Proceedings of the American Society for Engineering Management 2014 International Annual Conference
S. Long, E-H. Ng, and C. Downing eds.

DECISION-MAKING FOR LARGE-SCALE COLLABORATIVE POWER SYSTEMS

Bryony DuPont, Joseph Piacenza, Ridwan Azam, John Wardman, Chris Hoyle, Eduardo Cotilla-Sanchez
Oregon State University
204 Rogers Hall, Corvallis, OR, USA 97331

Danylo Oryshchyn, Steve Bossart
National Energy Technology Laboratory
P.O. Box 880
Morgantown, WV, USA 26507

Abstract
As demand for electricity in the United States continues to increase, it is necessary to explore the means through which the modern power supply system can accommodate both increasing affluence (which is accompanied by increased per-capita consumption) and the continually growing global population. Though there has been a great deal of research into the theoretical optimization of large-scale power systems, research into the use of an existing power system as a foundation for this growth has yet to be fully explored. Current successful and robust power generation systems that have significant renewable energy penetration - despite not having been optimized a priori - can be used to inform the advancement of modern power systems to accommodate the increasing demand for electricity. Leveraging ongoing research projects at Oregon State University and the National Energy Technology Laboratory, this work explores how an accurate and state-of-the-art computational model of the Oregon/Washington (OR/WA) energy system can be employed as part of an overarching power systems optimization scheme that looks to inform the decision making process for next generation power supply systems. A preliminary research scenario that explores an introductory multi-objective power flow analysis for the OR/WA grid will be shown, along with a discussion of the long-term research goals of the project.

Keywords
Power Systems Optimization, Security-Constrained Optimal Power Flow, Collaborative Power Systems

Introduction
The electric power infrastructure of the United States and many parts of the world is at the early stages of an unparalleled transformation to modern intelligent power systems. At the heart of the modern power system are advanced sensors, communications, and controls that manage the increasingly complex array of power generation, energy storage, and load assets. Power industry researchers and stakeholders are just beginning to observe major shifts toward more renewable energy, distributed generation, energy storage, demand response programs, electric vehicles, synchrophasors on the transmission system, and flexible fossil energy power plants. One of the greatest challenges of moving toward a modern power system is to optimize the integration and operation of existing grid assets with these new technologies. Each region is unique in regards to its existing grid assets and demand, but also in regards to its vision of a modern power system that will serve its future needs. This vision is guided by many factors including state and local policy, access to different types of generation, estimates of future power demand, and economic outlook. The modern power system must consider and balance the cost, reliability, and environmental impact.

Planners of future modern power systems need powerful tools to help them manifest their vision. Working toward the goal of an optimized design and roadmap to create modern power systems, this paper describes recent work that creates the foundation for a large-scale power systems optimization algorithm that can be applied to any region and make use of existing electric power infrastructure. We present a preliminary instance of this algorithm using the Oregon/Washington (OR/WA) power grid to model power flow and reliability.

A primary objective of power grid optimization is maintaining system reliability while considering various generation sources, transmission infrastructure, and demand populations. Understanding subsystem relationships creates a challenge for researchers to create computer simulation models that effectively capture significant interactions between these sub networks. Examining and modeling system failure due to cascading faults is an area of research intended to predict the probability and magnitude of outages across regions (Hines, 2007). Talukdar et al. have focused on power grid failure predictions addressing partial functionality of a grid after a failure event, instead of attempting to find a solution for prevention (Talukdar, Apt, Ilic, Lave, & Morgan, 2003). This methodology addresses system uncertainty from dynamic periods of change due to intended switching operations designed to bring systems back online. Fairley comments on this methodology, supporting the premise that failure is a byproduct of such a large complex system and research in mathematical modeling for failure management, instead of elimination, should be a primary strategy for increased reliability (Fairley, 2004).

