using the Alternating Direction Method of Multipliers (ADMM), suggesting that OPF solution algorithms can be designed that leverage more advanced computational hardware.[26,27,28] These same algorithms could enable the real-time coordination and/or optimization of large numbers of distributed energy resources. Finally, many unique methodologies using techniques such as genetic algorithms, neural networks, fuzzy algorithms and holomorphic embedding have also emerged, claiming, in many cases, to revolutionize solution methods for OPF. [29,30]

Looking beyond OPF, the Unit Commitment (UC) problem is also critically important and relies, in part, on an OPF solver.[31] The UC problem focuses on making multi-period (typically 24-72 hour ahead) generation commitment decisions such as generator start-up and shutdown while also respecting generation ramp and other intertemporal constraints. Similar to OPF, Unit Commitment has also been the subject of intense research over the past decade and many new solution methods have been proposed, particularly focusing on solving the problem in the context of higher uncertainty due to growth in renewable generation.[32,33] Traditionally, the UC problem has been viewed as a more difficult problem to solve since it involves binary decisions. Though, as more equipment with discrete controls are taken into account by OPF algorithms, the differentiation between those two problems is becoming less distinct. ARPA-E envisions that a UC algorithm competition would naturally follow and extend an OPF competition.

Despite numerous recent research projects and papers on improved OPF and UC solution strategies, most new advances have struggled to mature past the early-research stage. Few mechanisms currently exist to allow for the direct comparison of different solution methods; most recent advances remain non-validated on realistic, large-scale test models. It is difficult to know the precise relative strengths, weaknesses and operational limits of different algorithms.

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[24] J. Lavaei and S. Low, "Zero duality gap in optimal power flow problem," *IEEE Transactions on Power Systems*, vol. 27, no. 1, pp. 92-107, August 2011, doi: 10.1109/TPWRS.2011.2160974
[25] L. Gan et al., "Exact convex relaxation of optimal power flow in radial networks," *IEEE Transactions on Automatic Control*, vol. 60, no. 1, pp. 72-87, June 2014, doi: 10.1109/TAC.2014.2332712
[26] A. Sun, D.T. Phan, and S. Ghosh, “Fully decentralized AC optimal power flow algorithms,” Presentation at IEEE Power and Energy Society General Meeting, Vancouver, BC, Canada, July 2013, doi: 10.1109/PESMG.2013.6672864
[27] S. Magnússon, P. Weeraddana, and C. Fischione, "A distributed approach for the optimal power flow problem based on ADMM and sequential convex approximations," *arXiv preprint* arXiv:1401.4621, January 2014
[28] B. H. Kim and R. Baldick, "A comparison of distributed optimal power flow algorithms." *IEEE Transactions on Power Systems*, vol. 15, no. 2, pp. 599-604, May 2000, doi: 10.1109/59.867147
[29] X. F. Wang, Y. Song, and M. Irving, *Modern power systems analysis*, New York, NY: Springer Science & Business Media, 2008
[30] A. Trias, "The holomorphic embedding load flow method," Presentation at IEEE Power and Energy Society General Meeting, San Diego, CA, July 2012, doi: 10.1109/PESGM.2012.6344759
[31] A. Castillo, C. Laird, C.A. Silva-Monroy, J.P. Watson, and R. P. O’Neill, “The Unit Commitment Problem With AC Optimal Power Flow Constraints,” *IEEE Transactions on Power Systems*, (Early Access), January 2016, doi: 10.1109/TPWRS.2015.2511010
[32] Q.P. Zheng, J. Wang, A.L. Liu, “Stochastic Optimization for Unit Commitment – A Review,” *IEEE Transactions on Power Systems*, vol. 30, no. 4, pp. 1913-1924, July 2015, doi: 10.1109/TPWRS.2014.2355204
[33] D. Bertsimas, E. Litvinov, X.A. Sun, J. Zhao, and T. Zheng, "Adaptive robust optimization for the security constrained unit commitment problem," *IEEE Transactions on Power Systems*, vol. 28, no. 1, pp. 52-63, February 2013, doi: 10.1109/TPWRS.2012.2205021

Formal prize competitions appear to be an attractive mechanism for facilitating the development and comprehensive evaluations of new OPF and UC algorithms. Many other optimization and algorithm-intensive technical domains have successfully employed prize competitions to accelerate algorithm development and validation.[34,35,36] When objectives are clear and measurable and there exists a large population of potential solution providers, competitions have a number of advantages over traditional research grants. When employed properly, they can result in better solutions, more efficient use of funding, and engagement across broad communities of stakeholders. [37] Indeed, research at Harvard Business School has provided strong evidence that prize competitions can lead to faster, more efficient, and more-creative problem solving.[38] Prizes often also attract surplus investment, time, and talent from motivated participants. For example, teams competing for the $10 million Ansari X PRIZE collectively spent over $100 million to develop reusable manned spacecraft. Successful prize competitions that produce vetted solutions can also create momentum towards more ambitious programs and greater financial involvement from the private sector. Since the Ansari X PRIZE concluded in 2004, $1.5 billion has been invested in the nascent space taxi industry.[39] Prize competitions can also increase the number and the diversity of entities that are addressing difficult challenges.

By bridging across disciplines and involving the private sector through problem definition, financial sponsorship, judging, and commercialization, prize competitions create communities in ways that grants cannot achieve.

RFI Q1. How likely is it that a prize competition will accelerate the development, evaluation, and adoption of new OPF and UC algorithms? How can ARPA-E maximize potential participation in the competition? In particular, how can ARPA-E best publicize the existence of the competition (especially to communities of potential competitors who may not otherwise learn of the competition from ARPA-E's website)?

E. Competition Introduction

With this RFI, ARPA-E is announcing its interest in initiating a multiple phase competition to accelerate the development and comprehensive evaluation of OPF and UC solution methods. The primary purpose of this document is to solicit feedback regarding the details of the proposed competition design detailed in this document—including the baseline problem formulation and modeling approach for the initial OPF phase, competition rules, eligibility for participation, scoring metrics, criteria for winning, prize structure and online competition platform design.

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[34] https://cgc.darpa.mil/
[35] http://netflixprize.com/
[36] A. Ostfeld et al., "The battle of the water sensor networks (BWSN): A design challenge for engineers and algorithms," *Journal of Water Resources Planning and Management*, vol. 134, no. 6, pp. 556-568, November 2008, doi: 10.1061/(ASCE)0733-9496(2008)134:6(556)
[37] McKinsey & Company, "And the Winner is…Capturing the Promise of Philanthropic Prizes," July 2009, http://mckinseyonsociety.com/capturing-the-promise-of-philanthropic-prizes/
[38] G. Pisano, "You Need an Innovation Strategy," *Harvard Business Review*, June 2015, https://hbr.org/2015/06/you-need-an-innovation-strategy
[39] J. Bays, "Using Prizes to Spur Innovation" *McKinsey & Company*, http://www.mckinsey.com/insights/innovation/using_prizes_to_spur_innovation

“Straw-man” models for each of these competition design components are detailed. These models are provided to focus discussion and feedback; all of the parameters described in this document are not yet completely determined and/or are subject to change. If the competition is extended through Phase 2, the detailed problem formulation and modeling approach for that phase (focusing on UC) will be published at a later date. In the pages that follow, any language related to the competition’s existence and execution should be understood in context as occurring only under the scenario that ARPA-E decides to pursue a competition; ARPA-E reserves the right to not initiate a competition following the release of this RFI. Responses to this RFI will play an important role in helping ARPA-E determine whether or not to proceed with organizing a competition.

Respondents to this RFI should comment specifically on their technical and programmatic opinions regarding the proposed competition design, detailing exactly why the proposed design will or will not optimally deliver innovation in OPF and UC algorithm development. We are particularly interested in proposed competition design details that could prevent the competition from achieving the objective of providing a platform for the fair, transparent, comprehensive evaluation of new OPF and UC algorithms that can robustly address existing and emerging power system challenges. Respondents may comment on all or a subset of the components of the competition design. Respondents are also encouraged to propose alternative problem formulations and/or modeling approaches.

