Grid Modernization: Opportunities, Challenges, and Solutions

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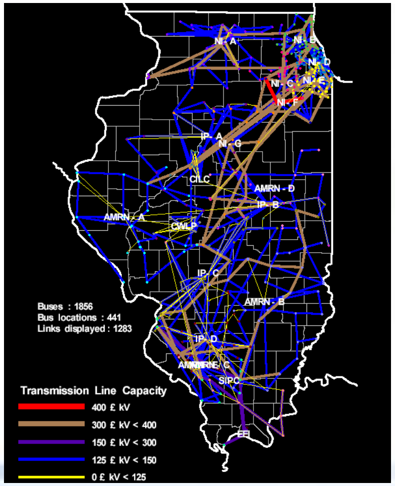
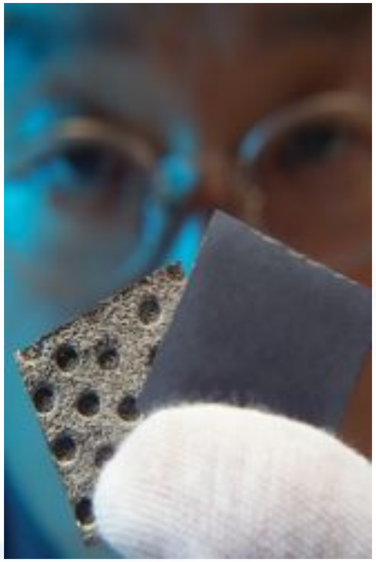
About the speaker

- Ph.D. Illinois Institute of Technology, 2007
- Affiliate Professor, Auburn University (2011-)
- Adjunct Professor, University of Notre Dame (2014-)
- Editor, *Applied Energy, Journal of Energy Engineering*
- Editor-in-Chief, *IEEE Transactions on Smart Grid*
- Authored/co-authored over 150 journal articles and 50 conference publications and 4800+ citations. Recipient of the IEEE PES Power System Operation Committee Prize Paper Award in 2015.
- Secretary of the IEEE Power & Energy Society (PES) Power System Operations committee and past chair of the IEEE PES Power System Operation Methods subcommittee
- Held visiting positions in Europe, Australia and Hong Kong including a VELUX Visiting Professorship at the Technical University of Denmark (DTU)
- Technical program chair of the IEEE Innovative Smart Grid Technologies (ISGT) conference 2012

Argonne is America's First National Laboratory and one of the World's Premier Research Centers

