CHANGING WHAT'S POSSIBLE

GRID DATA Program Overview

B. PROGRAM OVERVIEW

This program seeks to fund the development of large-scale, realistic, validated, and open-access electric power system network models (transmission and distribution) that have the detail required for the successful development and testing of transformational power system optimization and control algorithms. In conjunction, the program will also fund the creation of an open-access, self-sustaining repository for the storage, annotation, and curation of these power systems models, as well as others generated by the community. These advancements would promise to substantially reduce the barriers to the testing and adoption of new strategies for grid optimization and control, including new Optimal Power Flow (OPF) algorithms. The public availability provided by open-access to these models and the repository is required for more accurate and comprehensive evaluation of emerging grid operation optimization algorithms, including optimization competitions, as have been successfully employed in many other optimization-dependent fields and industries.[1,2,3] These new optimization algorithms promise to 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.

C. BACKGROUND

Since the dawn of the age of electrification, electric power system designers and operators have been required to manage (due to the absence of large-scale cost effective electricity storage) 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. These include tools for determining optimal transmission line and power plant siting and construction, maintenance scheduling, and long-term, day ahead, hour ahead, and five minute electricity dispatch rates.

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. For example, more active optimization and control of electric distribution systems are likely to be required, including the near real-time estimation, optimization, and control of distribution network power flows. The 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. While many new grid optimization methods have been proposed in the research community in recent years, the research community and industry currently lack high-fidelity, public, large-scale power system models for early-stage evaluation and investigation of these new tools. New power system models that realistically describe potential future grid characteristics, including high penetrations of renewable and distributed generation, are also needed to allow for a full assessment of the potential benefits associated with new optimization approaches. The absence of these models is substantially slowing the development and adoption of these new optimization and control strategies by industry.

This section is organized as follows. Section I.C.1 introduces the Optimal Power Flow (OPF) problem, briefly describes the benefits that could be offered by improved OPF algorithms, and introduces some of the new methods that have been recently proposed. Section I.C.2 describes the characteristics and limitations of existing publically available power system R&D models.

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[1] McKinsey & Company, "And the Winner is…Capturing the Promise of Philanthropic Prizes," July 2009, http://mckinseyonsociety.com/capturing-the-promise-of-philanthropic-prizes/

[2] T. Hong, P. Pinson and S. Fan, "Global Energy Forecasting Competition 2012," *International Journal of Forecasting,* vol. 30, no. 2, pp. 357-363, April-June 2014, doi: 10.1016/j.ijforecast.2013.07.001

[3] A. Ostfeld, "The Battle of the Water Sensor Networks (BWSN): A Design Challenge for Engineers and Algorithms," *J. Water Resour. Plann. Manage.,* vol. 134, no. 6, pp. 556-568, November 2008, doi: 10.1061/(ASCE)0733-9496(2008)134:6(556)

1. Opportunities in Grid Optimization

The OPF problem is the central optimization challenge underlying the entire suite of grid planning and operations tools. Simply stated, the OPF problem is that of finding the optimal dispatch settings for power generation, flexible customer demand, energy storage, and grid control equipment that maximize one or more grid objectives.[4,5,6] 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).[7]

Improved OPF algorithms could yield significant benefits. 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).[8, 9] In addition to monetary savings, improved optimization algorithms are likely to help ensure reliable system operations as power flows become more dynamic in the future.[10] To fully realize the potential benefits of 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 (and fundamentally non-linear) 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 cost effective and reliable operation of future renewable-intensive electric power systems is likely to rely more on algorithm outputs and decision support tools and less on operator intuition.

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. Therefore grid operators and OPF vendors 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 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 of solutions before implementation. When non-physical solutions are found, the OPF algorithm must be run again with a modified set of constraints to generate a new solution.

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.[12] 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).[13,14] Improvements in optimization and search methods have evolved similarly, especially those related to Mixed

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

[5] 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

[6] 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 is often focused on minimization of system losses.

[7] 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

[8] 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 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

[9] 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

[10] GE Energy, "Western wind and solar integration study," National Renewable Energy Laboratory, Technical Report No. NREL/SR-550-47434, May 2010, http://www.nrel.gov/docs/fy10osti/47434.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] 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

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

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

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.[15,16] "Cloud computing as a service," which can be used to leverage many of these gains, has also started to gain more widespread interest within the power system engineering community.[17]

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 full AC-OPF may be within sight. 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 (under certain system assumptions and conditions).[18,19,20,21] Often it can be shown that these relaxations give global solutions to the original, non-convex problem.[22,23] Distributed and parallelizable OPF algorithms have also been proposed, for example, using the Alternating Direction Method of Multipliers (ADMM), suggesting that AC-OPF can leverage more advanced computational hardware.[24,25,26] 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. [27,28]

The end-result has been numerous research projects and papers on improved grid optimization strategies and many new algorithms that may be able to significantly impact grid operation and control. However most of these advances have not yet moved past the early research stage. One critical roadblock to their adoption has been the lack of publicly available, large-scale, and high-fidelity power system network models on which to test new solution methods and/or perform valid comparisons. Most recent grid operation optimization advances remain non-validated on realistic, large-scale test models and their operational limits also remain largely unexplored.

2. Existing R&D Power System Models

The value of benchmark systems for the comparison of algorithms for optimizing grid operations has long been recognized.[29] There exist a number of standard power system network models that have been used extensively (mostly for early development of new transmission system optimization algorithms). The transmission power system models currently available comprise a total of 30-40 unique topologies. An illustration of one such topology, corresponding to the

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

[16] 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

[17] 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

[18] 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

[19] 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

[20] 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

[21] 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

[22] 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

[23] 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

[24] 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

[25] 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

[26] 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

[27] X. F. Wang, Y. Song, and M. Irving, *Modern power systems analysis*, New York, NY: Springer Science & Business Media, 2008

[28] 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

[29] P. Wong et al., "The IEEE Reliability Test System-1996. A report prepared by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee," *IEEE Transactions on Power Systems,* vol. 14, no. 3, pp. 1010-1020, August 1999, doi: 10.1109/59.780914

widely used IEEE 118 bus system, is illustrated in Figure 1. These are available from different sources, including a University of Washington test archive, the Edinburgh Test Case Archive, and as part of the popular MATPOWER toolkit.[30,31,32] Similarly, there are a relatively small number of existing distribution system models and several different distribution test case archives.[33,34,35] These benchmark systems were originally created with various goals in mind. For example, some of the systems were developed primarily for teaching purposes. [36] For some of the benchmark models, the data (many of which date back several decades) were designed with the goal of testing simple AC power flows, and were not originally intended for more complicated tasks such as the investigation and/or benchmarking of AC-OPF, unit commitment, optimal transmission line switching, stochastic network planning, load forecasting, distributed energy resource coordination, and other emerging problems of interest to the optimization, grid reliability, and regulatory communities.