It is important to note that a necessary first step for any meaningful competition must be the development of many small, medium and large-scale, realistic power system network descriptions and operating scenarios defining a variety of challenging operating conditions (reflecting both the current electricity system and that in the future). The primary objective of the ARPA-E GRID DATA (Generating Realistic Information for the Development of Distribution And Transmission Algorithms) program, launched in early 2016, is the development of these datasets. It is anticipated that the GRID DATA program will provide many of the power system datasets to be used in the proposed competition.[40]

In each phase of the competition, a specific problem formulation will be provided along with a detailed set of scoring criteria. To the greatest extent possible, the problem will be selected and formulated to be solution method agnostic. The provided problem formulation and modeling approach described will be used for solution evaluation. Competitors will be permitted and encouraged to use any alternative problem formulation, modeling conventions, and/or solution method within their own software. Indeed, we anticipate competitors will use a variety of model formulations (to enhance computational efficiency and/or promote finding a solution) and will use a mix of formal optimization solution methods and unique heuristics. Regardless of the method and model formulation used by competitors within their software, competitors will be required to present their final solution (the final control variable set points) in a form that is compatible with the selected, published competition problem formulation. It is important to note that while the final solution will be required to be AC feasible (satisfying all system constraints including those related to voltage and reactive power), competitors do not have to employ full AC optimization methods within their competition software.

[40] http://arpa-e.energy.gov/?q=arpa-e-programs/grid-data

Competitors will interact with the competition via a hosted computational platform with a web front-end portal. Competitors will submit their software for formal evaluation (and scoring) by the official competition platform throughout all phases of the competition. Submissions can either be source code that must be compiled, linked, and executed; interpreted and executed; or a binary execution file. Each submission will be run on the controlled, secure evaluation platform with no external communications. The competition evaluation platform will provide access to several popular licensed solvers. Solutions requiring licensed software not provided by the platform will have to be be self-contained.

The methods used by the platform for the evaluation and scoring of algorithms are described in detail later in this document. Public leader boards will be maintained during the competition on the web portal as described below. Competitors can participate as individuals or in teams and the competition platform will be made available to both domestic and international teams. Specific eligibility details will be published separately if ARPA-E proceeds with the competition.

ARPA-E envisions the competition consisting of the following phases:

Phase 1: Optimal Power Flow (Spring 2017-Spring 2018)

Phase 1 will focus on the OPF problem and utilize four unique datasets. Each dataset will consist of a collection of power system network models of different sizes with associated operating scenarios. It is expected that all datasets will be open source and include models generated by the ARPA-E GRID DATA program. These will likely contain equipment and available controls not typically found in existing open source power system benchmark datasets, including, for example, transformer voltage taps and discrete capacitor banks. The “Phase 1 Original Dataset (P1OD)” will be released at the start of Phase 1 in order to allow competitors to start to develop solution methods. Competitors will be able to download the dataset in order to test algorithms within their own development environment. Competitors can also submit software to be scored against the P1OD dataset using the official competition platform at any time. Aggregate scores (as well as individual scores for evaluation time, objective function value and constraint violation for each individual power system network/scenario pair within P1OD) will be generated after each algorithm submission and will be displayed on a set of competition leaderboards, accessible via the competition website. Competitors may choose to remain anonymous on the leaderboards or may have their team name associated with their scores.

Trials (Summer 2017, Fall 2017)

Approximately six and nine months into Phase 1, two dry-run “trial” rounds for the OPF competition will be held utilizing new power system datasets (Phase 1 Trial Dataset 1 (P1TD1) and Phase 1 Trial Dataset 2 (P1TD2)). It is expected that these models will be similar in complexity and scope to those in P1OD, but they will not be publically released until after the conclusion of each trial event.

A deadline for the submission of OPF solution software will be established at least one month prior to each trial event. Immediately following the deadline, the software from all competitors will be run and scored against P1TD1 and P1TD2, respectively. After each trial event, aggregate scores (as well as individual scores for evaluation time, objective function value and constraint violation for each power system network/scenario pair in P1TD1 and P1TD2) for each competitor submission will be displayed on a set of competition leader boards. The objective of the trial events is to give competitors experience in using the portal for the competition and to troubleshoot any potential algorithm submission and evaluation problems in the context of a specified deadline, as will be required in the Phase 1 Final Event.

The network/scenario pairs used for scoring for each trial event (P1TD1 and P1TD2) will be released to the public as soon as scoring and evaluation of all algorithms has been completed. P1TD1 and P1TD2 will remain available for scoring runs using the official competition platform throughout the remainder of the competition and competitors will have the ability to submit new software/algorithms (to be tested against P1TD1 or P1TD2) at any time. An evolving, continuously updated leaderboard will be maintained corresponding to each individual competition dataset.

Phase 1 Final Event (Spring 2018)
At the conclusion of Phase 1, the first officially scored round of the competition will occur. Conditions will be similar to those in each trial event, with a new Phase 1 Final Dataset (P1FD) used for evaluation and scoring. A deadline for the submission of OPF solution software will be established at least one month prior to the final event. Immediately following the deadline, the software from all competitors will be run and scored against P1FD. Aggregate scores (as well as individual scores for evaluation time, objective function value and constraint violation for each power system network/scenario pair in P1FD) for each competitor submission will be displayed on a series of competition leader boards.

Competition winners will be determined based on the final aggregate scores subject to the winning criteria specified in the final competition rules.

RFI Q2. To what extent is the described competition structure and sequence (with trial events followed by a finals event) compatible with running a fair, transparent, and impactful OPF algorithm competition? How could it be improved? How compatible is the described competition structure and evaluation approach with an iterative algorithm development process?

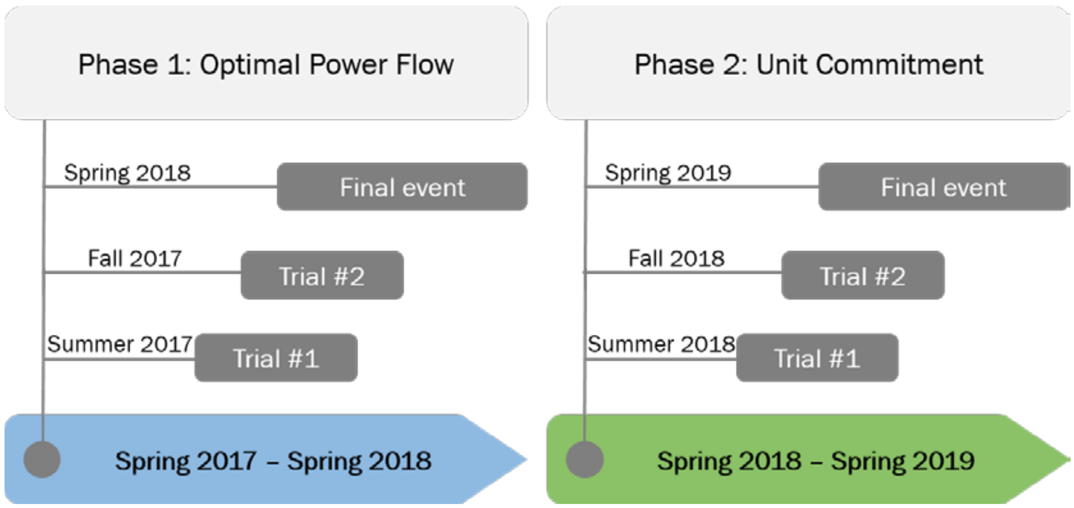
Phase 2: Unit Commitment (Spring 2018-Spring 2019)

ARPA-E tentatively plans to focus Phase 2 on a Unit Commitment problem. This phase will follow a similar structure and timeline as Phase 1 with two trial events and a final event. Similarly, Phase 2 will utilize four distinct, previously unreleased datasets. In addition to transformer taps and capacitor switching controls, the power system models included in the Phase 2 datasets, if focused on UC, will likely be augmented with additional generator constraints such as ramp rates and start-up and shut-down costs will be included. Competitors will be asked to solve a multiple time interval problem in this phase of the competition. A detailed formulation and dataset format specification will be published later.

RFI Q3. Phase 2 could focus on Unit Commitment (as described here), a more difficult variant of OPF, or another grid optimization problem. What problem would be most impactful

to focus on for Phase 2? Please describe the strengths and weaknesses of focusing the second phase of the competition on different problems. Please be as specific as possible.