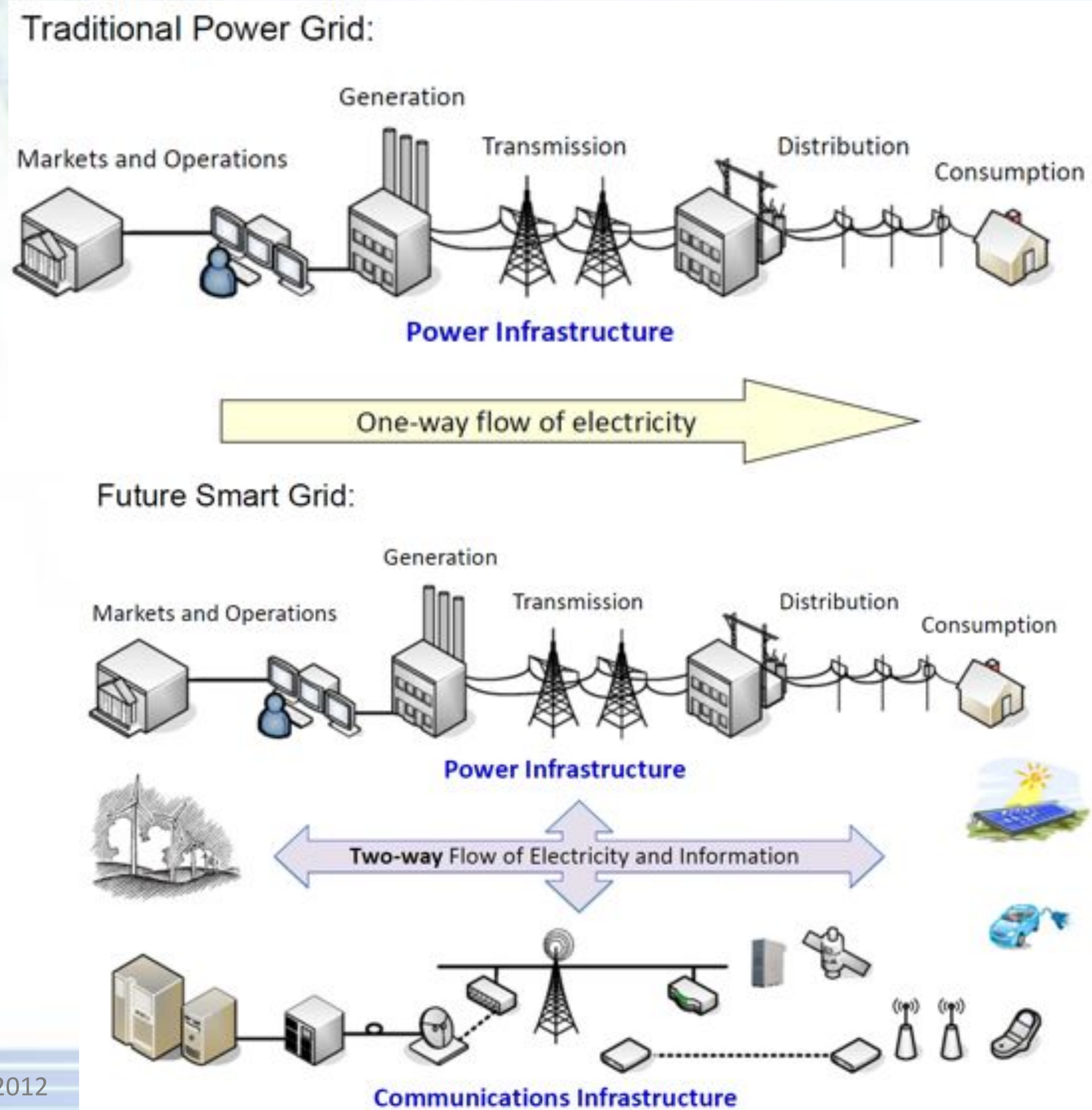
- Founded in 1943, designated a national laboratory in 1946
- Part of the U.S. Department of Energy (DOE) laboratory complex
  - 17 DOE National Laboratories
- Managed by UChicago Argonne, LLC
  - About 3,398 full-time employees
  - 4,000 facility users
  - About $760M budget
  - Main site: 1500-acre site in Illinois, southwest of Chicago
- Broad R&D portfolio and numerous sponsors in government and private sector
- Three Nobel Prize Laureates