Though it is currently accepted practice, there are several problems with using these models to evaluate many of the emerging grid optimization algorithms. First, existing models are, in general, far smaller than the field operating systems that need to be optimized in many modern grid applications and do not generally allow for thorough testing of the

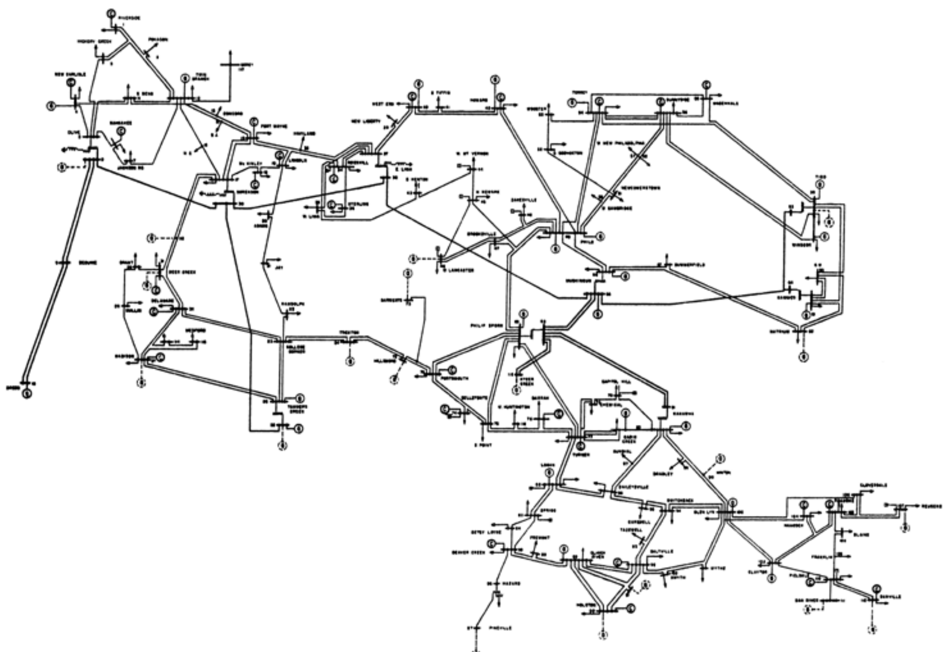

Figure 1: Illustration of the IEEE 118 Bus Test Case representing a portion of the American Electric Power System as of December 1962.

scalability of grid optimization algorithms. Small-scale models also cannot generally be used to estimate the benefits offered by new grid optimization approaches as they neither reflect the scale of real networks, nor the physical coupling existing between different parts of the grid. Most existing transmission system models consist of fewer than 1,000 electrical buses and few generators; the IEEE 118 bus model, for example, only has 19 generators. Modern transmission system algorithms must optimize systems ranging from 5,000 to 50,000 buses, with hundreds to thousands of generators. In recent years, a few new models have gained traction in the research community, including several Polish power system cases that are included within the MATPOWER package and, more recently, a 9,421 bus case that was constructed as

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[30] R. D. Christie (August 1999), *Power Systems Test Case Archive* [Online], Available: http://www.ee.washington.edu/research/pstca/

[31] W. A. Bukhsh and Ken McKinnon (April 2013) *Network data of real transmission networks* [Online], Available: http://www.maths.ed.ac.uk/optenergy/NetworkData/

[32] R.D. Zimmerman, C.E. Murillo- Sánchez, and R.J. Thomas, “MATPOWER: Steady-State Operations, Planning, and Analysis Tools for Power Systems Research and Education,” *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 12 -19, February 2011, doi: 10.1109/TPWRS.2010.2051168

[33] R. Kavasseri and C. Ababei, *REDS: REpository of Distribution Systems* [Online], Available: http://www.dejazzer.com/reds.html

[34] Distribution Test Feeder Working Group, IEEE Power and Energy Society Distribution System Analysis Subcommittee (August 2013), *Distribution Test Feeders* [Online], Available: http://www.ewh.ieee.org/soc/pes/dsacom/testfeeders/index.html

[35] K.P. Schneider et al., “Modern Grid Initiative: Distribution Taxonomy Final Report,” Pacific Northwest National Laboratory, November 2008, http://www.gridlabd.org/models/feeders/taxonomy_of_prototypical_feeders.pdf

[36] R. N. Allan et al., "A reliability test system for educational purposes-basic distribution system data and results," *IEEE Transactions on Power Systems*, vol. 6, no. 2, pp. 813-820, May 1991, doi: 10.1109/59.76730

part of the Pan European Grid Advanced Simulation and State Estimation (PEGASE) project.[37,38] Distribution system models are also lacking; most commonly used test feeders have fewer than 1,000 nodes and have few defined, independent scenarios. While the recently developed IEEE 8,500 node case represents a challenging voltage control case, most existing distribution system network models were not designed to challenge distribution system OPF algorithms.[39]

Existing publically available power system models also generally have few different loading conditions (scenarios) explicitly defined. The changing relative magnitude of electricity demand and/or distributed generation at various system locations is not accurately captured in most models. The small number of scenarios available with most existing models does not adequately address the scale at which industry requires OPF to be solved. As an example, solving an OPF problem on a one hour-ahead timescale requires finding solutions for 8,760 different scenarios ***for a single electrical network every year***. It is also critically important to test the robustness of new OPF solutions and the ability to investigate “corner cases,” such as degenerate operating conditions that result in a large family of equivalent optima. Unfortunately, publicly available power system models typically do not have a sufficient number of scenarios to fully test the robustness of new algorithms.