The proposed competition timeline is illustrated below.



ARPA-E intends for the competition platform to be capable of hosting a wide range of power system algorithm research competitions. Once the processes are established and the prize competition model has been validated, private sector entities or other government agencies would have the option of commissioning and sponsoring additional prize competitions, contributing to a new era of innovation in electric power systems optimization research.

RFI Q4. Once the model for optimization competitions in the power systems domain has been established, how likely is it that other government agencies or private sector organizations will formulate and/or run additional competitions? What can ARPA-E do in the design of the initial competition phases to maximize the likelihood that this occurs?

F. PHASE 1 PROBLEM SPECIFICATION (OPF)

There are many utility industry decision-making processes that rely on OPF software. Each specific application requires a different OPF problem variation. In this competition, we seek to select a single problem variant with wide applicability, with the aim that solution methods identified in the competition can be adapted for use in a wide range of other contexts. We also seek to balance the need to accurately reflect complexities inherent to real-world problems and the desire to offer a problem that is accessible to a large number of potential competitors (including those with no background in the power systems domain).

Ensuring wide applicability requires the selection of an OPF problem variant with explicit consideration of system contingency events. Therefore, as formulated in detail below, we propose to focus the first phase of the competition on the identification of physically feasible, low cost solutions to a preventive security constrained OPF (PSCOPF) problem. The objective of this problem is to provide setpoints for generation and other controllable resources or equipment to meet system load (demand) at the least cost in the base case that are secure against all credible contingency cases (e.g., N – 1, common mode, and other contingencies), respecting physical and system constraint limits.

The preventative SCOPF problem seeks to prevent system violations that are not feasible or not acceptable even for a short time during the initial post-disturbance system state. Equipment failures (including generators) within an electric power system often change the magnitude of total power loss in the system from the base case as well as the power balance between aggregate supply and demand. A power imbalance results in deviations of the interconnection frequency from its nominal value. Electric power systems sequentially rely on system inertial response, speed droop controls on generators (a.k.a. governor response or primary regulation)[41], and further adjustments made by automatic generation control (AGC), contingency reserve activation, and other control actions to arrest the initial change of frequency and fully restore system frequency to its nominal value.

There is no single universally accepted method for modeling system changes immediately following a contingency.[42] Exact formulations of the preventative SCOPF problem are remarkably lacking in the literature. Preventative SCOPF formulations are often stated without explicitly modeling the preventative post-contingency actions of power systems components.[43,44, 45] To model post contingency changes accurately would require equations for the frequency evolution of the system and its components. In particular, one would need to know the system inertia and speed droop control setpoints for all generators. While there have been some attempts at this in the literature, there is not yet an agreed upon formulation in the community. We opt, in Phase 1 of this competition, for a significantly simplified formulation that includes only the balance between generation, load and power losses using pre-specified generator participation factors. This model implies that the system imbalance caused by a disturbance and power losses is allocated to generators based on known participation factors, which reflect, in part, their speed droop characteristics. The use of participation factors (α in the formulation below) allows for a relatively straightforward extension of the basic OPF problem. For the purposes of the initial stage of the competition, the factors for all generators in each system, and for each contingency will be provided as an input for competitors.

In the problem formulation selected for Phase 1 of the competition, the term "preventive" indicates that the generator control settings must be selected such that all base case and

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[41] Many generators in AC power systems are equipped with speed governors, which are automatic devices that change the real power output to arrest and oppose significant frequency variations.

[42] B. Stott and O. Alsaç, "Optimal power flow–basic requirements for real-life problems and their solutions," *White Paper*, July 2012, http://www.ieee.hr/_download/repository/Stott-Alsac-OPF-White-Paper.pdf

[43] F. Capitanescu et al., "Applications of security-constrained optimal power flows," *Proceedings of Modern Electric Power Systems Symposium MEPS06*, Wroclaw, Poland, September 2006.

[44] F. Capitanescu et al., "State-of-the-art, challenges, and future trends in security constrained optimal power flow," *Electric Power Systems Research*, vol. 81, no. 8, pp. 1731-1741, August 2011, doi: 10.1016/j.epsr.2011.04.003

[45] Y. Dvorkin, P. Henneaux, D.S. Kirschen, H. Pandžić, "Optimizing Primary Response in Preventive Security-Constrained Optimal Power Flow," *IEEE Systems Journal*, (Early Access), March 2016, doi: 10.1109/JSYST.2016.2527726

contingency constraints are satisfied. One is not allowed the recourse of adjusting control setpoints to re-establish feasibility in the face of a contingency.

Note also that the objective function representing system operating cost is assumed to depend only on the pre-contingency set point of generator active power output, and does not consider the deviation induced by speed droop control. This assumption may be justified in a market environment by observing that the compensation paid to a generator will typically be based only on the commanded power set point. We will use this model in Phase 1 of the competition.

RFI Q5. To what extent is SCOPF with participation factors a sufficiently accurate surrogate for modeling initial generator changes immediately following contingencies? Is this an appropriate, sufficiently realistic formulation to yield algorithms likely to be compatible with real-world needs? How could this be improved to maximize the impact of the competition?

Phase 2 of the competition is expected to focus on a Unit Commitment problem. This problem is expected to be more complex to solve relative to the OPF problem in Phase 1. A detailed problem specification for Phase 2 will be provided later.

RFI Q3 (repeated from above). Phase 2 could focus on Unit Commitment (as described here), a more difficult variant of OPF, or another grid optimization problem. What problem would be most impactful to focus on for Phase 2? Please describe the strengths and weaknesses of focusing the second phase of the competition on different problems. Please be as specific as possible.

G. Phase 1 Formulation & Modeling Approach

A common problem formulation and modeling approach is required to enable fair, transparent, and automated evaluation of solutions. Any OPF or UC competition involving models will necessarily involve approximations to the true fidelity and engineering concerns of real-world power systems. In the text that follows, we propose using a relatively simple formulation based on complex power (in rectangular representation) and voltage (in polar representation). Competitors do not need to use this particular formulation within their own software and/or algorithms. Indeed, there has been some discussion in recent literature that alternative problem formulations could facilitate finding improved solutions in less time.[46] Competitors are encouraged to use these or other formulations in their software. Nonetheless, competitors will be required to translate their solutions into the standard competition formulation for scoring and evaluation.

In Phase 1, we propose to include real/reactive generation dispatch along with a limited number of transformer tap and capacitor setpoints (i.e. discrete control opportunities) for OPF; in Phase 2 we proposed to augment this formulation with additional details such as generator ramp rate limits and start-up and shut-down costs for application to a multi-period problem such as Unit Commitment. In the text that follows, we outline a preliminary problem formulation and

[46] Castillo, Anya, and Richard P. O'Neill. "Computational performance of solution techniques applied to the ACOPF." Federal Energy Regulatory Commission, Optimal Power Flow Paper 5 (2013).

modeling approach that we propose to use in Phase 1. There exists the danger that these choices and the specific modeling approach outlined below will not adequately represent the most essential concerns of real power system optimization problems. However, selecting a more complex or challenging formulation could discourage broader participation, especially from potential competitors with creative ideas but only limited experience in the power system domain.

There are many open questions that we would appreciate feedback on: For example, is there value in using non-convex generator cost curves? How important is it to represent generator capability curves ("D-curves") with high fidelity? Should a voltage angle constraint be imposed or is this too conservative? If so, should it be a limit between adjacent buses or globally pairwise between any two buses in the entire grid? Are there better ways to represent post-contingency control other than speed droop control using generator participation factors?

Are there appreciable cost savings or other benefits to using higher model fidelity? Are some of these concerns likely to be more or less important as new control devices become cost effective and/or high penetrations of renewables are introduced?

Similar questions exist related to the control variables for Phase 2 of the competition. Answering each of these questions requires weighing the relative value to industry and society of each modeling choice against the added complexity that they bring to the problem.

RFI Q6. Please describe the level of modeling fidelity you believe would be required to maximize the likely impact of the competition in both Phase 1 (OPF) and in Phase 2 (UC). Is it necessary, valuable and/or feasible to include other control variables? What formulation in the published literature (or that could be published) is most valuable and/or most appropriate to use for the competition? Respondents may consider model elements such as non-convex generator cost functions, high fidelity generator capability curves ("D-curves"), voltage angle constraints and alternatives for post-contingency control.