Several accepted solutions have been developed to respond to power grid failure such as the Flexible AC Transmission System (FACTS) (Hingorani, 1988). This technology enables the control of power flow on Alternating Current (ac) transmission lines to optimize loading (Asare, Diez, Galli, O'Neill-Carillo, & Robertson, 1994). Lininger et al. incorporated the FACTS device into a computer simulation using a Maximum Flow algorithm to detect failure types in various outage scenarios (Lininger, McMillin, Crow, & Chowdhury, 2007). Similar research led to a computer model to replicate power outages due to line outages or losses due to excessive load limits (Carreras, Lynch, Dobson, & Newman, 2002). Pinar et al. have also addressed power grid vulnerability by outlining optimization strategies for power line failure prevention (Pinar, Meza, Donde, & Lesieutre, 2010). Pahwa et al. have examined system failure modes by simulating a power grid within a standard network such as the IEEE 300 bus to examine cascading system failures (Pahwa, Hodges, Scoglio, & Wood, 2010). Mitigation strategies to reduce failures include targeted range-based load reductions and intentional islanding. Mavris and Griendling have created a Relational-Oriented Systems Engineering and Technology Tradeoff Analysis (ROSETTA) tool that explores trade-offs between Quality Function Deployment, modeling and simulation, and theoretical mathematics to manage power demand response (Mavris & Griendling, 2011; ReVelle, Moran, & Cox, 1996). This is a key issue with renewable resources such as solar, hydro, and wind as environmental conditions can fluctuate, causing variable power output (U.S. Department of Energy, 2010).

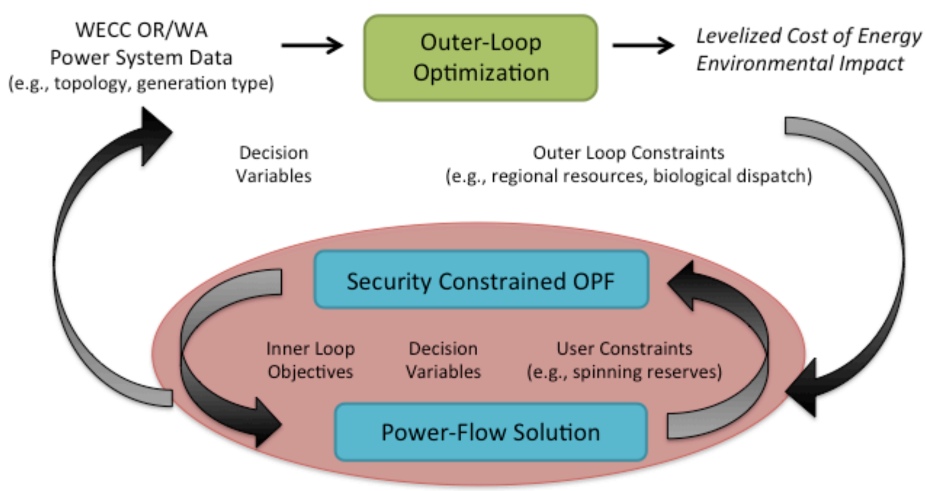
In order to accurately simulate conditions in a given power system, physics-based computation techniques must be utilized. MATPOWER is an analysis toolbox designed to operate within the MATLAB computing environment, which is widely used in the power systems engineering community (The Mathworks Inc., 2011; Zimmerman, Murillo-Sanchez, & Thomas, 2011). MATPOWER is a package designed for solving power flow and optimal power flow problems. The power flow problem is a numerical analysis of a power system in steady-state conditions using voltage magnitudes and phase angles at each bus. The input data consist of Ybus data, generator limits, and transmission line data. The outputs of these calculations are the active and reactive power injections at each bus. Optimizing generation while enforcing transmission line limits requires the use of linear programming with the power flow data. This is known as the optimal power flow (Glover, Sarma, & Overbye, 2012). Additional information such as generation costs will provide the user with the lowest cost per kilowatt-hour delivered.

The dc power flow approximation is a linear and simplified version of an ac power flow. A dc power flow looks purely at active power flows, neglecting transmission losses, voltage support, and reactive power management. As we are only interested in active power, we will be focusing on dc optimal power flow (dc-OPF). The dc-OPF solver in MATPOWER takes in linear constraints and quadratic cost functions. In this case, the voltage magnitude and reactive power are eliminated from the problem completely, and real power flow is modeled as a linear function of the voltage angles (Zimmerman et al., 2011). MATPOWER will then output total generator costs and active power limits.

Methodology

In this work, a preliminary exploration of a single stage of a two-stage optimization framework designed to better understand varying objectives of large scale power systems will be shown. Potential trade-offs include performance metrics such as cost and environmental impact based on the present-day OR/WA power system configuration. The framework proposed here consists of an inner (i.e., power flow) and outer (i.e., system-level) loop optimization process to estimate system performance (Exhibit 1). While discussion of both optimization schemes is included, this paper will primarily focus on the initial inner loop optimization formulation and test cases.