Existing R&D power systems models are also incomplete. OPF problems must include a minimum set of line thermal limits, generator cost functions, and generator capacity information to be reflective of real-world optimization challenges. As has been pointed out, many of the models in common use today are missing this critical data.[40] For research purposes, this data is often generated artificially and arbitrarily, in ways that poorly represent real, modern transmission systems.[41,42,43] For example, in some models, many line limits are set to large values which never bind and generator cost curves are often assigned identical quadratic functions (introducing an unrealistic amount of symmetry and degeneracy into the problem). It is clear, however, that the way in which these constraints are added can result in substantially different solutions; in particular adding constraints in an unprincipled way can easily lead to infeasibility and lack of convergence. [44]

Many of the available power system models have also been shown to poorly represent real system characteristics. It has been pointed out, for example, that many of the existing IEEE transmission test systems have low base voltages and an overabundance of voltage control capacity compared to modern transmission systems.[45] This can result in AC-OPF solutions that are physically not achievable or undesirable, such as unrealistically large voltage drops across some lines. Existing models also do not capture the full detail and control range of the grid today. Lists of contingencies, emergency (short term) equipment ratings, protection system details, generator ramp rates and real and reactive capability curves, transformer tap settings, capacitor bank locations and settings, phase shifting transformer characteristics, energy storage capacity, line switching capabilities, and flexible demand are more often than not omitted from publically available R&D power system models. Furthermore, most existing models use a bus-branch description that necessarily removes some system details, including, for example, substation circuit breaker topologies. The additional details included in node-breaker models are important for some emerging optimization algorithms such as those involving line switching or distribution system automatic reconfiguration. Security constraints and relative control priorities and costs are particularly poorly described in existing power system models.

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[37] http://www.fp7-pegase.com/

[38] S. Fliscounakis et al., "Contingency ranking with respect to overloads in very large power systems taking into account uncertainty, preventive, and corrective actions," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4909-4917, November 2013, doi: 10.1109/TPWRS.2013.2251015

[39] R.F. Arritt and R.C. Dugan, “The IEEE 8500-node test feeder,” *Proceedings of the 2010 IEEE PES Transmission and Distribution Exposition*, New Orleans, LA, USA, April 2010, pp. 1-6, doi: 10.1109/TDC.2010.5484381

[40] C. Coffrin, D. Gordon, and P. Scott., "Nesta, the NICTA energy system test case archive," *arXiv preprint arXiv:*1411.0359 (2014)

[41] W.A. Bukhsh et al., "Local solutions of the optimal power flow problem," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4780-4788, August 2013, doi: 10.1109/TPWRS.2013.2274577

[42] S. Dutta and S. P. Singh, "Optimal rescheduling of generators for congestion management based on particle swarm optimization," *IEEE Transactions on Power Systems*, vol. 23, no. 4, pp. 1560-1569, November 2008, doi: 10.1109/TPWRS.2008.922647

[43] F. Gubina and B. Strmcnik, "Voltage collapse proximity index determination using voltage phasors approach," *IEEE Transactions on Power Systems*, vol. 10, no. 2, pp. 788-794, May 1995, doi: 10.1109/59.387918

[44] P. A. Lipka, R. P. O’Neill, and S. Oren, "Developing line current magnitude constraints for IEEE test problems," Staff Technical Paper, April 2013, http://www. ferc. gov/industries/electric/indus-act/market-planning/opf-papers/acopf-7-lineconstraints.pdf

[45] R. D. Christie (August 1999), *Power Systems Test Case Archive* [Online], Available: http://www.ee.washington.edu/research/pstca/

As recently discussed,[46] many of the existing publically available power system models and recently proposed approaches to solving OPF problems also do not realistically reflect:

- the distinction between "soft" constraints (which can be violated at a difficult-to-quantify cost) and "hard" constraints, which must never be violated.
- priority levels for different types of control objectives (for example, prioritizing "cost free" controls not captured in the objective function); this is especially important when the full optimization problem is infeasible.
- other engineering-level objectives such as suppressing oscillations and penalizing too frequent control movements.

These control requirements or preferences are central to the design and testing of industrial tools and they often fundamentally impact the core formulation of OPF software. However, existing power system models simply do not provide sufficient information on these requirements. The important evolution of control variables and constraint functions during an OPF solution process (possibly in ways that cannot be formulated analytically) is, of course, very difficult to capture in a model.

Existing publically available power system models appear unrealistically easy to optimize. While the general ACOPF problem is mathematically NP hard,[47] finding near optimal solutions to many of the existing benchmark power system models has proven to be easier than experience with more realistic systems indicates. Fast AC heuristics have found OPF solutions that are <1% from the total cost global minimum for the vast majority of existing publically available power system models.[48] The lack of difficulty is likely to be due to the above factors, i.e. the lack of realism in the existing models. A recent effort to improve some of the most commonly used power system models by performing data mining on public datasets describing generation characteristics (to establish missing generator capacities) and by estimating the distributions of thermal line limits in real world power systems (to establish missing realistic line limits with the models). These modifications significantly increased the difficulty of solving OPF.[49]

Existing models also do not typically have sufficient detail related to emerging trends in power system infrastructure. For example, existing models typically have limited descriptions of solar and/or wind generation resources and do not adequately describe the correlation between generation located at various network locations. Most models also omit large penetrations of distributed generation such as rooftop photovoltaics, fuel cells, or small-scale engines. The development of GridLAB-D has recently provided the research community with new capabilities for the detailed analysis of electric distribution systems, including detailed descriptions of electrical loads in buildings.[50] However, most existing publically available distribution feeder models have limited details on flexible demand control and optimization characteristics. More detailed system models incorporating large penetrations of distributed generation are needed to comprehensively evaluate new, possibly more decentralized models for grid optimization and control.

Given the challenges described above, an obvious solution might be to perform research only on real information on power system networks provided by utility companies. Indeed, ARPA-E has had some recent success required this approach in other power systems optimization-related programs.[51] Demonstrating new algorithms on utility data is critical to gaining commercial traction, however, in these situations, research groups can only report results in aggregate form without detailed information about the power system or their optimization solutions. If new insights are discovered, they cannot be made public in any detailed way. Access to such models also requires non-trivial and lengthy Non-Disclosure Agreement and confidentiality approval processes to address proprietary, security, and privacy concerns. If these issues are surmounted, it is usually a challenge to clean and prepare the model information for simulations; research groups often spend more time cleaning and completing the model (which typically was never intended for early stage applied R&D) than developing and studying their new algorithms. Difficulty in obtaining realistic power system models for open research also substantially increases the barrier to entry for technical experts from other disciplines who have no previous power systems research experience.