The following problem formulation and modeling approach is proposed to be used for the competition:

Index/Set Definitions

The power grid is defined as a set of buses N (also called nodes), and branches E, which are composed of lines and transformers connecting the buses together in a network. Network components are indexed as:

i, j	bus indices
G_i	set of generators connected to bus i
l	generator index for multiple generators connect to bus i , $l \in G_i$
$N(i)$	set of neighboring buses directly connected to bus i, i.e., $\{j \in N \mid \exists (i,j) \in E\}$

N^G set of buses connecting to at least one generator

A contingency k defines an instance where the unexpected loss of one or more generators, large loads, or transmission equipment occurs. When computing optimal power flow, the base case $k = 0$ is considered to be the "no contingency" case. In some power system scenarios, system elements such as generators or transmission lines will be given as unavailable in the base case. Known, planned, or scheduled outages like these are not considered contingencies. Let $k \in \{1,2, \dots, K\}$ label the continency number of a set of K contingencies ($k = 0$ corresponds to the base case). Let also:

G_i^k set of available generators connected to bus i in contingency k

E^k set of available branches in contingency k

Data

The admittance matrix Y is an N by N complex matrix consisting of conductance (G) and susceptance (B) matrices built from line impedances, transformer tap ratios, and phase shifting transformer setpoints.[47,11]

Y admittance matrix with $Y_{ij} = G_{ij} + j\, B_{ij}$

Collectively, the admittance matrix Y maps out the impedance relationships between buses and thus determines how power will flow through lines and transformers in the network. Elements Y_{ij} for pairs of buses that share no branch between them have a value of zero; in typical transmission networks, Y is a sparse matrix.

In general, a power system may have switchable devices, *e.g.* capacitor banks, tap change transformers, and phase shifting transformers with multiple setpoints, and Y can be a function of integer variables representing the states of these switchable devices.

RFI Q7 What is the list of power system equipment that should be included in OPF models for the competition? For example,which types of switchable devices should be included?

The following variables define the physical limits of power networks:

p_l^{max}, p_l^{min} maximum and minimum real power generation limit at generator l, MW[48]

q_l^{max}, q_l^{min} maximum and minimum reactive power generation limit at generator l, MVar

V_l^{max}, V_l^{min} maximum and minimum voltage magnitude limits at bus i, kV

[47] R. D. Zimmerman and C. E. Murillo-Sánchez, "Matpower 6.0.b1 User's Manual", 2016
[48] Example units are provided throughout this formulation to aid the reader. Precise unit definitions to be used in input and output data files will be provided on the competition website at a later date.

S_{ij}^{max} Mega-Volt Ampere (MVA) capacity of branch (i, j) for $(i, j) \in E$

Each branch (i, j) has a specified limit S_{ij}^{max} for the amount of apparent (i.e. complex) power that can physically flow through it. Breaching these limits would risk a thermal overload that could disable transmission lines and transformers. Different limits may be specified for base case and contingency conditions.

Real and reactive demand are referred to by:

D_i^P, D_i^Q real and reactive demand at bus i, MW and MVar

After a contingency occurs, the network automatically readjusts by modulating the amount of power being generated according to each generator's participation factor α_i (here the participation factor is referred to without contingency subscript; in the actual formulation these may also be functions of each contingency). This factor is predetermined and the adjustments are assumed to occur instantaneously. Let Δ_k be a variable that is proportional to the imbalance of real power in contingency k. For this contingency, generator l will adjust its generation by the amount $\alpha_l \Delta_k$.

α_l participation factor for generator l

Δ_k system-wide imbalance of real power in contingency k before generator droop control

Variables

p_l^k real power dispatched at generator l in contingency k, MW

q_l^k reactive power dispatched at generator l in contingency k, MVar

In the base case, real and reactive power dispatch at generator l will be referred to as p_l^0, q_l^0 or equivalently as p_l, q_l (in general if a relevant variable is referred to without a contingency superscript, it should be assumed to refer to the base case). Power flows throughout the network are determined by the structure of the network, the magnitude of power injections and withdrawals at buses, and the setpoints for grid control equipment. These power flows are represented as:

p_{ij} real power flow on branch (i, j), measured from bus i, MW

q_{ij} reactive power flow on branch (i, j), measured from bus i, MVar

s_{ij} apparent power flow on branch (i, j), measured from bus i, MVA

v_i voltage magnitude at bus i, kV

θ_i voltage phase angle at bus i, radians

Functions

$C_i(p_i)$ cost of producing power p_i at generator l, \$

There are several parameters that affect the cost of production (e.g. fuel costs, heat rates, environmental regulations, etc.). In this formulation, all of these factors (where relevant) are assumed to be included within the function definition. Generator cost functions will be specified with each test case and may be non-convex.

Objective Function:

The objective function of the SCOPF problem is to minimize the aggregate cost of electricity production by optimizing the output of each generator:

$$\min \sum_{i \in N} \sum_{l \in G_i} C_i(p_l^0) \qquad [1]$$

In this formulation, the objective function representing system operating cost is assumed to depend only on the pre-contingency set point of generator active power output, and does not consider deviations after contingencies. This assumption may be justified in a market environment by observing that the compensation paid to a generator will typically be based only on the commanded power set point.

Constraints:

This objective function is subject to the following constraints:

$$\sum_{j \in N(i) \cup i} p_{ij}^0 = -D_i^{P0} + \sum_{i \in G_i} p_l^0 \quad \forall i \in N \qquad [2]$$

$$\sum_{j \in N(i) \cup i} q_{ij}^0 = -D_i^{Q0} + \sum_{i \in G_i} q_l^0 \quad \forall i \in N \qquad [3]$$

$$p_{ij}^0 = v_i^0 v_j^0 \left(G_{ij} \cos\left(\theta_i^0 - \theta_j^0\right) + B_{ij} \sin\left(\theta_i^0 - \theta_j^0\right)\right) \quad \forall (i,j) \in E \qquad [4]$$

$$q_{ij}^0 = v_i^0 v_j^0 \left(G_{ij} \sin\left(\theta_i^0 - \theta_j^0\right) - B_{ij} \cos\left(\theta_i^0 - \theta_j^0\right)\right) \quad \forall (i,j) \in E \qquad [5]$$

$$p_l^{min} \le p_l^0 \le p_l^{max} \quad \forall l \in G_i, \forall i \in N \qquad [6]$$

$$q_l^{min} \le q_l^0 \le q_l^{max} \quad \forall l \in G_i, \forall i \in N \qquad [7]$$

$$V_i^{min} \leq v_i^0 \leq V_i^{max} \quad \forall i \in N \tag{8}$$

$$\left(p_{ij}^0\right)^2 + \left(q_{ij}^0\right)^2 \leq \left(S_{ij}^{max}\right)^2 \quad \forall (i,j) \in E \tag{9}$$

$$\theta_0^0 = 0 \tag{10}$$

The first two equations describe real and reactive power demand satisfaction while the next two are the physical power flow equations. The remaining describe physical generator limits on real and reactive power, a minimum/maximum voltage for each bus (any buses that have fixed voltage setpoints are delineated by setting equal upper and lower limits), and power flow constraints across branches (which are dictated, for example, by thermal limits on transmission and distribution lines). The final equation simply assigns a phase angle of zero to a reference bus.

The power flow solution is subject to additional contingency constraints for each contingency k. Other than a few exceptions, the optimization constraints after a contingency has occurred are similar to those in the base case. The important consideration is that the constraints must be met in the post-contingency case without any changes to the base case control settings other than control dictated by fixed generator participation factors.

For each contingency $k = 1, \ldots, K$ the contingency constraints are

$$p_{ii}^k + \sum_{\substack{(i,j)\in E^k \\ j\in N(i)}} p_{ij}^k = -D_i^{P0} + (\sum_{i\in G_i^k} p_l^0 - \alpha_l \Delta_k) \quad \forall i \in N \tag{11}$$

$$p_l^{min} \leq p_l^0 - \alpha_l \Delta_k \leq p_l^{max} \quad \forall l \in G_i, \forall i \in N \tag{12}$$

$$q_{ii}^k + \sum_{\substack{(i,j)\in E^k \\ j\in N(i)}} q_{ij}^k = -D_i^{Q0} + \sum_{i\in G_i^k} q_l^k \quad \forall i \in N \tag{13}$$

$$q_l^{min} \leq q_l^k \leq q_l^{max} \quad \forall l \in G_i^k, \forall i \in N \tag{14}$$

After a contingency occurs, each generation plant l will automatically adjust its output by its predetermined participation factor α_i to compensate the system imbalance Δ^k due to contingency k (accounting for both lost generation and changes in system losses).