Exhibit 1. Two-Stage Optimization Framework.



Outer-Loop Optimization Model

The outer-loop optimization contains overarching performance objectives directly relating to both system requirements (e.g., predicted demand) and designer preferences (e.g., use of renewables). Currently, the outer loop optimization model's focus is to optimize system performance based on the existing available power generation sources in Oregon and Washington. However, multiple objectives - such as the reduction of environmental impact - must also be captured in the model. Using multi-objective optimization, design trade offs can be explored between cost and environmental impact. A theoretical formulation for the multi-objective approach is given in Equations 1-6.

$$find\ A_n \tag{1}$$

minimize:

$$f_1(A_n) = LCOE \tag{2}$$

$$f_2(A_n) = EI_{tot} \tag{3}$$

subject to:

$$h_1:\ G_i - G_{\max} \le 0 \tag{4}$$

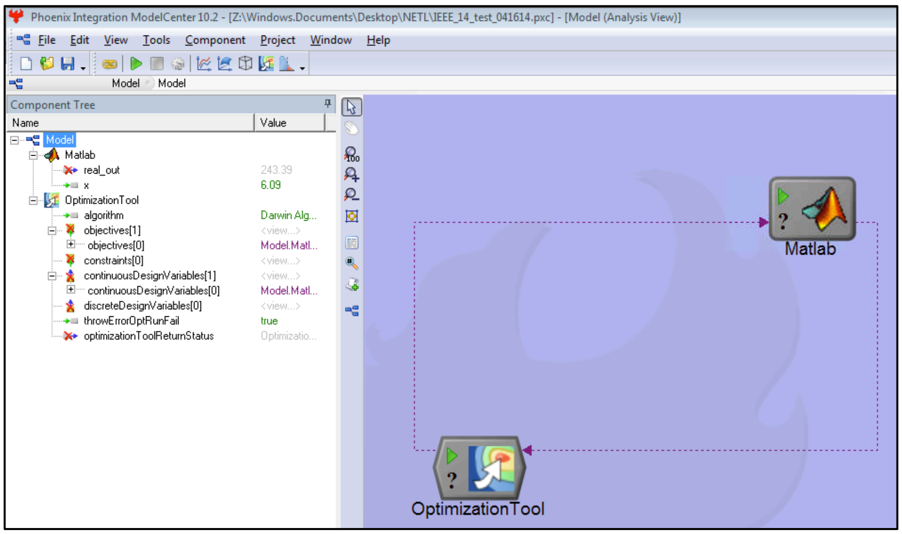
$$h_2: D_{\text{Satisfied}} - D_{\text{Predicted}} \le 0 \tag{5}$$

$$h_3: BD_i - BD_{\max} \le 0 \tag{6}$$

The decision variable A_n is an adjacency matrix representing the topology of power generation sources in the OR/WA system. $LCOE$ is the leveled cost of energy –the cost of generating electricity – given in dollars per MWh as a function of A_n. EI_{tot} is the total environmental impact (which we will seek to reduce as part of the future outer-loop optimization scheme), measured in carbon dioxide equivalent, or $C0_2E$, also as a function of A_n. Constraint h_1 ensures that the power generation at each generator does not exceed its maximum capability, where G_i is the individual power generation at each generator, and $G_{\max}$ is the total maximum power generation of each generator. Constraint h_2 ensures that the predicted demand is satisfied, where $D_{Predicted}$ is the predicted demand and $D_{Satisfied}$ is the total power generation of the system. The final constraint h_3 ensures that the biological dispatch (local environmental effects, such as fish mortality rates (Bonneville Power Administration, 2013)) for each generator (BD_i) is less than a specified amount.

Based on the outer-loop system objectives described above, the two-stage optimization framework was created within ModelCenter. This tool, by Phoenix Integration Inc., is a graphical environment for automation, integration, and design optimization that enables users to create models by integrating individual design analysis and subsystem design modules (Phoenix Integration Inc., 2011) It also allows the user to import data and coding from other software packages such as MATLAB/MATPOWER, described below (The Mathworks Inc., 2011). This model will assist in concept validation during the preliminary research phase, allowing us to explore the feasible trade space and work toward identifying internal subsystem trends and relationships. Exhibit 2 displays a preliminary developmental screen shot from ModelCenter, which shows each element of the two-stage optimization framework.