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[46] 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

[47] B. Alzalg et al., "A Computational Analysis of the Optimal Power Flow Problem," Institute for Mathematics and Its Applications, University of Minnesota, IMA Preprint Series #2396, May 2012, http://www.ima.umn.edu/preprints/pp2012/2396.pdf

[48] C. Coffrin, D. Gordon, and P. Scott, "Nesta, the NICTA energy system test case archive," *arXiv preprint arXiv*:1411.0359 (2014)

[49] *Ibid.*

[50] http://www.gridlabd.org

[51] ARPA-E "Green Electricity Network Integration (GENI)" Funding Opportunity Announcement Number DE-FOA-0000473, April 2011, https://arpa-e-foa.energy.gov/Default.aspx?Archive=1#FoaId21311ad3-e25b-408d-8429-4c6efdd867a7

The cumulative result of the lack of adequacy of existing publically available power system models is that recently proposed grid operation optimization approaches (including new OPF solution approaches) cannot be tested and verified openly and transparently; the early-stage applied research community has remained "siloed" with extremely limited standard benchmarking or comparison of results, and also largely disconnected from the industrial power systems engineering community. This is a particularly acute issue for researchers from other technical disciplines whose expertise may have value in application to power systems optimization. Given the dynamics, complexity, and uncertainty of emerging power systems, this broader research community could provide transformative opportunities for achieving timely and effective solutions.

D. TECHNICAL PROGRAM OBJECTIVES

ARPA-E seeks to fund innovative ideas for the creation of large-scale, realistic power system models (transmission, distribution, and hybrid models that include both transmission and distribution), validated by real data, and relevant for the testing and evaluation of emerging power system optimization algorithms. The models created under this program must be releasable to the public with no restrictions. Power system network models (section D.1) will be accompanied by a large number of detailed scenarios that represent specific operating points. These scenarios should correspond to the characteristics of the grid today as well as future (i.e. scenarios that reflect different load characteristics or with substantial renewable generation). ARPA-E also seeks to fund the creation of a public power system model repository (section D.2). It is intended that the repository will become a long-term community resource existing well past ARPA-E's initial investment. The models and repository created in this program may be used as the basis for an ARPA-E OPF algorithm competition.

The models to be developed in this program must be able to support the many aspects to efficiently and reliably solving OPF problems, including the design of solution algorithms and the design of the mathematical representation or modeling of the power system to be used by those algorithms. However, the development of new OPF solution methods and the development of solution enhancing modeling approaches are not included in the scope of this FOA. Instead, the goal of this FOA is to create power system models that, as accurately and comprehensively as possible, describe "the world" (both current and future) of one or more representative power systems. New OPF solution methods and/or innovative solution enabling modeling approaches for OPF may be pursued in the future in an ARPA-E OPF algorithm competition.

1. Power System Model Creation

ARPA-E seeks applications to create three different types of models and associated scenarios in this program: transmission system models, distribution system models, and hybrid power system models that include detailed representations of both transmission and distribution networks with associated generation and load details. Throughout this FOA we refer to the physical description of a power system and limits of control equipment available (including generators, loads, capacitor banks, LTC taps, etc.) as a "power system model." Variable input data defining each snapshot in time for that model (defining instantaneous power demand, renewable generation, generator and line availability, etc.) is referred to as a "scenario."

Power system models created within this program should include a clear, detailed description of the suitability of proposed models for addressing the grid objectives defined in Section I.C and evaluating algorithms seeking to solve one or more specified OPF problems. The objective and required information for the selected OPF problem(s) must be comprehensively described. Applicants must clearly describe the extent to which improved OPF algorithms for the selected OPF problem would address ARPA-E's mission areas.

Models should correspond to today's grid and provide for assessment of OPF algorithms with future possible infrastructures as anticipated by current projections. For example, models should include significant renewable penetration and/or increased demand-side flexibility and control, with the ability to modify the amount and configuration of those new resources in reasonable ways. The models should be designed in a way that allows users to introduce independent variables (e.g. #, type, location of electricity storage facilities) and determine the dependent changes in system efficiency, reliability, etc. However, the models should also explicitly define a baseline system configuration that can be used without further modification to evaluate new OPF algorithms.

Finally all models must include hypothetical GPS coordinates for major components of their systems. Applicants may also consider adding hypothetical:

- details on system geography (coasts, rivers, mountains, etc.)
- demographic information related to population and load centers (including divisions into commercial and residential electricity consumption)
- correlation of environmental variables with traditional and renewable generation resources.

In models that include hypothetical geographic information, the physical location of power system infrastructure (lines, generators, energy storage, etc.) should reasonably correspond with geographic features.

A. Electric Transmission System Models

Transmission system models created within this program must include a clear, detailed description of all system attributes relevant to calculating system power flows and solving one or more specific bulk power system, security constrained OPF problems. Transmission system models must include, at minimum:

- transmission system network topology
- detailed generator characteristics and limits (including economic details such as heat rate and start-up/shut-down costs)
- thermal line ratings and lengths
- voltage limits on all equipment and at all buses
- detailed transformer specifications (including LTC positions)
- details on reactive power sources/sinks
- critical contingency lists (including multi-element contingencies)
- descriptions of local (automated) control schemes
- energy storage equipment details
- renewable generation capacity and characteristics.

In addition, Applicants may also consider including

- detailed generator and load dynamic characteristics in order to allow for comprehensive stability evaluations of OPF solutions (or to enable the evaluation of future OPF solution methodologies that explicitly include consideration of system stability)
- individual contingencies that explicitly test voltage and/or transient stability
- contingencies that can result in inter-area oscillations
- protection system details, including Remedial Action Schemes or Special Protection Systems
- environmental details such as generator emissions characteristics or water use
- forecasts for fuel costs, renewable generation, loads, and/or other uncertain phenomena.

B. Electric Distribution System Models

Electricity distribution system models created in this program will need to include many of the same details as required for transmission network models. However, in contrast to transmission networks, distribution systems are inherently unbalanced and therefore, require more detailed individual phase descriptions. The application of OPF in distribution systems also often has different objectives. As distributed energy resources (including photovoltaic generation) proliferate, dynamic phenomena such as rapidly varying voltage magnitudes are likely to play a role of growing importance in the operation of distribution systems. Therefore, all distribution models created in this program must include sufficient detail necessary to optimize distribution system operation subject to rapid resource changes (though, the primary focus may remain on steady state optimization and not dynamic control). Distribution models that include a very large number of customers (> 1 million customers) would also be particularly valuable to evaluate the full potential of meshed distribution systems or distribution systems that can be routinely reconfigured.