In addition to automatic adjustments in real power output outlined in the first two equations above each generator's control system will attempt to modulate reactive power output to maintain the base case voltage at each bus. Competitors must select pre-contingency system setpoints with sufficient reactive power capacity to ensure that voltage at bus i can be maintained within limits $V_i^{min} \leq v_i^k \leq V_i^{max}$ in all contingencies. After a contingency occurs, the voltage magnitude v_i^k at each generation bus i will preferentially equal the voltage determined in the base case v_i^0 while maintaining the aggregate reactive power output at each generation bus i if doing so can be achieved within the total reactive power limits of local generators: $\sum_{l\in G_i^k} q_l^{min} < \sum_{l\in G_i^k} q_l^k < \sum_{l\in G_i^k} q_l^{max}$, $\forall i \in N^G$. If this is not possible, aggregate local reactive power will bind at the lower bound $\sum_{l\in G_i^k} q_l^{min}$ or upper bound $\sum_{l\in G_i^k} q_l^{max}$, and bus voltages will be adjusted. Said mathematically,

$$v_i^k - v_i^0 = 0 \qquad [15]$$

and

$$\sum_{l\in G_i^k} q_l^{min} < \sum_{l\in G_i^k} q_l^k < \sum_{l\in G_i^k} q_l^{max} \qquad [16]$$

or

$$V_i^{min} \le v_i^k \le V_i^{max} \qquad [17]$$

and

$$\sum_{l\in G_i^k} q_l^k = \sum_{l\in G_i^k} q_l^{max} \qquad [18]$$

or

$$V_i^{min} \le v_i^k \le V_i^{max} \qquad [19]$$

and

$$\sum_{l\in G_i^k} q_l^k = \sum_{l\in G_i^k} q_l^{min} \qquad [20]$$

Competitors must give solutions whose post-contingency control variables satisfy one of these three conditions at each node of the network. Note that for scoring (see next section), competitors will be timed only until pre-contingency (base case) set-point values are submitted. Additional unscored time will be allowed for the submission of post-contingency feasible states (though such states will be checked for feasibility).

Power flow constraints and the reference bus assignment under contingency conditions are similar to the base case:

$$p_{ij}^k = v_i^k v_j^k \left(G_{ij}\cos\left(\theta_i^k - \theta_j^k\right) + B_{ij}\sin\left(\theta_i^k - \theta_j^k\right)\right) \quad \forall (i,j) \in E^k \qquad [21]$$

$$q_{ij}^k = v_i^k v_j^k \left(G_{ij}\sin\left(\theta_i^k - \theta_j^k\right) - B_{ij}\cos\left(\theta_i^k - \theta_j^k\right)\right) \quad \forall (i,j) \in E^k \qquad [22]$$

$$\left(p_{ij}^k\right)^2 + \left(q_{ij}^k\right)^2 \le \left(S_{ij}^{max}\right)^2 \quad \forall (i,j) \in E^k \qquad [23]$$

$$\theta_0^k = 0 \qquad [24]$$

RFI Q8. Please provide feedback on the Phase 1 formulation and modeling approach. Is this formulation sufficient to promote the development and evaluation of OPF algorithms that are likely to be relevant for industry? How can this formulation be improved?

RFI Q9. Please comment specifically and/or provide guidance for the proposed model of post-contingency generator response, in particular with respect to real and reactive power changes. ARPA-E realizes that the real-world post contingency scenarios are dictated by the particulars of many different generator control systems; the proposed formulation is an attempt to meaningfully model this response, albeit in a highly approximate manner (which has the benefit of abstracting away an extremely large set of additional modeling variables).

H. Phase 1 Solution Evaluation & Scoring

A fundamental principle underlying the design of effective competitions is the establishment of a fair, transparent, unambiguous, and quantitative method for scoring (and ranking) solutions. This is particularly difficult in the context of complex challenges like OPF where multiple objectives or desired solution characteristics can be in conflict. There are at least three obvious metrics to be considered when designing an overall score for an OPF algorithm (and more broadly, for any optimization algorithm competition):

- **Objective function value**: OPF is an extremely challenging problem, with a range of local optima that are likely to be found by different competitors' algorithms. The core objective is to find the lowest cost set of system control settings that are physically feasible.
- **Time to convergence**: Unless submitted algorithms converge in an operationally relevant timescale for power grid operators, they are unlikely to be taken seriously or gain widespread interest or adoption in the power systems community.
- **Constraint violation**: Ideally, all OPF problems would be solved without constraint violations. However, it is well known that constraint violations are often unavoidable in practice. Often a distinction is made between "soft" constraints that may be violated weakly or temporarily and "hard" ones which must never be violated to maintain system reliability. It is not yet known if the large scale, realistic models emerging from the GRID DATA program will have certified feasible points without violating at least some constraints. The formulation proposed in this document does not make this distinction but proposes to penalize solutions that violate constraints.

Given the diversity of real-world OPF applications, we acknowledge that there is no single way to describe the relative importance of these three metrics. In some settings, the likelihood that a solution method provides a physically feasible solution within a given time threshold may outweigh concerns for just how close to the global optima (or even a local optima) that particular solution's objective function cost might be. Given the importance of these three metrics, we believe it will be important to always separately report the performance of proposed solution methods in public leaderboards on the competition website. It would be possible to define multiple, parallel competition tracks that emphasize different solution attributes. However, doing so could reduce the depth and quality of competition in any individual competition track.

Designing a competition with multiple tracks would also run the risk of over-emphasizing a single solution characteristic over others.

Therefore, we believe the most effective competition design will be one that uses a single, composite scoring procedure that reflects all of the above objectives. In the text that follows we propose a comprehensive framework for a composite score to be used in Phase 1 of the competition that incorporates these metrics. We seek feedback on the particular realizations of this framework that make the most sense to implement in the proposed OPF competition. We have also developed two more detailed “straw man” scoring procedures based on previous input from the community. In addition to comments on the general approach to scoring in the proposed OPF competition, we also seek input on the specific details of these individual scoring proposals.

RFI Q10. To what extent should other solution attributes (in addition to cost, time and constraint violations) be considered in the competition scoring framework? What constraint violations should be permitted? Should a distinction be made between “soft” and “hard” constraints? How should this be done?

Each particular choice of scoring requires, at the very least, a choice of a common unit to relate cost, constraint violation and algorithmic time (and at very most, the choice of many different non-linear functions). This is admittedly somewhat arbitrary, but ARPA-E seeks to develop a score that is in close alignment with industry priorities, and most aligned with the largest number of different actual OPF applications as possible. There is, however, a natural tension between such a score and one that is simple, transparent, and likely to minimize disagreement and the potential for “gaming” (developing algorithms that technically score well but may not reflect true industry value). Therefore, ARPA-E is requesting responses that describe the “best-way” to make the above choices within the given framework (or arguments for why this framework is incorrect).

RFI Q11. Please describe the “best-way” to make the scoring attribute weighting decisions outlined above. Please make and justify individual choices to give a concrete and unambiguous scoring metric while keeping in mind the dual objectives of industry realism and competition simplicity, fairness, and transparency.

Below, two possible “straw-man” versions of this framework are described. In the following exposition let m index the competition power system network models while s indexes particular “scenarios.” In this context, each “model” corresponds to a different hypothetical grid, with defined network characteristics and locations of generators, loads, transmission lines, transformers, etc. Each “scenario” corresponds to an operating instance in time for that model. The scenarios define instantaneous demand at each bus, renewable resource availability, and other temporary system conditions. The best solution methods should be able to produce high quality (low cost), physically feasible solutions across a wide range of different models and scenarios. A particular competitor’s solution for a given power system model and scenario will be referred to as $s_{m,s}$.