Exhibit 2. Two-stage optimization framework screen shot from ModelCenter.



Inner-Loop Optimization Model: Quasi-Steady State System Performance in MATPOWER

The inner-loop optimization calculates instantaneous power flow based on physical relationships such as generation, demand, and existing topology. The power flow is a numerical analysis performed in MATPOWER, consisting of a power system in steady-state conditions using voltage magnitudes and phase angles at each bus (Glover et al., 2012; The Mathworks Inc., 2011; Zimmerman et al., 2011). For this model, the OR/WA input data is filtered from the Western Electricity Coordinating Council (WECC) database. The output is the active power injections required at each bus to keep the system within operating specifications. If any power flow violations are detected, the power-flow solution will be calculated again. Linear programming is used to optimize generation ramping while enforcing transmission line limits required to avoid an overload. The simulation fidelity can be increased by adding additional details such as generation costs (at each source), and will provide the user with the lowest cost per kilowatt-hour delivered option. This is known as the optimal power flow, or OPF (Glover et al., 2012).

In this research we use the de-coupled (dc) power flow approximation since we are explicitly addressing energy consumption. In a dcOPF solver, the power flow equations are linearized and neglect reactive power and off-nominal voltage magnitudes, thus modeling active power flow as a linear function of the voltage angles (Zimmerman et al., 2011). This simulation contains its own set of subsystem objectives, constraints, and decision variables. The objective of the dcOPF is to minimize the cost of the active power injections (i.e., generator ramping) required to maintain system stability based on a single loading scenario (Equation (8)). The inner-loop optimization can be defined as:

$$find \ \mathrm{P}_g, \theta \tag{7}$$

minimize:

$$f_1 = \sum_{i=1}^{n_g} f_p^i \left(p\right)_g^i \tag{8}$$

subject to:

$$g_P\left(\Theta, P_g\right) = B_{bus} + P_{bus,\,shift} + P_d + G_{sh} - C_g P_g = 0 \tag{9}$$

$$h_f\left(\Theta\right) = -B_f \Theta - P_{f,\,shift} - F_{\max} \le 0 \tag{10}$$

$$h_t\left(\Theta\right) = -B_f \Theta - P_{f,\,shift} - F_{\max} \le 0 \tag{11}$$

$$\theta_i^{ref} \le \theta_i \le \theta_i^{ref}, \qquad i \in I_{ref} \tag{12}$$

$$p_g^{i,\,\min} \le p_g^i \le p_g^{i,\,\max}, \qquad i = 1 \ldots n_g \tag{13}$$

The objective function f_1 is a summation of individual polynomial cost function f_i^P, of real power injection of P_g, and the voltage angle θ, at each generator p_g^i. The objective function is subject to a power balance constraint where B_{bus} is the bus susceptance, $P_{bus,\,shift}$ is the transformer phase shift angle (in degrees), P_d is the real power demand, G_{sh} is the shunt conductance, C_g is a sparse $n_b \times n_g$ generator connection matrix, and P_g is the real power generated. The inequality constraints consist of 2 sets of n_l branch flow limits as nonlinear functions of the bus voltage angles and magnitudes, one for the *from* end and one for the *to* end of each branch (Equations (10) and (11)). Finally, variable limits include equality constraints on any reference bus angle and upper and lower limits on all bus voltage magnitudes and real generator injections (Equations (12) and (13)).

In our model, the OPF is expanded beyond cost optimization, and system robustness is captured by extending the dcOPF formulation to include stability (security) constraints. This power system protection practice is defined as *security-constrained* dcOPF (SCdcOPF). The SCdcOPF is an OPF-like problem, in which security can be viewed as a set of constraints in addition to the traditional OPF voltage and thermal constraints. For example, bus voltage magnitudes between zones of intertie exchange can be limited using the following equality constraint:

$$V_m \le |V| \le V_M \tag{14}$$

where V_m and V_M are the lower and upper voltage limits, respectively. Another example is the definition of spinning reserves requirements for the balancing area under study.