Distribution models created in this program must include, at minimum:

- detailed three phase topology for multiple distribution feeders originating from one or more substations
- feeder connected equipment descriptions (including transformer characteristics and any reactive power sources/sinks)

- detailed electricity load characteristics (including a variety of load in appropriate proportions)
- sufficient detail to optimize distribution system operations subject to rapidly changing distribution generation.

C. Hybrid Transmission/Distribution Models

Realizing the full range of benefits offered by growing penetrations of distribution generation may also require more complete studies of the interactions between transmission and distribution systems. Therefore, in addition to improved transmission and distribution models described above, there is a critical need for hybrid transmission/distribution models that contain all of the above details and also represent the coupling between systems in a realistic way. In order to be most useful, hybrid models must meet the requirements for both transmission and distribution systems.

The development of hierarchical power system models would be attractive. Hierarchical modeling has been used extensively in other disciplines such as electrical circuit simulation. Hierarchical models can function with a high level behavioral description of a part of the network when detailed information is not required for a particular type of analysis. Switching between high-level behavioral views and detailed representations can allow much faster simulation, while preserving the details in the part of the network, where detailed solutions are desired.

2. Power System Scenario Creation

Applicants must also plan to deliver a large number of scenarios or specific operating points for each infrastructure model. These must include:

- the magnitude of real and reactive power demand (or other parameters that define electricity demand characteristics) at each bus
- information on temporary equipment unavailability (generators, lines, transformers, etc.)
- details regarding instantaneous variable power generation capabilities (i.e. solar and wind generation potential)

and any other variables that change over time.

Scenario sets should be designed with temporal resolutions and time coupling suitable for solving one or more specific OPF problems (for example, solving one day-ahead unit commitment problems would require at least 1-hour resolution whereas 5-minute economic dispatch problems would require scenarios with at least 5-minute resolution). Models created for the analysis of electric distribution systems often feature time resolutions of at least 1-minute. Scenario sets with shorter time resolutions will be preferred (as long as there is no loss in scenario or model fidelity).

Scenarios may also include:

- fuel costs
- instantaneous demand response capacity available
- probabilistic information (such as provided probability distribution functions or lists of forecasted vs. actual values) for renewable generation and/or power consumption for future periods.

It is important for power systems network models to represent a range of difficulty to OPF optimization algorithms. Applicants must confirm that the majority of scenarios are AC-OPF feasible. However, an important feature of some OPF algorithms is the explicit identification of system infeasibility. Therefore, it will also be valuable to generate some scenarios that are confirmed to be infeasible. For example, there should be at least some scenarios where a major generator is unavailable and/or there is unusual congestion. The scenarios should also probe a range of operating conditions including realistic peak/minimum load conditions as well as peak/minimum renewable generation and combinations thereof. Applicants should describe their plan for generating and testing scenarios of varying difficulty.

3. Possible Approaches to Model and Scenario Creation

There are two possible tracks for model and scenario creation (though a hybrid of these tracks is also possible). The first option is for Applicants to partner with an ISO or utility and use actual data to generate new models. Due to the obvious concerns regarding both the proprietary nature of some data and critical infrastructure security concerns, this approach to model creation would necessarily involve careful anonymization (for example topology perturbation, randomization/obfuscation of edge and generator details, etc.). Indeed, this method has been used successfully in the past for public distribution system model development.[52] Applicants wishing to pursue this track must clearly and comprehensively describe their technical approach to anonymization. Applicants must describe in detail the process for utility review and release and should include letters of support acknowledging the certain future public release of the models created in the program. Risk mitigation plans for likely, possible, and unforeseen barriers in this process should also be described in detail. This aspect of the proposed work is critical.

A second possible method for high fidelity model creation is to construct purely synthetic power system models. There are a number of routes Applicants might pursue to keep models highly reflective of real power networks. One option would be to derive these from power system expert input, or other, auxiliary datasets known to correlate to power networks (such as roadway maps). Applicants might also construct a set of new random graph models, similar to those that have been developed for social and informatics networks, relevant to transmission and/or distribution systems.[53] These synthetic models might be developed by constructing new ensembles or using a set of ensembles already in the literature (for example, Exponential Random Graph Models), with sufficient statistics chosen specifically for transmission or distribution networks. [54] The parameters of this model might be set by mining existing public power system models, extracting parameters from related auxiliary datasets (for example EIA data for generator characteristics, real estate and census data for electricity load estimation, satellite photos for infrastructure information, etc.), or by using features from real data in collaboration with an ISO or utility company.

Methods for scenario creation are likely to share many similarities to those for model creation. Data defining specific scenarios can be created using engineering judgment or may be based on historical data. For example, information on equipment availability should correlate to established failure rates for each specific type of equipment (if known). Historical data, such as weather-related information can also be used to help define specific scenarios. Applicants may also propose to collect new measurements on system characteristics or performance.

Applicants are also encouraged to build or adapt model conversion tools to convert the new models developed in this program to and from commonly used formats for existing commercial and open source simulation tools. Tools to extract model details for specific types of analysis would also be valuable.

4. Power System Model Validation

Ultimately, the value of the new models created under this program will be determined by the extent to which they are sufficiently representative of one or more real-world power systems. In particular, new power system network models should reflect the characteristics of one or more actual utility systems. Network models should reflect heterogeneity in network density corresponding to different population densities as well as the appropriate level of mismatch between the location of generation and major population centers (especially, for example, large-scale renewable generation). Applications may also include explicit recognition of the existence of multiple balancing authorities and/or the existence of loosely connected (asynchronous) interconnections. Finally, network models should have a realistic distribution of system voltages and an appropriate mix between ac and dc transmission lines.