“Straw-man” #1:

Each algorithm submitted for evaluation is run independently against all power system network models (m) and scenarios (s) in the current competition dataset. For each individual network/scenario pair, the best 20 physical solutions (satisfying power flow and other hard constraints) evaluated thus far in (1) algorithmic run-time, (2) objective function, or (3) magnitude of soft constraint violations receive a positive score. For each scoring criteria, the "top 20" solution values (across all competitors) are linearly remapped (based on the range of those 20 scores) to a high score of +25 and low score of +1. The solutions with the best objective function value, the shortest run-time, and the lowest magnitude of soft constraint violations each receive a score of +25. For example, a solution which is the fastest submission but does not make the top 20 of objective function or soft constraint violation gets a score of +25. If a solution simultaneously achieves the best objective function value, the shortest run-time, and the lowest magnitude of constraint violations, that solution would score a +75. Solutions that do not place within the top 20 in any of the scoring criteria receive a score of 0. Solutions that are non-physical (violating power flow or other hard constraints, as specified in the final competition design) are given a score of -75.

As an example, we consider the scoring of five algorithmic solutions to one model/scenario pair. For simplicity, we assume there are no soft constraints and remove them from the scoring. We also assume that the best algorithmic run-time for a physical solution submitted is $t_1 = 1\ s$ and the 20th ranked is $t_{20} = 150\ s$. Similarly we assume the best objective function value is $c_1 =$ \$1000 and the 20th ranked is $c_{20} =$ \$1200. The table below illustrates the scoring for five example submissions

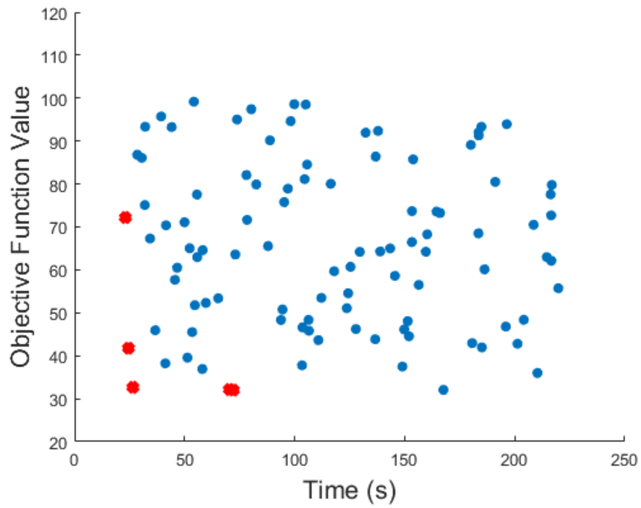
Solution	Physical?	Time (s)	Time Rank	Objective (\$)	Objective Rank	Score
s_1	Y	1	1	1100	10	25+13=38
s_2	Y	300	42	1003	3	0+24.64=24.64
s_3	N	N/A	N/A	N/A	N/A	-75
s_4	Y	30	10	1106	12	20.33+12.28=32.61
s_5	Y	500	75	2000	83	0+0=0

An aggregate score for each competition submission is determined by summing the individual network/scenario scores corresponding to all competition network/scenario pairs in the current competition dataset. Note that in this scoring rubric, team scores may change over time, even in the absence of resubmission.

This particular straw-man proposal is a specific instance of a more general scalar scoring framework, detailed in Appendix 1. Respondents to this RFI who wish to propose alternative scoring proposals may wish to use the framework described in Appendix 1 for ease of pedagogy and communication with ARPA-E.

"Straw-man" #2:
Another option is to consider a multi-objective optimization approach to scoring. For example, one may first set criteria for solution consideration (physical, upper bounds on objective function, time and constraint violation) and then score +1 on each model/scenario pair where an algorithm is Pareto optimal (in the sense that any other non-scored algorithmic solutions are not a simultaneous improvement on time, optimality or soft-constraint violation).

An example of this scoring is shown in the figure below (only two of the dimensions are considered for graphical clarity). Of the 100 allowed solutions listed, only the five red marked ones are Pareto optimal--these would be given a score of +1 on this fictional scenario.



RFI Q12. Please provide feedback on the strengths and weaknesses of the two scoring straw-man proposals described above. Are there more useful scoring paradigms that ARPA-E should consider? Are there more concrete and realistic ways, based on public data, to represent the tradeoffs between objectives (for example, assigning a realistic dollar value to constraint violations)? Do either of the proposed straw-man scoring approaches contain unforeseen characteristics that would make them vulnerable to "gaming" by competition participants? If proposing alternate scoring metrics, respondents should make and justify any individual choices to give a concrete and unambiguous scoring metric while keeping in mind the dual objectives of industry realism and competition simplicity, fairness, and transparency. It may be useful to communicate alternative scoring procedures using the general scalar scoring framework outlined in Appendix 1.

I. Competition Software/Algorithm Evaluation

Competitors will interact with an online competition portal throughout the competition. The portal will be made available prior to the start of Phase 1 of the competition. The proposed competition algorithm evaluation system is split into two parts: a web front end and a back end algorithm execution and scoring platform.

On the website front end, one will be able to find complete information on the final competition design, register as a competitor, download (publically released) problem datasets, make software submissions for evaluation and scoring, and track leaderboards describing the performance of all previously submitted algorithms. Most of the website will be accessible without an account. Registration will be necessary to participate as a competitor. If desired by the community, the website could also be enhanced to include forum tutorials that help explain data sets or optimization techniques. We seek ideas for website enhancements that could help make the competition more approachable to contestants not intimately familiar with the specific competition domain.

In order to compete, it is envisioned that competitors will first have to commit competition source code (or compiled software) to their GitHub repository (we expect many competitors to create a GitHub repository specifically for this competition). Then, competitors will log into the competition website and use a Submission Request page to initiate an algorithm evaluation cycle. The contestant will have to grant read access for their competition GitHub account to the evaluation platform via an SSH token provided by the evaluation platform after registration. Competitors will specify the location of the code they wish to have evaluated during the submission process and select the specific competition dataset that they would like used in the evaluation. Competitors will also have to specify which language script the evaluator should access. Detailed instructions for the use of the website will be provided prior to the start of Phase 1.

Upon receiving a submission request, the competition back end execution platform will retrieve the competitor's code from GitHub. The execution platform is being designed to enable high consistency of computational performance and fairness between all competitors. The backend is built on the Java Play framework. For security and fairness reasons, all competitor codes will be run within Docker containers. Docker is a lightweight container, similar to a virtual machine, which is used to encapsulate and wall-off competitor's codes while they are being executed. Unlike a virtual machine, however, Docker instances allow code to run natively on the underlying Linux kernel, which results in little or no performance overhead. The use of Docker will allow the competition platform to completely deny all network access to competitor's codes as well as to restrict file system access and permissions to only the directories that contain the code to be run, the dataset/scenarios to be solved, and into which the code will write results.

The proposed evaluation system design provides a number of critical advantages, including:

- Adding an additional layer of security to prevent competitors' codes from maliciously accessing other hardware or data within the IT environment where the system is hosted;
- Ensuring that competitors' codes can't access code submissions by other competitors; and
- Preventing competitors' codes from using the internet to circumvent competition rules --- for example by sending a competition dataset/scenario out to be run on external hardware.

ARPA-E intends to make a number of common software packages and solvers available by default in the competition platform. As of the release of this RFI, this is expected to include several general purpose solvers (Knitro, CPLEX, and GUROBI), GAMS, and MATLAB. The vendors for all of these tools have contributed licenses to the competition in return for acknowledgement of their support. These software tools were chosen due to their particularly widespread use in the research community. It is important to note that the competition platform is intended for algorithm evaluation only. Competitors will need to purchase their own licensed copy of solvers to develop their algorithms. ARPA-E intends to also offer competitors the ability to request special licensed software (other than those provided by default) to be integrated into the evaluation platform and run with their algorithms. We will attempt to work with vendors and competitors on a case-by-case basis to acquire a license for the requested software. Competitors may be required to pay a license fee for non-standard software that they request to be run with their algorithms on the evaluation platform. ARPA-E reserves the right to make the additional software available to all competitors if the license allows. (The license fee will be paid for by ARPA-E in instances where ARPA-E makes the software available to all competitors.) More detailed rules on how ARPA-E will consider requests to integrate non-standard software inside of Docker instances for use by competitors codes will be published prior to the start of the competition. Feedback regarding any additional software tools (either commercial or open-source) that may be important to include in the standard competition evaluation Docker instances is also welcome.