A "*planning* time-scale" solution to the SCdcOPF would be a set of generator set-points that satisfy equations and inequalities (Equations 9 – 14) for a set of credible contingencies. However, this nonlinear programming problem contains both algebraic and differential equation constraints, and existing optimization methods cannot address this easily. To overcome this issue, we can convert the differential-algebraic equations to numerically equivalent algebraic equations. This results in an abstracted "*design* time-scale" solution, which is a sufficient approximation for this research (Gan, Thomas, & Zimmerman, 2000).

In summary, the two-stage optimization model first solves the power flow problem for the existing OR/WA power grid using a SCdcOPF simulation in MATPOWER. The power flow solution produces decision variables for the number and location of agents to the outer-loop optimization. This allows a designer to explore Pareto solutions, based on their requirements and preferences.

Preliminary Results and Discussion

One challenge that was overcome at the onset of this work was that the WECC data was initially formatted for the power system simulator PowerWorld, and was therefore incompatible with MATPOWER. To convert the WECC matrix to a MATPOWER-ready format, the PowerWorld data was first filtered to only include the assets (buses, branches, and generators) located within the OR/WA area. in order to meet MATPOWER formulation criteria, some of the data columns in PowerWorld required conversion from text to numerical values. Individual data columns were arranged so that they conformed to the MATPOWER case struct. An example of the input bus, branch, and generator data is given in Exhibit 3.

Exhibit 3. Bus, Branch, and Generator Input Data.

BUS DATA

BusNum	BusCat	BusLoadMW	BusLoadMVR	BusG:1	BusB:1	AreaNum	BusPUVolt	BusRad	BusNomVolt	ZoneNum
1	PQ	3.6	1.2	0	0	40	1.02867	0.94	230	404
2	PQ	12.1	4	0	0	40	1.03007	0.92	230	404
3	PQ	14.4	4.7	0	0	40	1.02808	0.94	230	404
4	PQ			0	0	40	1.01876	0.83	115	400
5	PQ	75.3	24	0	0	40	1.02062	0.86	115	400
6	PQ			0	0	40	1.03419	0.89	230	400
7	PQ			0	0	40	1.03511	0.89	230	400
8	PQ	0.5	0.2	0	0	40	1.04959	0.67	115	401
9	PQ	5.9	1.9	0	0	40	1.02485	0.34	115	401
…4013	PQ			0	0	40	1.00674	1.17	13.8	447

BRANCH DATA

BusNum	BusNum:1	LineR	LineX	LineC	LineAMVA	LineAMVA:1	LineAMVA:2	LineTap	LinePhase	LineStatus
1	41348	0.00368	0.01915	0.03516	310.7	310.7	310.7	1	0	Closed
1	40533	0.00106	0.00626	0.01086	310.7	310.7	310.7	1	0	Closed
2	40065	0.00084	0.00788	0.0156	255	255	557.7	1	0	Closed
2	40003	0.00134	0.01276	0.0245	255	255	557.7	1	0	Closed
3	41346	0.00156	0.01515	0.02768	255	255	557.7	1	0	Closed
5	40277	0.039	0.06139	0.00636	85.6	85.6	105.6	1	0	Closed
5	47341	0.02415	0.04039	0.00422	85.6	85.6	105.6	1	0	Closed
5	40007	0.00971	0.08444	0.0107	85.6	85.6	105.6	1	0	Closed
7	46792	0.00259	0.05244	0	20	20	20	1	0	Closed
…4013	47050	0.00307	0.00842	0.00116	95.2	95.2	104.2	1	0	Closed

GENERATOR DATA

BusNum	GenMW	GenMVR	GenMVRMax	GenMVRMin	GenVoltSet	GenMVABase	GenStatus	GenMWMax	GenMWMin
15	5.58	0	0	0	1	2.4	Closed	5.6	0
28	13.95	-2.97	8.9	-9.9	1.01	18.15	Closed	16	0
30	13.95	-2.97	8.9	-9.9	1.01	18.15	Closed	16	0
63	1151.2	50	50	-200	1.08	1230	Closed	1200	0
199	9.97	0	0	0	1.02	100	Closed	10	0
201	6.98	0	0	0	1	13	Closed	13	0
293	620	-10.92	281.42	-121.08	1.08	707.7	Closed	707	0
295	620	-10.92	281.42	-121.08	1.08	707.7	Closed	707	0
296	720.56	-10.92	285.61	-289.44	1.08	825.6	Closed	825.7	0
…4013	100	16.81	42.3	-31.4	1	130.3	Closed	113.8	0

Once the selected data were filtered and arranged accordingly within PowerWorld, the data were exported into three separate comma-separated value format (csv) files for bus, branch, and generator data. A MATLAB code was then created to combine all three data sets, make the necessary conversions, and generate a file to integrate into the MATPOWER simulation.