Model validation will be an essential component of all projects in this program. Specific approaches to validation are expected to be unique to each model creation method; Applicants must describe their specific approach to carefully validating new power system models and must provide specific quantitative validation criteria and targets in their applications. This validation will be critically important to ensuring that the research community quickly and widely adopts the new models. Model validation approaches may include (but are not limited to) one or a combination of the following:

- Statistical comparison (for example degree distributions, clustering, etc.) and/or goodness of fit testing against real power systems and/or auxiliary datasets
- Detailed validation from industry stakeholders including utility and/or ISO staff
- An evaluation of the performance of OPF algorithms on the new model compared to the same on real-world systems (obtained under NDA)

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[52] K.P. Schneider et al., "Modern Grid Initiative: Distribution Taxonomy Final Report," Pacific Northwest National Laboratory, November 2008, http://www.gridlabd.org/models/feeders/taxonomy_of_prototypical_feeders.pdf

[53] M. E. J. Newman, "The structure and function of complex networks," *Society for Industrial and Applied Mathematics (SIAM) Review*, vol. 45, no. 2, pp. 167-256, May 2003, doi: 10.1137/S003614450342480

[54] G. Robins et al., "An introduction to exponential random graph (p*) models for social networks," *Social Networks*, vol. 29, no. 2, pp. 173-191, March 2007, doi: 10.1016/j.socnet.2006.08.002

- Validation of system frequency response after a simulated disturbance and/or characterization of system oscillatory modes (for those models that include detailed dynamic data).

Applications will be judged on level of detail to be included in the proposed network models, the strength of proposed validation approaches, and the ability of the models to test the limitations of existing and emerging OPF algorithms.

5. Power System Model Repository Creation

The establishment of the large global open source software development community over the past 20 years have enabled, for the first time, highly productive, widely distributed, technical collaboration involving thousands or millions of individual users.[55] In addition to formal technical collaboration sites, crowd-sourced information and review websites allow users to provide detailed comments and reviews on everything from local businesses to the latest electronic gadgets. ARPA-E believes such resources could be leveraged to substantially strengthen the power system optimization research community given the development of a large-scale power system network model repository. This is likely to become even more important as the scale and level of detail contained in power system models increase.

ARPA-E seeks to fund the development of a public, interactive, high-fidelity, power system model repository that supports additional collaborative power system model creation in the future. As described above, public archiving of network models suitable for OPF optimization algorithm development and testing is currently limited almost entirely to the University of Washington's Power Systems Test Case Archive and the MATPOWER MATLAB package, which store versions of the commonly used IEEE test-sets and several other systems.[56,57] These archives are "what you see is what you get" in nature and do not include the ability for researchers to easily contribute and share new models. (Applicants who modify the archived power systems have few options for distributing their modified test systems to the broader community).

A repository designed specifically to allow the power system engineering technical community to collaboratively build, refine, and review various types of power system models could accelerate the pace of grid optimization algorithm development. An example is recent success with a model repository and simulation platform known as the "Open Model Framework"[58] developed by the National Rural Electric Cooperative Association (NRECA) for cooperative utilities. While there are many forms that the repository could take, it should serve initially as a central location where the research community can both contribute and download power system models for a wide range of analysis. Users should have the ability to provide detailed reviews on individual models. These reviews could assess different attributes of models (for example, completeness, relative difficulty, and/or realism). Version control is often a critical feature in online technical collaboration tools. In this context, individual users should have the ability to submit modified versions of existing models (with explicit recognition of the relationship between different models), allowing the models to evolve continuously as the most important power system challenges and opportunities evolve over time. To be most effective, the repository must be designed to allow specific model versions to be referenced in technical publications. The use of a unique identifier would also, of course, facilitate collaborations between research groups in different locations (who might not be able to easily exchange larger, more detailed models). The ability for the repository to hold multiple versions of models in different file formats would also be valuable, as would the ability for the repository to have the capability to convert models from one format to another or to/from a standard format that could be used to represent all models. The repository should be fully compatible with network models for a range of different types of analysis and control and optimization algorithm design. Further, in the future, it would be valuable for the repository to validate the interoperability of different models (for example detailed models for specific types of equipment). The capability for the repository to validate model formats would be particularly valuable if hierarchical modeling frameworks are used. The repository would likely be used to provide access to the power system models used in ARPA-E's envisioned OPF competition.

The most valuable repository would be one that is self-funded or maintained well after ARPA-E's development funding ends. Applications must describe a plan for self-funding maintenance and curation of the repository past the initial period of ARPA-E funding. This plan should detail annual cost and delineate specific and reliable funding sources and cash flows

[55] https://github.com/about/press, Accessed May 2015.

[56] R. D. Christie (August 1999), *Power Systems Test Case Archive* [Online], Available: http://www.ee.washington.edu/research/pstca/

[57] R.D. Zimmerman, C.E. Murillo- Sánchez, and R.J. Thomas, "MATPOWER: Steady-State Operations, Planning, and Analysis Tools for Power Systems Research and Education," *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 12 -19, February 2011, doi: 10.1109/TPWRS.2010.2051168

[58] http://www.nreca.coop/what-we-do/bts/smart-grid-demonstration-project/open-modeling-framework/

(with detailed letters of support from any relevant agencies, companies, or universities). Once again, this aspect of the application is critically important; without a detailed, specific and realistic plan for sustenance beyond ARPA-E's initial funding, applications will be judged as non-responsive.

E. POWER SYSTEM MODEL & REPOSITORY TECHNICAL REQUIREMENTS

ARPA-E intends to fund projects in two separate categories, power systems models and power systems model repositories. Applicants may apply to one or both categories.

1. Category I: Power System Network Model and Scenario Creation

Applicants seeking to build new power system network models ("system models") and sets of scenarios must address all technical specifications in Tables 1 and 2.

NOTE: System models developed by GRID DATA awardees shall not contain or constitute Critical Energy Infrastructure Information (CEII).[59] **Award terms will require certification that such models do not contain or constitute CEII.**

TABLE 1: POWER SYSTEM MODEL TECHNICAL SPECIFICATIONS

ID	TITLE	TECHNICAL SPECIFICATION
1.1	Problem Specification	System models created within this program must include a clear, detailed description of the suitability of proposed models for addressing the grid objectives defined in the introduction to Section I.C and evaluating algorithms seeking to solve one or more specified OPF problems. The objective and required information for the selected OPF problem(s) must be comprehensively described. Applicants must clearly describe the extent to which improved OPF algorithms for the selected OPF problem would address ARPA-E's mission areas.
1.2	Power System Model Creation Method	Any method(s) may be used to create test systems (using real-world data or purely synthetic approaches). Preference will be given to Applicants proposing to create test systems based on one or more real world transmission or distribution networks in collaboration with utilities, ISOs, or existing industry vendors.
1.3	Power System Model Scale	All Applicants must plan to create models at multiple scales, and may choose to address (i) a transmission/bulk power system, (ii) a distribution system, or (iii) a hybrid transmission and distribution system. The application should clearly indicate which type is of system is addressed. Applicants who choose to create electric transmission system network models must plan to create at least one small network model having between 50 and 250 electrical buses (for initial OPF algorithm development) and at least one large network model having > 5,000 buses. Larger test systems may not consist of repeated duplicates of smaller systems. Applicants are encouraged to include the design, validation, and release of smaller scale models early in the project to allow for immediate, early feedback from the broader research community.