Grid Modernization and a Vision for the Future

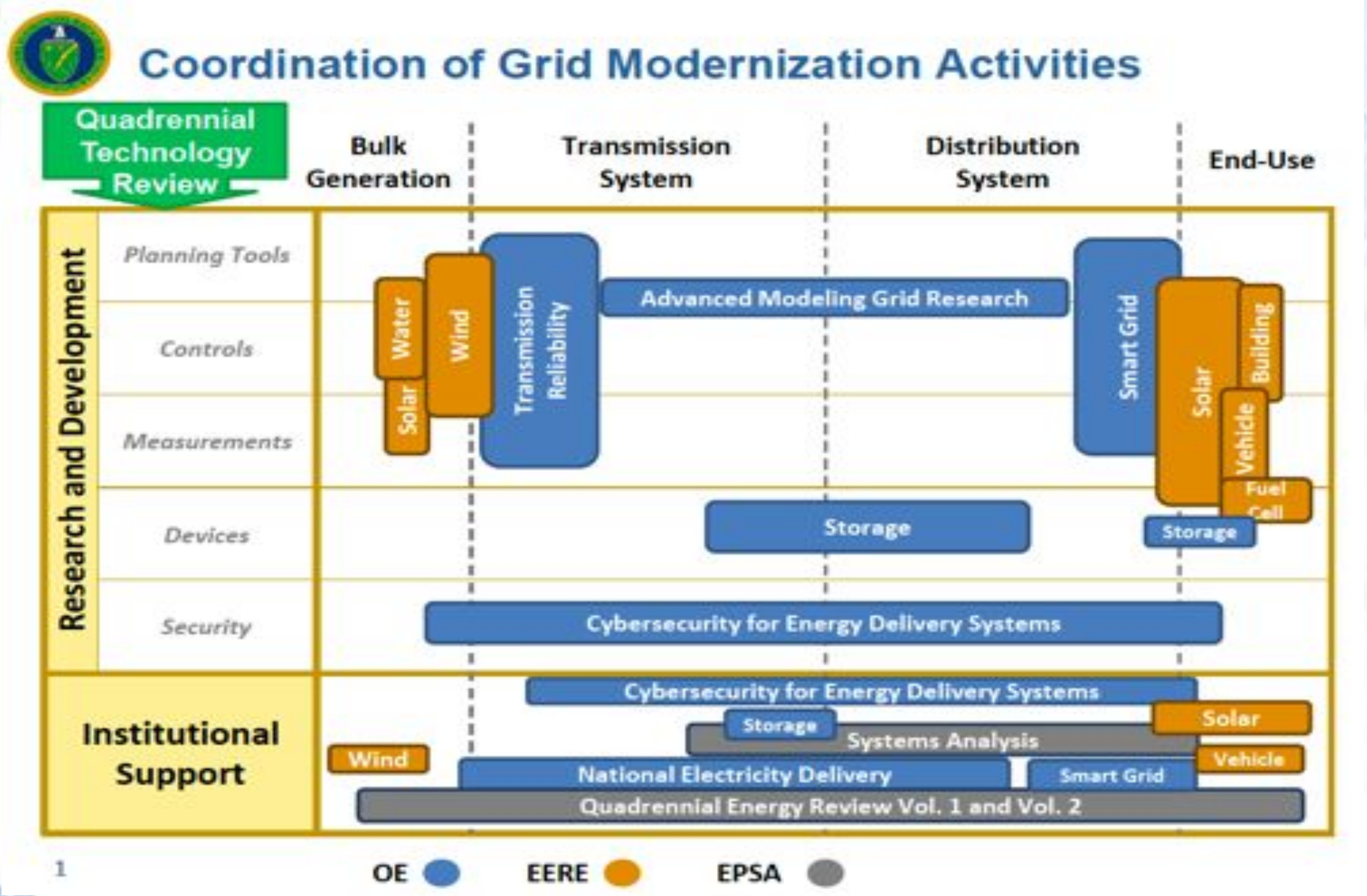
- Centralized generation
- Generation follows load
- One-directional power flow
- Limited automation
- Limited situational awareness
- Consumers lack data to manage use
- Limited accessibility for new producers



- Centralized + distributed generation
- Variable resources
- Consumers become producers
- Multi-directional power flow
- Flexible load