Presently, interchange schedules for the OR/WA boundaries are computed at the top of every hour. However, regional balancing authorities are considering moving to shorter computational timescales, such as every 30 min or possibly as frequently as every 15 min. Power companies are expected to begin testing the feasibility of shorter time scales with the California intertie in the near future. Thus, an ongoing challenge for our model will be whether the optimization problem can be solved within these shorter time frames, so that system operators can accommodate wind dispatch, improve load-forecasting models, allocate spinning reserves, etc.

The initial results shown here are for the preliminary inner-loop optimization, where the data and methodology proposed in this work have been used to perform a standard dc power flow simulation on the OR/WA isolated grid. By default, the results of the simulation are pretty-printed to the screen, displaying a system summary, bus data, branch data and, for the SCdcOPF, binding constraint information (Exhibit 4).

Exhibit 4: System Summary for OR/WA dc Power Flow Analysis

```
Converged in 0.01 seconds
================================================================================
|     System Summary                                                           |
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses              4013   Total Gen Capacity   34801.5           0.0 to 0.0
Generators          404   On-line Capacity     34801.5           0.0 to 0.0
Committed Gens      404   Generation (actual)  25021.0               0.0
Loads              1727   Load                 25021.0               0.0
  Fixed            1727     Fixed              25021.0               0.0
  Dispatchable        0     Dispatchable          -0.0 of -0.0      -0.0
Shunts                0   Shunt (inj)             -0.0               0.0
Branches           4631   Losses (I^2 * Z)         0.00              0.00
Transformers       4631   Branch Charging (inj)     -                0.0
Inter-ties            3   Total Inter-tie Flow     0.0               0.0
Areas                 2

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   1.000 p.u. @ bus 40001       1.000 p.u. @ bus 40001
Voltage Angle       1.41 deg   @ bus 40028    1814.62 deg   @ bus 45690

================================================================================
|     Bus Data                                                                 |
================================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
40001  1.000 1790.823       -         -         3.60      0.00
40002  1.000 1790.148       -         -        12.10      0.00
40003  1.000 1790.761       -         -        14.40      0.00
40005  1.000 1784.955       -         -          -         -
40007  1.000 1786.994       -         -        75.30      0.00
40009  1.000 1788.462       -         -          -         -
40011  1.000 1788.598       -         -          -         -
40013  1.000 1788.618       -         -         0.50      0.00
40015  1.000 1770.954      5.58      0.00       5.90      0.00
```

A dc power flow analysis shows that the 404 generators (maximum generating capacity of 34, 801.5 MW) in the OR/WA areas meet a demand of 25,021 MW of active power that is transmitted to 1,721 load points. A total of 4,631 lines carry power between 3 inter-tie zones. No transmission losses are incurred during the dc simulation, and the minimum and maximum voltage magnitudes and angles are displayed together with the respective busses. The partial display of bus data in Exhibit 4 includes the voltage, angle and total generation and load at each bus. It would also includes nodal prices, and constraint information in the case of the SCdcOPF. The branch data (not shown in Exhibit 4) indicates the flows and losses in each branch. These results represent a comprehensive overview of the OR/WA dc power flow dynamics.

From these preliminary results, it is shown that the approach presented in this work is a promising first step towards large-scale power systems optimization for varying objectives. The SCdcOPF inner-loop analysis will allow for the optimization of the existing OR/WA power system, which the overarching optimization scheme will be able to optimize from a systems level for reliability against cascading failures and the reduction of environmental impact. These tools will be indispensable as the US grid continues to modernize, and will eventually help inform the creation of larger generation systems.

Acknowledgements

As part of the National Energy Technology Laboratory's Regional University Alliance (NETL-RUA), a collaborative initiative of the NETL, this technical effort was performed under the RES contract 1100426.

References

Asare, P., Diez, T., Galli, A., O'Neill-Carillo, E., & Robertson, J. (1994). *An Overview of Flexible AC Transmission Systems*. West Lafayette, Indiana, USA.