[59] See 18 C.F.R. § 388.113(c)(1). The term "CEII" means "specific engineering, vulnerability, or detailed design information about proposed or existing critical infrastructure that:

(i) Relates details about the production, generation, transportation, transmission, or distribution of energy;
(ii) Could be useful to a person in planning an attack on critical infrastructure;
(iii) Is exempt from mandatory disclosure under the Freedom of Information Act,5 U.S.C. Part 552; and
(iv) Does not simply give the general location of the critical infrastructure."

		Applicants who choose to create electric distribution system models must create at least one model with at least 3 independent feeders originating at one or more substations, corresponding to a minimum of at least 5,000 individual customers.
1.4	Power System Model File Format	Applicants may select any existing file format for new power system network models. To the greatest extent possible, Applicants are encouraged to use existing commonly used power system model formats, such as those associated with common commercial power flow tools and/or the IEEE common data format.[60,61] Unfortunately, many of these existing formats have limited flexibility and/or are limited to static data (i.e. not time-based information). ARPA-E expects that new formats may need to be developed (or extended from emerging ones such as the utility Common Information Model or the recently proposed utility Open Data Model) to include the required system information such as generator dynamic characteristics, market data, descriptions of the limits of power flow controllers, and/or to define the characteristics of local control schemes. [62] Many of these specific details are rarely available in existing OPF-focused power system network models. Applicants may utilize either a bus-branch or a breaker-node system representation of power systems. Applicants are encouraged to develop equivalent versions for all test systems (with consistent naming conventions) in both formats. The availability of a more detailed breaker-node representation could be particularly useful for emerging grid optimization strategies such as those that employ line switching. Applicants who choose to develop a data standard for OPF-compatible power system models should describe in detail how they intend to design the new format. ARPA-E expects Applicants to have an explicit plan for soliciting detailed input on any new data formats from other projects in the GRID DATA program, the power engineering community at-large, and other related technical fields (such as mathematics, computer science, or operations research). Those Applicants who anticipate creating new model formats should also plan to create model conversion tools to convert models into more common formats (to the greatest extent possible). Tools to extract model details for specific types of analysis would also be valuable.
1.5	Power System Model Details	Transmission system models created within this program must include a detailed description of all system attributes relevant to calculating system power flows and solving one or more specific bulk power system, security constrained OPF problems. Transmission system models must include, at minimum: ▪ transmission system network topology ▪ detailed generator characteristics and limits (including economic details such as heat rate and start-up/shut-down costs) ▪ thermal line ratings and lengths ▪ voltage limits on all equipment and at all buses ▪ detailed transformer specifications (including LTC positions) ▪ details on reactive power sources/sinks ▪ critical contingency lists (including multi-element contingencies) ▪ descriptions of local (automated) control schemes ▪ energy storage equipment details ▪ renewable generation capacity and characteristics. In addition, Applicants may also consider including:

[60] http://w3.usa.siemens.com/smartgrid/us/en/transmission-grid/products/grid-analysis-tools/transmission-system-planning/pages/psserawdataformat.aspx
[61] IEEE Working Group. "Common data format for the exchange of solved load flow data." Trans. Power App. Syst 92.6 (1973): 1916-1925.
[62] http://community.interpss.org/Home/ieee-pes-oss

		▪ detailed generator and load dynamic characteristics in order to allow for comprehensive stability evaluations of OPF solutions (or to enable the evaluation of future OPF solution methodologies that explicitly include consideration of system stability) ▪ individual contingencies that explicitly test voltage and/or transient stability ▪ contingencies that can result in inter-area oscillations ▪ protection system details, including Remedial Action Schemes or Special Protection Systems ▪ environmental details such as generator emissions characteristics or water use ▪ environmental details such as generator emissions characteristics or water use ▪ forecasts for fuel costs, renewable generation, loads, and/or other uncertain phenomena. Electricity distribution system models created in this program must include many of the same details as required for transmission network models. This must include, at a minimum: ▪ detailed three phase topology for multiple distribution feeders originating from one or more substations ▪ feeder connected equipment descriptions (including transformer characteristics and any reactive power sources/sinks) ▪ detailed electricity load characteristics (including a variety of load in appropriate proportions) ▪ sufficient detail to optimize distribution system operations subject to rapidly changing distribution generation. Models should correspond to today's grid and allow introduction of variable future possible infrastructures as indicated by current projections. For example, models with significant renewable penetration or increased demand-side flexibility and control should be included, with opportunity to vary the amount and distribution of each. Hybrid transmission/distribution models should contain all of the above details and also represent the coupling between systems in a realistic way. Finally all models must include hypothetical GPS coordinates for major components of their systems. Applicants may also consider adding hypothetical: ▪ details on system geography (coasts, rivers, mountains, etc.) ▪ demographic information related to population and load centers (including divisions into commercial and residential electricity consumption) ▪ correlation of environmental variables with traditional and renewable generation resources. In models that include hypothetical geographic information, the physical location of power system infrastructure (lines, generators, energy storage, etc.) should reasonably correspond with geographic features.
1.6	Power System Model Validation	Applicants must include a detailed plan for validation with technical success/fail criteria to ensure models are sufficiently representative of one or more real-world power systems.
1.7	Documentation and Public Access Requirement	Applicants are required to generate detailed, user-friendly documentation for all new power system models. This documentation must describe general power system characteristics while also providing details on the precise format and/or any naming conventions that are used. The documentation must specify units for all numerical quantities described in each model. Applications must include a Data Management Plan for making the models publicly available without restriction, which plan must include addressing intellectual property issues. The award for successful applications will include contract provisions

		implementing the proposed plan. For those Applicants proposing to use real-world data, all protected, proprietary, and/or security sensitive details must be removed prior to release. Final models must not contain any Critical Energy Infrastructure Information (CEII) and awardees must certify that models do not contain or constitute CEII before any public release.[63] In cases where real world network model data is provided by a grid operator or utility, Applicants must have an established plan and timeline for the review, approval, and certification of models prior to public release. Risk mitigation plans for likely, possible, and unforeseen barriers in this process must also be described in detail.