The evaluation procedure used by the competition platform is designed to check solution objective function values and constraint violations. Competitors' codes will be required to output solutions in a specific standardized format. The information that will be required in solution output is envisioned to include:

- Real and reactive power generation at each generator
- Real power (injections or withdrawals), reactive power (injections or withdrawals), voltage magnitude and phase angle at each bus for the base case and each of the contingency cases
- System-wide power imbalance magnitude for each contingency case.

The automated evaluation process will use the information in competitors' solutions to calculate the objective function value and will assess solution constraint violations. For each contraint and each limit specificed in the standard formulation, the evaluation scripts will calculate a relative constraint violation. For example, consider a scalar constraint $g(x) \le a$ and given solution $\hat{x}$. The relative constraint violation will be $[g(\hat{x}) - a]^{+} / |a|$, where $[x]^{+} = \max\{0, x\}$. The total constraint violation will be the sum of the constraint violation over all constraints and limits.

The evaluation process will assess solutions against the official competition problem formulation and modeling approach (as described in this document). However, competitors will be free to utilize any other formulation or modeling approach within their solution software. In order to ensure fairness and to enable the use of alternative problem formulations where appropriate, there will be two timers for each competition algorithm. The first timer will record the computation time required by competitors' codes to solve the OPF problem and report the objective function value, real and reactive power generation dispatch decisions at each bus, and control setpoints for any other equipment that has been declared controllable by the problem statement). The first timer will stop immediately after this information is reported by each algorithm.

In theory, the evaluation platform could use the decision variable solution provided by competitors to calculate power flow solutions and use that solution to assess constraint violations and objective function value. However, solving for power flows and checking for the existence of feasible power flow solutions are also non-trivial problems.[49,50] Existing (commercial or open-source) power flow tools that could be used by the evaluation platform may find different power flow solutions given the same inputs or may not always converge to a feasible power flow solution even when one exists. The failure of the evaluation platform to find feasible power flow solutions could unfairly penalize the scores of individual competitors. Therefore, we believe the best method for evaluating solutions is to require competitors to calculate and report power flow solutions for the base case and all contingency cases (given their previously reported decision variables). Given this additional information, all OPF solutions will be validated in a uniform way by forward constraint evaluation.

The second timer will track the additional time required to provide the additional solution details required for solution validation by the competition platform. The time required to calculate the additional solution information beyond decision variables will not be counted in an algorithm's computation time score. Allowing solution software to calculate these quantities only after the first timer has been stopped is important as some competitors will utilize insights on the problem structure or inputs to quickly screen out some contingency cases. Therefore, the software that competitors submit to the competition, may not need to calculate actual power flow solutions for every contingency prior to reporting generator and equipment control setpoints. We realize that requiring competitors to calculate power flow solutions represents an expansion of the scope of the competition to include producing feasible power flow solutions. While this is not the primary objective of the competition, a second timer will be used to track the amount of time required by competitors for this second step. At the current time, the second timer is not expected to be used in scoring competitors' OPF algorithms (though may be reported alongside other solution information).

Solution data generated by algorithm evaluation will include objective function values, algorithmic run-time and constraint violation magnitudes for each network and scenario pair tested. This data will be logged by the competition evaluation platform and associated with a specific competitor or team. These logs and the public names of the associated competitors will be released into the public domain after the conclusion of each Trial or Final Event. More detailed information on the specific solutions identified by competitors or logs associated with the execution of a competitor's code (i.e. general purpose solver log files) will not be retained or disclosed publically during or after the competition.

RFI Q13. To what extent is the described website and evaluation platform design sufficient to enable a fair and transparent OPF competition? How might this be improved?

J. PARTICIPATION AND WINNING

ARPA-E intends to encourage both domestic and international participation in the competition. It is anticipated that each competition team will have to be comprised of an entrant (either an

[49] K. Lehmann, A. Grastien and P. van Hentenryck, "AC-feasibility on tree networks is NP-hard," *IEEE Transactions On Power Systems*, vol. 31, no. 1, pp. 798-801, January 2016, doi: 10.1109/TPWRS.2015.2407363

[50] R. Madani, J. Lavaei and R. Baldick, "Convexification of power flow problem over arbitrary networks," IEEE Conference on Decision and Control, Osaka, Japan, December 2015.

organization or individual), an individual team leader and an optional set of additional team members.[51] ARPA-E proposes to allow but not require teams to enter under an official affiliation (e.g., a university, corporation, etc.). Teams may also have an official set of sponsors. ARPA-E may require entrants to be a U.S. citizen, permanent resident, or private U.S. entity in order to be eligible to receive a prize. If ARPA-E decides to move forward with the competition, a detailed set of competition eligibility rules will be published on the competition website prior to the start of Phase 1.

RFI Q14. What eligibility requirements for participation in the competition or prize eligibility are important to maximize the impact of the competition?

For both Phase 1 and Phase 2, ARPA-E proposes to provide two parallel paths for participating in the competition: a *Proposal Track* and an *Open Track*. Competitors scores and rankings throughout the competition will be based on the same technical evaluation criteria and scoring mechanisms for all competitors, irrespective of the track they belong to.

If ARPA-E chooses to use this structure it is anticipated that a formal Funding Opportunity Announcement (FOA) will be used to select Proposal Track teams prior to the start of Phase 1, subject to the availability of appropriated funds. Proposal Track teams for Phase 1 will be competitively selected on the basis of proposals submitted to the FOA. It is anticipated that up to 10 teams selected under this FOA would receive grants of up to $500,000.[52] The FOA's purpose would be to enable teams to participate in the competition who would otherwise not have the resources to participate.The FOA will specify certain requirements for teams to receive grant funding from ARPA-E, including, for example, the submission of a technical paper to ARPA-E describing the team's approach. The FOA will also include specific information on the treatment of intellectual property (IP) specifically used or first produced in the performance of Proposal Track awards. This will include provisions dealing with rights in patents and data.

Teams who do not apply to the Proposal Track FOA described above or are not selected under that FOA, may participate in the competition's Open Track. Open Track registration materials will be made available on the competition website prior to Phase 1 and a deadline for registration will be established. The Open Track registration materials will include a detailed set of requirements that teams will have to satisfy in order to be eligible to receive prize funding. This will likely include the submission of an an acceptable technical paper to ARPA-E describing the team's solution approach. Submitted technical papers will be used only by ARPA-E to assess competition impact and success. ARPA-E does not intend to disclose the submitted Technical Papers outside the Government.[53] ARPA-E does not plan to claim rights to software developed

[51] Individual entrants may be the same individual named as team leader.
[52] The grants will be subject to the administrative requirments and cost principles set forth at 2 CFR Part 200 and 2 CFR Part 910 (collectively the "Uniform Administrative Requirements, Cost Principles, and Audit Requirements for Federal Awards").
[53] Technical Papers may be handled by ARPA-E support contractor personnel for administrative purposes and/or to assist with technical evaluation. All ARPA-E support contractor personnel performing this role are bound by nondisclosure agreements. ARPA-E support contractors are subject to the Organizational Conflict of Interest restrictions of their contracts and may not participate in any ARPA-E sponsored competitions. ARPA-E does not intend to disclose Technical Papers to contractors to duplicate, commercialize, or for reprocurement or reverse engineering purposes.

by Open Track competitors as a result of participation in the competition and ARPA-E will not require Open Track teams to publically disclose their solution methods.

ARPA-E will reserve the right to disqualify a participant or team at any time whose actions are deemed to violate the rules of the competition, including but not limited to, the violation of relevant laws or regulations in the course of participation in the competition. ARPA-E will not authorize or consent to competition participants infringing on any U.S. patent or copyright while participating in the competition. No illegal activities may be undertaken for the purpose of participation in the competition.