Source: ABB 2009; Texas Tech 2012

Grid Modernization – a $220 million DOE initiative

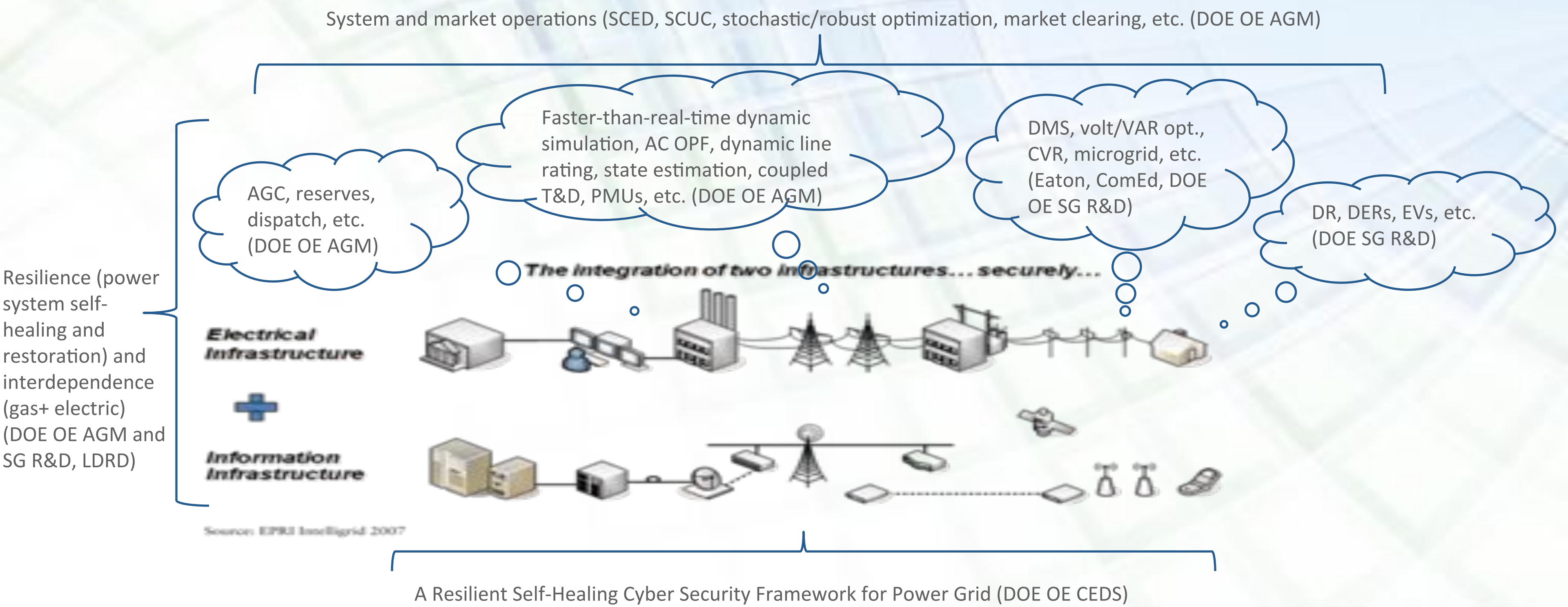


My Version of the Future Power Grid

- **Integrative** Planning and operation (temporal), information technology and power engineering (cyber), integrated T&D (spatial), supply and demand (system-wide)
- **Interdependent** coupling of critical infrastructures (e.g., gas, water, power, communications.)
- **Robust, Flexible and Resilient** (e.g., uncertainty and variability of clean renewable energy, extreme weather events)
- **Hybrid Dynamic Control Architecture** centralized (e.g., HPC for faster-than-real-time interconnection-level simulation AND decentralized (e.g., microgrids, electric vehicles)
- **Cyber and Physical Secure**

Source: DOE, 2011

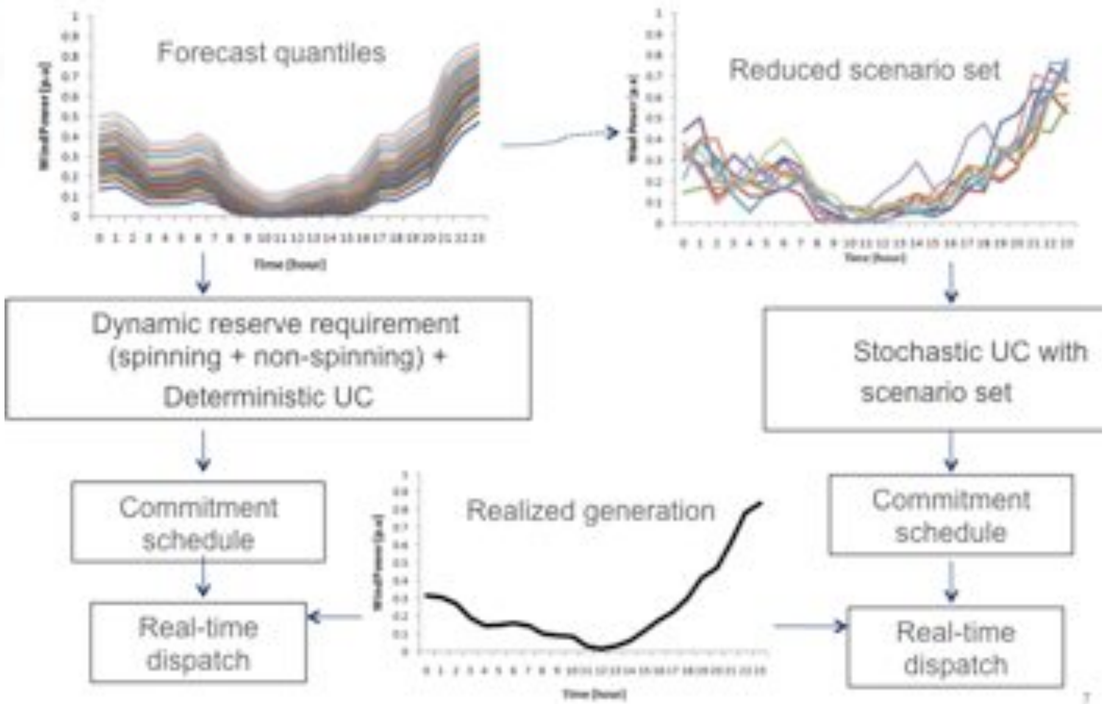
CEEESA Advanced Grid Modeling Program – Power Grid Resilience, Security and Economics