TABLE 2: SCENARIO TECHNICAL SPECIFICATIONS

ID	TITLE	TECHNICAL SPECIFICATION
2.1	Problem Specification and Minimum Number of Scenarios	Scenario sets must be designed with temporal resolutions and time-coupling suitable for solving one or more specific OPF problems. Applicants must clearly describe the problem(s) they anticipate addressing with their scenario sets and how improved OPF algorithms for the selected OPF problem would address ARPA-E's mission areas. This description must describe the OPF problem objective and the minimum information that must be included in the power system scenarios. Applicants must develop at minimum a full year of time-coupled physically feasible scenarios with at least hourly granularity. (i.e. Applicants must develop at least 8,760 individual scenarios with each snapshot corresponding to a single snapshot in time.). Applicants are strongly encouraged to propose using the shortest feasible time step between scenarios (5 minutes, 15 minutes, etc.). Scenario sets with shorter time resolutions will be preferred (as long as there is no loss in scenario or model fidelity). Applicants may also wish to design particularly difficult scenarios for single period OPF studies. Therefore, not all scenarios are required to be part of a time-coupled set. Applicants are also encouraged to design infeasible scenarios to test the ability for OPF algorithms to identify infeasibility quickly.
2.2	Scenario Creation Method	Any method(s) may be used to create power system scenarios (using real-world data or purely synthetic approaches). Data defining specific scenarios can be created using engineering judgment or may be based on historical data. Historical data, such as weather-related information can also be used to help define specific scenarios. Applicants may also propose to collect new measurements on system characteristics or performance.
2.3	Scenario Details	Scenarios must include all of the time-dependent operating characteristics required to fully evaluate new OPF algorithms. At minimum, scenarios must include: • the magnitude of real and reactive power demand (or other parameters that define electricity demand characteristics) at each bus • information on temporary equipment unavailability (generators, lines, transformers, etc.) • details regarding instantaneous variable power generation capabilities (i.e. solar and wind generation potential) and any other variables that change over time.

[63] http://www.ferc.gov/legal/ceii-foia/ceii.asp

		These scenarios should be designed with temporal resolutions and time coupling suitable for solving one or more specific OPF problems (for example, solving one day-ahead unit commitment problems would require at least 1-hour resolution whereas 5-minute economic dispatch problems would require scenarios with at least 5-minute resolution). Models created for the analysis of electric distribution systems often feature time resolutions of at least 1-minute. Scenario sets with shorter time resolutions will be preferred (as long as there is no loss in scenario or model fidelity). Scenarios may also include: ▪ fuel costs ▪ instantaneous demand response capacity available ▪ probabilistic information (such as probability distribution functions or lists of forecasted vs. actual quantities) for fuel costs, renewable generation, and electricity demand for future periods. It is important for power systems network models to represent a range of difficulty to OPF optimization algorithms. Applicants must confirm that the majority of scenarios are AC-OPF feasible. It will also be valuable to generate some scenarios that are confirmed to be infeasible. For example, there should be at least some scenarios where a major generator is unavailable and/or there is unusual congestion. The scenarios should also probe a range of operating conditions including realistic peak/minimum load conditions as well as peak/minimum renewable generation and combinations thereof. Applicants should describe their plan for generating and testing scenarios of varying difficulty.
2.4	Scenario Validation	Applicants must include a detailed plan for validation with technical success/fail criteria to ensure scenarios are sufficiently representative of a range of real-world power system operating conditions.

2. *Category II: Repository Creation*

Applicants seeking to establish a repository must address all technical specifications in Table 3.

NOTE: System models available through the repository must be open-access to the public and shall not contain or constitute Critical Energy Infrastructure Information (CEII). Prior to uploading system models in the repository, system model submitters must certify that models do not contain or constitute CEII.

TABLE 3: REPOSITORY TECHNICAL SPECIFICATIONS

ID	TITLE	TECHNICAL SPECIFICATION
3.1	Open access	The repository and portal must be completely open (including international access), giving researchers the ability to upload modified versions of existing models and designate relationships between different models (i.e. version control) as well as provide annotation and/or comments on specific models (similar to, for example, GitHub).
3.2	Flexibility	The repository should be able to accommodate different kinds of power system models (not just ones suitable for OPF control and optimization). For example, it should be flexible enough for planning cases and/or models specifically designed to study system dynamics and stability. The initial (beta form) for the repository must include a variety of existing power system models that are already in the public domain, including the standard IEEE power system models for OPF studies.

3.3	Scalability	The repository should have the ability to scale the repository to archive an arbitrary number of power system models within the proposed budget.
3.4	Self Sustainability	Applicants should propose a self-funding model that extends well beyond ARPA-E's development funding. The project should also include the establishment of a set of standards for models and a clear self-governance model for the portal. The Applicant should have a plan for increasing awareness and use of the repository throughout its operations.
3.5	Curation	The proposed work should include a plan for active curation of power system models, during and after ARPA-E's development funding. This should include standards for nomination of curators (either by the team in charge of the portal or the community at-large). Applicants should make clear the specific role of curators; these should include, at a minimum: the ability to annotate models, define new types of models, organize existing models, evolve existing standards for models and delete models which do not meet current standards. Applications must address intellectual property issues and acknowledge that if the repository is not maintained to the satisfaction of ARPA-E after a period of time the repository may be transferred to the Government or a party designated by the Government. The Government will also be afforded the right to create an additional repository with all publicly available models. For the repository, Applicants should include in their plan trademark protection of the identifier of the repository and possibly, the models and for managing the trademark(s) during the duration of the repository. The trademark(s) ownership would transfer with the management of the repository. The award for successful applications will include contract provisions requiring implementation of the proposed plan.

ARPA-E will not consider selecting projects for award that do not clearly demonstrate realistic, well-justified potential to meet or exceed the required technical targets.