Bonneville Power Administration. (2013). BPA's Fish and Wildlife Program: The Northwest working together. Retrieved from http://www.bpa.gov/news/pubs/FactSheets/fs-201305-BPAs-Fish-and-Wildlife-Program-the-Northwest-working-together.pdf

Carreras, B., Lynch, V. E., Dobson, I., & Newman, D. E. (2002). Dynamics, Criticality, and Self-Organization in a Model for Blackouts in Power Transmission Systems. In *IEEE Proceedings of the International Conference on System Sciences*.

Fairley, P. (2004). The Unruly Power Grid. *IEEE Spectrum*, 23–17.

Gan, D., Thomas, R. J., & Zimmerman, R. D. (2000). Stability-Controlled Optimal Power Flow. *IEEE Transactions on Power Systems*, *15*(22), 535–540.

Glover, J. D., Sarma, M. S., & Overbye, T. J. (2012). *Power System Analysis & Design* (5th ed.). Samford, Connecticut, USA: Cengage Learning.

Hines, P. (2007). *A Decentralized Approach to Reducing the Social Costs of Cascading Failures*. Carnegie Mellon University.

Hingorani, N. G. (1988). High Power Electronics and Flexible AC Transmission System. *IEEE Power Engineering Review*.

Lininger, A., McMillin, B., Crow, M., & Chowdhury, B. (2007). Use of Max-Flow on FACTS Devices. In *39th North American Power Symposium* (pp. 288–294).

Mavris, D. N., & Griendling, K. (2011). Relational Oriented Systems Engineering and Technology Tradeoff Analysis (ROSETTA) Environment. In *IEEE Proceedings of the 6th International Conference on Systems Engineering* (pp. 49–54).

Pahwa, S., Hodges, A., Scoglio, C., & Wood, S. (2010). Topological Analysis of the Power Grid and Mitigation Strategies Against Cascading Failures. *Statistical Mechanics and Its Applications*, *338*(1-2), 92–97.

Phoenix Integration Inc. (2011). *ModelCenter Basics* (Vol. 24060, pp. 1–167). Blacksburg, VA, USA.

Pinar, A., Meza, J., Donde, V., & Lesieutre, B. (2010). Optimization Strategies for the Vulnerability Analysis of the Electric Power Grid. *Society for Industrial and Applied Mathematics*, *20*(4), 1786–1810.

ReVelle, J. B., Moran, J. W., & Cox, C. A. (1996). *The QFD Handbook*. John Wiley and Sons.

Talukdar, S. N., Apt, J., Ilic, M., Lave, L. B., & Morgan, M. G. (2003). Cascading Failures: Survival Versus Prevention. *The Electricity Journal*, 25–31.

The Mathworks Inc. (2011). *MATLAB Version 7.13.0.564*. Natick, Massachusetts, USA.

U.S. Department of Energy. (2010). *2010 Smart Grid System Report*. Washington, DC, USA.

Zimmerman, R. D., Murillo-Sanchez, C. E., & Thomas, R. J. (2011). MATPOWER: Steady-State Operations, Planning and Analysis Tools for Power Systems Research and Education. *Power Systems, IEEE Transactions*, *26*(1), 12–19.

About the Authors

Dr. Bryony DuPont is an Assistant Professor in the School of Mechanical, Industrial, and Manufacturing Engineering at Oregon State University. She completed both her M.S. (2010) and her Ph.D. (2013) in Mechanical Engineering at Carnegie Mellon University. She is affiliated faculty of Oregon State's Design Engineering Laboratory - one of the largest academic mechanical design groups in the country - and the Northwest National Marine Renewable Energy Center (NNMREC). Her work is mechanical design, specifically the development and application of computational optimization tools for renewable and collaborative energy systems, and for sustainable product development.

Dr. Joseph Piacenza earned his B.S. in mechanical engineering from the University of South Florida (USF), and completed his MBA at USF in 2008 with a focus on entrepreneurship and management. While working toward the MBA, he founded an automotive-based small business, specializing in the restoration and service of European vehicles. This business was sold in early 2010, and he completed his M.S and Ph.D. in mechanical engineering at Oregon State University (2012 and 2014 respectively). Dr. Piacenza's dissertation explored the robust design of complex infrastructure systems. However, his research interests extend to design theory and methodology, automotive engineering, and design sustainability.