- Work spans generation, transmission, distribution, consumption + market & cybersecurity
- Projects from multiple DOE programs and industry (e.g., DOE OE AGM, DOE OE Smart Grid R&D, DOE OE Cybersecurity for Energy Delivery System (CEDS), FEMA, ARPA-E, ComEd, Eaton, etc.)
- Highly visible staff in the research community (e.g., Editor-in-Chief of IEEE Transactions on Smart Grid, IEEE Power and Energy Society (PES) committee chairs, affiliate/adjunct professorship at universities)
- Highly productive in research and publications (more than 80 IEEE transactions and other journal papers in the past five years). Work widely cited (over 4800 times).
- Close collaboration with industry and universities (e.g., ComEd, Eaton, PJM, IIT, Northwestern, etc.)

Renewable Energy Integration

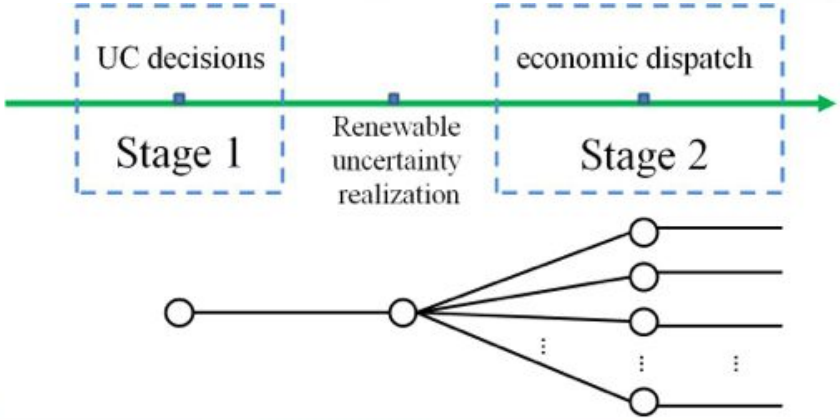
- Argonne developed new stochastic planning model to evaluate different operational practices and market policies to reduce the cost of wind integration
- Model is applied to case studies for Illinois (20% Wind)



Reference: A. Botterud, Z. Zhou, J. Wang, R. Bessa, H. Keko, J. Mendes, J. Sumaili, V. Miranda, Use of Wind Power Forecasting in Operational Decisions, *Argonne National Laboratory Technical Report*, Sept. 2011, available at http://www.dis.anl.gov/pubs/71389.pdf.

Classical Stochastic Optimization Approach

- Two-stage stochastic UC: large-sized scenarios (renewable energy variations)
  - Stochastic UC formulations (Philpott 06, Sen 06)
  - Active management of uncertainties
    (Bouffard and Galiana 08, Ruiz et al. 09, Wang et al. 08, Oren et al. 10)
  - Chance-constrained optimization (Wang et al. 12, 13a, 13b)
- Potential challenges
  - How to precisely estimate the (joint) probability distributions?
  - How to solve the large-sized extensive formulation?