Following the Phase 1 Final Event, ARPA-E proposes to determine the top ten winning teams based on aggregate scores across the full competition dataset as described in the scoring section above. Following receipt and acceptance of final Technical Papers from these teams, ARPA-E will publicly announce these teams as Phase 1 winners. It is anticipated, subject to the availability of appropriated funds, that each winning Proposal Track team will receive an additional $500,000 grant to support their participation in Phase 2 of the competition. Winning Open Track teams will receive a $500,000 prize, subject to the availability of appropriated funds. Open Track teams will not be restricted in how they utilize the funds. However, Open Track teams will be encouraged to use those funds to participate in Phase 2 of the competition.

Based on finalized scoring of the Phase 2 Final Event, ARPA-E will determine 1st, 2nd, and 3rd place winners to receive prizes. Following receipt and acceptance of final Technical Papers from each winning team, ARPA-E will publicly announce the 1st, 2nd and 3rd place winners. ARPA-E currently anticipates final Phase 2 prizes in the following amounts, subject to the availability of appropriated funds:[54]

- 1st place: $2,000,000
- 2nd place: $1,000,000
- 3rd place: $500,000

In this proposed competition structure, both Proposal Track and Open Track teams will be eligible to receive prizes following the Phase 2 Final Event, subject to federal prize authority and any additional requirements outlined on the competition website (to be published prior to the start of the competition).

ARPA-E expects to actively publicize the results of the competition. Prize winners should expect the active publicizing of their results by ARPA-E and winners may be required to participate in related events such as the annual ARPA-E Energy Innovation Summit.

RFI Q15. To what extent is the described competition structure with both a Proposal Track and an Open Track likely to maximize the impact that ARPA-E can have with this competition? Are the proposed grant and prize magnitudes appropriate to incentivize widespread participation in the competition? How can this be improved?

[54] The actual prize amounts will be announced on the competition website prior to the start of Phase 1. We seek feedback on how to best structure these prizes to maximize competition impact.

APPENDIX 1: GENERALIZED SCORING FRAMEWORK

Let $c_m(s_{m,s})$ be the aggregate cost (which we will use here without loss of generality as the objective function) evaluated on a particular solution. In addition, let $t_{m,s}$ be the time required to calculate a particular solution $s_{m,s}$. Shorter solution times are often preferred over longer ones. Finally, let $v_{i,m,s}$ be the absolute value of the magnitude of constraint violation for each constraint $i_{m,s}$, $i_{m,s} = 1 \ldots l_{m,s}$. There are many possible ways to quantify constraint violations in a score. One could simply count the number of constraint violations of each different type (over-voltage, under-voltage, line thermal limits, etc.). Instead, one could use the $v_{i,m,s}$'s directly and calculate a sum (or mean) of the magnitude of violations of each type throughout $s_{m,s}$. Finally, the magnitude and type of each individual constraint violation could be individually recorded and penalized in the composite score. The framework described below is inclusive of each of these possibilities.

Our particular method for constructing a score for a model/scenario pair that incorporates objective function, constraint violation, and solution time, is

$$Score_{m,s} = f_{m,s}(v_{1,m,s} \ldots v_{l,m,s}) + g_{m,s}(t_{m,s}) + h_{m,s}(c_m) \qquad [A1]$$

For (yet to be defined) functions $f_{m,s}$, $g_{m,s}$, and $h_{m,s}$. One might also imagine the score as a multiplicative combination[55] of the three metrics. We discuss the additive case for pedagogy, but many of the scoring challenges are similar and directly analogous in the multiplicative case.
In the simplest form, the $f_{m,s}$, $g_{m,s}$, and $h_{m,s}$ functions have a linear dependence on the solution quantities

$$f_{m,s}(v_{1,m,s} \ldots v_{l,m,s}) = \sum_{i=1}^{l_{m,s}} \alpha_{i,m,s}\, v_{i,m,s} \qquad [A2]$$

$$g_{m,s}(t_{m,s}) = \beta_{m,s} t_{m,s} \qquad [A3]$$

$$h_{m,s}(c_m) = \gamma_{m,s}\, c_m(s_{m,s}) \qquad [A4]$$

with coefficients $\alpha_{i,m,s}$ and $\beta_{m,s}$ (without loss of generality $\gamma_{m,s}$ sets the overall scale so we set it to 1). One choice is to penalize solution time equivalently for all models/scenarios, i.e. $\beta_{m,s} = \beta$. One might also weight the coefficients by a parameter which is a surrogate for complexity of the models (one choice, though not terribly well motivated is $\beta_{m,s} = \left(\frac{1}{n^2}\right)\beta$ with n the number of buses in the power system model). In this context, "hard" constraints can be delineated by assigning them extremely high linear coefficients.

[55] Indeed, there may be reasons to favor the multiplicative over the addive form of scoring related to the tradeoff between arithmetic and geometric means. Respondents are invited to explore the advantages and disadvantages of an additive vs. multiplicative score.

More generally, one could imagine making $f_{m,s}$ and $g_{m,s}$ nonlinear functions of the metrics (for example weakly penalizing variations in some "dead band" range near zero and much more drastically penalizing outside either with a piecewise linear or more complicated function). As above, these can be further weighted by model complexity.

One might also develop these functions with respect to some reference solver/solution pair given by a known benchmark solution method (such as a classic DC-OPF formulation solved using a commercially available general purpose solver or a specialized tool developed by the competition hosting team). For example, one might consider the time penalty functions:

$$g_{m,s}(t_{m,s}) = \beta H(t_{m,s} - \delta t_{ref,m,s}) \qquad [A5]$$

or

$$g_{m,s}(t_{m,s}) = \beta\left(1 - e^{-\left(\frac{t_{m,s}}{\delta t_{ref,m,s}}\right)}\right) \qquad [A6]$$

For some coefficient δ with H the Heaviside step function and β chosen to heavily penalize solutions very far away from the reference. This reference solution could also be the fastest or slowest solution submitted for scoring or be built out of a quantity related to the distribution of submissions (for example, replacing $\delta t_{ref,m,s}$ with a value two standard deviations above the average solution time). Similar considerations hold for constraint violations and objective function.

Without loss of generality, the final score for each algorithm submitted to the competition is then

$$Score_{final} = \sum_{m,s} Score_{m,s} \qquad [A7]$$

For concreteness, we now show how "straw-man #1" in Section H can be understood as a particular instance of this framework.

Defining $c_{20,m,s}$ as the 20th lowest objective function for a particular model/scenario combination and $c_{1,m,s}$ as the lowest objective function submission (i.e. the "best solution"), let

$$h_{m,s} = -75 * (1 - I_p) + I_p * H\left(\frac{c_{20,m,s} - c_m(s_{m,s})}{c_{20,m,s} - c_{1,m,s}}\right) * \left(1 + 24\ \frac{c_{20,m,s} - c_m(s_{m,s})}{c_{20,m,s} - c_{1,m,s}}\right) \quad [A8]$$

The first term contains an indicator function which indicates if a solution is physical (obeys hard constraints and the power flow equation). The second term adds linearly to a submissions total score from 1 to 25, depending on the objective function value of the top 20 submitted objective functions, assigning a score of zero to all algorithms below these ($H$is again the Heaviside step function).

Next we divide constraints into $i = 1 \ldots k$ hard constraints and $i = k + 1 \ldots l$ soft constraints. We set

$$f_{m,s} = I_p * H\left(\frac{v_{20,m,s} - \sum_{i=k+1}^{l} v_{i,m,s}(s_{m,s})}{v_{20,m,s} - v_{1,m,s}}\right) * \left(1 + 24\ \frac{v_{20,m,s} - \sum_{i=k+1}^{l} v_{i,m,s}(s_{m,s})}{v_{20,m,s} - v_{1,m,s}}\right) \quad [A9]$$

where $v_{20,m,s}$ and $v_{1,m,s}$ are the 20th best and 1st best summed absolute constraint violation, respectively.

Similarly, we, the time-relevant function is defined as

$$g_{m,s} = I_p * \ H\left(\frac{t_{20,m,s} - t_{m,s}}{t_{20,m,s} - t_{1,m,s}}\right)\left(1 + 24\ \frac{t_{20,m,s} - t_{m,s}}{t_{20,m,s} - t_{1,m,s}}\right) \quad [A10]$$

with corresponding definitions for $\boldsymbol{t_{20,m,s}}$ and $\boldsymbol{t_{1,m,s}}$.