Ridwan Azam graduated from Oregon State University in 2014 with a B.S. in Electrical and Computer Engineering. He is now pursuing his Masters of Science degree in the energy systems group in the same institution. He is currently working with Dr. Cotilla-Sanchez and researchers from the School of Mechanical, Industrial and Manufacturing Engineering on a collaborative power grid system optimization project for the National Energy Technology Laboratory (NETL). His tasks include running optimal power flow analysis on the Oregon/Washington power grid. His research interests include power flow optimization and smart grid modeling.

Dr. John Wardman received the BSc from Eckerd College in 2007 and a PhD degree in Hazard and Disaster Management from the University of Canterbury, New Zealand in July 2013. He has published papers on his research in top international journals in both volcanology and electrical engineering and has mentored several electrical engineering and geology undergraduate students in his time as a doctoral candidate. Related projects have included 'Revising Insulator Design to Aid the Electrostatic Repulsion of Volcanic Ash**'** (Mee et al., 2012) and 'The Adherence Properties of Volcanic Ash to HV Insulators' (Bruce, 2012). Wardman is an active student-member of the IEEE and the IEEE Dielectrics and Electrical Insulation Society.

Dr. Christopher Hoyle is currently Assistant Professor and Arthur Hitsman faculty scholar in the area of Design in the Mechanical Engineering Department at Oregon State University. He received his PhD from Northwestern University in Mechanical Engineering in 2009 and his Master's degree in Mechanical Engineering from Purdue University in 1994. He was previously a Design Engineer and an Engineering Manager at Motorola, Inc. for 10 years before enrolling in the PhD program at Northwestern University. His current research interests are focused upon decision making in engineering design, with emphasis on the early design phase when uncertainty is high and the potential design space is large. He is coauthor of the book *Decision-Based Design: Integrating Consumer Preferences into Engineering Design*, published in 2012.

Dr. Eduardo Cotilla-Sanchez is an Assistant Professor of Electrical and Computer Engineering at Oregon State University. He is part of the Energy Systems research group housed at the Wallace Energy Systems andRenewables Facility (WESRF). He earned the M.S. and Ph.D. degrees in Electrical Engineering from the University of Vermont in 2009 and 2012, respectively. His primary field of research is the vulnerability of electrical infrastructure, in particular, the study of cascading outages. Part of his research is developed through collaborations with Sandia National Laboratories and Pacific Northwest National Laboratories, among others. He is the secretary of the IEEE Cascading Failures Working Group.

Danylo Oryshchyn is a Research Mechanical Engineer at the United States Department of Energy, National Energy Technology Laboratory. Danylo completed his BS in Mechanical Engineering at Oregon State University, and is currently a PhD Candidate in Mechanical Engineering at Oregon State University. He is currently leading NETL's SFIRE (Synergies Fostering Implementation of Reliable Energy in the modern (clean, sustainable) power system) working group, fostering research into synergies to provide a robust path through our nation's current power system to its modern configuration. His current research interests include heat transfer for direct power extraction from combustion. Previously, he served as the Principle Investigator for Integrated Pollutant Removal (IPR) CO2 capture process with water recovery. He also holds multiple patens: Oxy-fuel combustion with integrated pollution control (2012) US patent 8087926; Integrated Capture Of Fossil Fuel Gas Pollutants Including CO_2 With Energy Recovery (2011) US patent 8038773 B2; and Module-based oxy-fuel boiler (2009) US patent 8082737.

Steve Bossart has a B.S. degree in chemical engineering from Pennsylvania State University. He is a senior energy analyst at the U.S. Department of Energy's National Energy Technology Laboratory (NETL). His primary area of study is the electric power sector with an emphasis on modernization of the nation's power system and cost and benefit analysis of 131 Smart Grid Projects funded through the American Recovery and Reinvestment Act. He is a member of Federal Smart Grid Task Force and Smart Grid Policy Center. He has 30 years of project management and analytical experience at the NETL and its predecessor organizations. He is author of over 75 publications covering a wide range of subjects including coal gasification, wastewater treatment, solid waste management, environmental controls, nuclear decommissioning, and Smart Grid.

DISCLAIMER

This project was funded by the Department of Energy, National Energy Technology Laboratory, an agency of the United States Government, through a support contract with URS Energy &Construction, Inc. Neither the United States Government nor any agency thereof, nor any of their employees, nor URS Energy & Construction, Inc., nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.