Robust Unit Commitment

- Robust optimization concepts and incorporating pumped-storage units to hedge wind power output uncertainty
- An uncertainty set description that can capture the wind power "ramp" events

(NOM)

$$
\begin{aligned}
\min \quad & c(y) + f(x) & \\
\text{s.t.} \quad & Ay \leq b & (1) \\
& Gx + Hq \leq d & (2) \\
& Wy + Tx \leq h & (3) \\
& y \in \{0, 1\} &
\end{aligned}
$$

Objective function:

- c(y) represents the start-up/shut-down and fixed costs.
- f(x) represents the fuel and operational costs.

Constraints:

- Min-up/-down time, start-up/shut-down operations, and system spinning reserves.
- Power flow balance, transmission capacity limits.
- Power generation upper/lower bounds and ramp-rate limits.

Two-Stage Robust UC Model

- To minimize the total cost under the worst-case scenarios.
- Describe renewable output by an uncertainty set.
- Problem decomposed into two stages:

  1st stage: UC decisions.

  2nd stage: Economic dispatch under the worst-case scenario.

$$\text{(RUC)} \quad \begin{aligned} \min_{y} \quad & R(y) = c(y) + \max_{q \in \mathcal{D}} \min_{x \in \mathcal{X}(y,q)} f(x) \\ \text{s.t.} \quad & Ay \leq b, \\ & y \in \{0,1\}. \end{aligned}$$

Reference: R. Jiang, J. Wang, Y. Guan, Robust Unit Commitment with Wind Power and Pumped Storage Hydro, *IEEE Transactions on Power Systems*, Vol. 27, No. 2, pp. 800-810, 2012.

Uncertainty Set Definition

- Each renewable output q_{bt} running in interval $[Q_{bt}^{n} - Q_{bt}^{v}, Q_{bt}^{n} + Q_{bt}^{u}]$.
  - E.g., the interval can be generated based on .05- and .95-percentiles of q_{bt}.
  - $z_{bt}^{\pm}$ describe the magnitude of increase/decrease from the forecasted value.
- Integer $\Gamma_b \in [0, T]$ restricts the number of deviations:
  - $\Gamma_b = 0 \rightarrow$ all $q_{bt} = Q_{bt}^{n}$; $\Gamma_b = 2T \rightarrow$ all q_{bt} free.
  - Γ_b : “budget of uncertainty.”

Uncertainty set

$$\mathcal{D} := \Big\{ q \in \mathbb{R}^{|B| \times T} : \sum_{t=1}^{T} (z_{bt}^{+} + z_{bt}^{-}) \le \Gamma_b, \quad q_{bt} = Q_{bt}^{n} + z_{bt}^{+} Q_{bt}^{u} - z_{bt}^{-} Q_{bt}^{v}, \ \forall t, \forall b \in B \Big\}$$

Simulation Results : IEEE 118-bus System

- Ratio = $\dfrac{\text{Hydro capacity}}{\text{Average renewable output}}$
- Γ = Budget of uncertainty
- Opt. Gap: optimality gaps
- WV Gap: worst-case performance difference between robust UC and deterministic solutions

Ratio		Γ				
		2	4	6	8	10
0	Opt. Gap(%)	0.06	0.09	0.09	0.10	0.08
	WV Gap(%)	8.10	14.06	18.02	20.32	20.32
	Time (s)	194	353	578	1024	1876
0.1	Opt. Gap(%)	0.08	0.09	0.10	0.10	0.09
	WV Gap(%)	7.52	12.77	15.57	16.41	16.40
	Time (s)	101	309	546	997	542
0.2	Opt. Gap(%)	0.08	0.07	0.08	0.08	0.08
	WV Gap(%)	7.97	11.78	14.70	16.23	16.32
	Time (s)	145	331	908	1852	2053
0.3	Opt. Gap(%)	0.09	0.08	0.09	0.09	0.10
	WV Gap(%)	7.05	12.11	14.52	16.36	16.46
	Time (s)	178	361	736	1116	3101
0.4	Opt. Gap(%)	0.08	0.09	0.08	0.09	0.10
	WV Gap(%)	6.07	9.87	12.00	12.98	13.12
	Time (s)	218	463	1113	1446	1141
0.5	Opt. Gap(%)	0.08	0.09	0.09	0.09	0.07
	WV Gap(%)	5.65	9.29	11.33	12.30	12.49
	Time (s)	178	686	1114	995	3594

Robust UC performs better than deterministic UC

A Resilient Self-Healing Cyber Security Framework for the Power Grid

Argonne NATIONAL LABORATORY

Partners: Pacific Northwest NATIONAL LABORATORY · Illinois Institute of Technology · Iowa State · OPAL-RT · RTDS Technologies

Attack-resilient Wide-Area Monitoring, Protection, and Control (WAMPAC) framework

- Development of a self-healing Phasor Measurement Unit (PMU) network infrastructure through a risk mitigation model
- Development of bad data detection and attack-resiliency methods for the State Estimation (SE) algorithm
- Development of anomaly detection and attack-resilient control methods

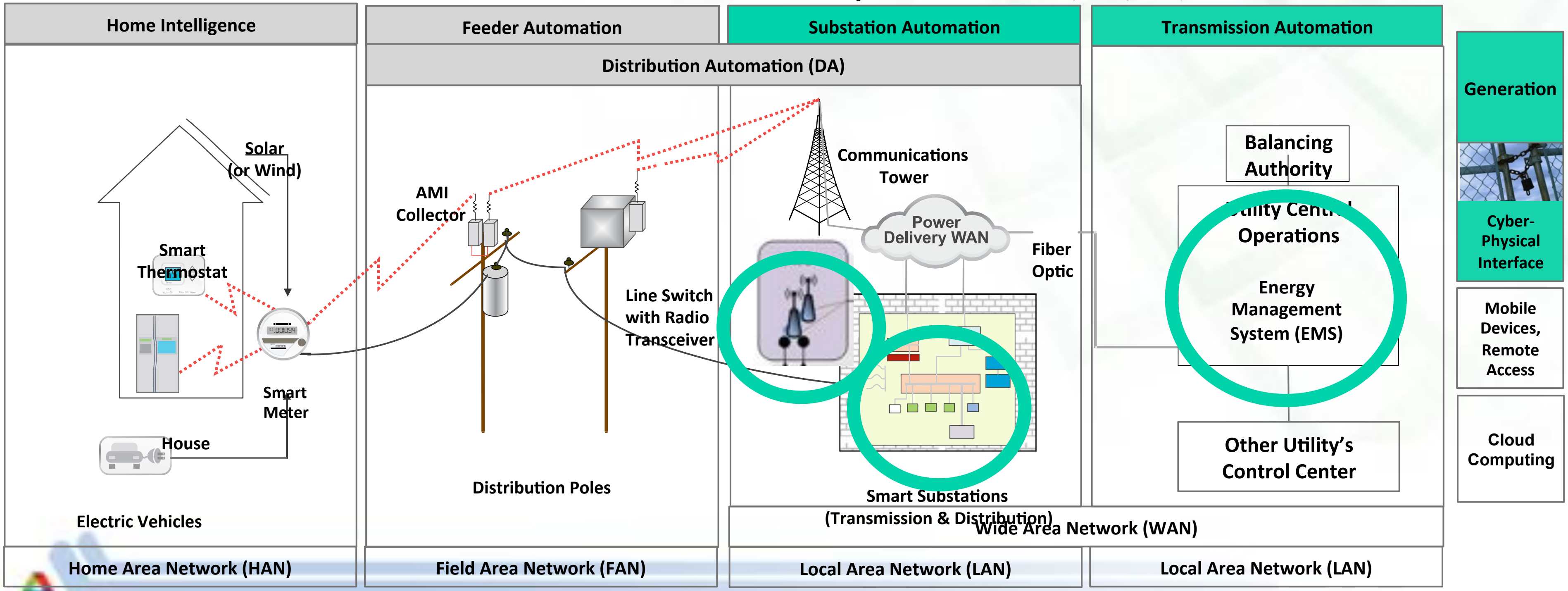
Mitigation and prevention of cyber attacks

- PMU risk mitigation model employs optimal response to cyber-attacks with the goal of preventing the propagation of the attacks and maintaining the observability of the power system
- SE algorithm encompasses stealthy attack vector formulations, attack impact analysis, and Moving Target Defense (MTD) strategies to mitigate sophisticated cyber-attacks

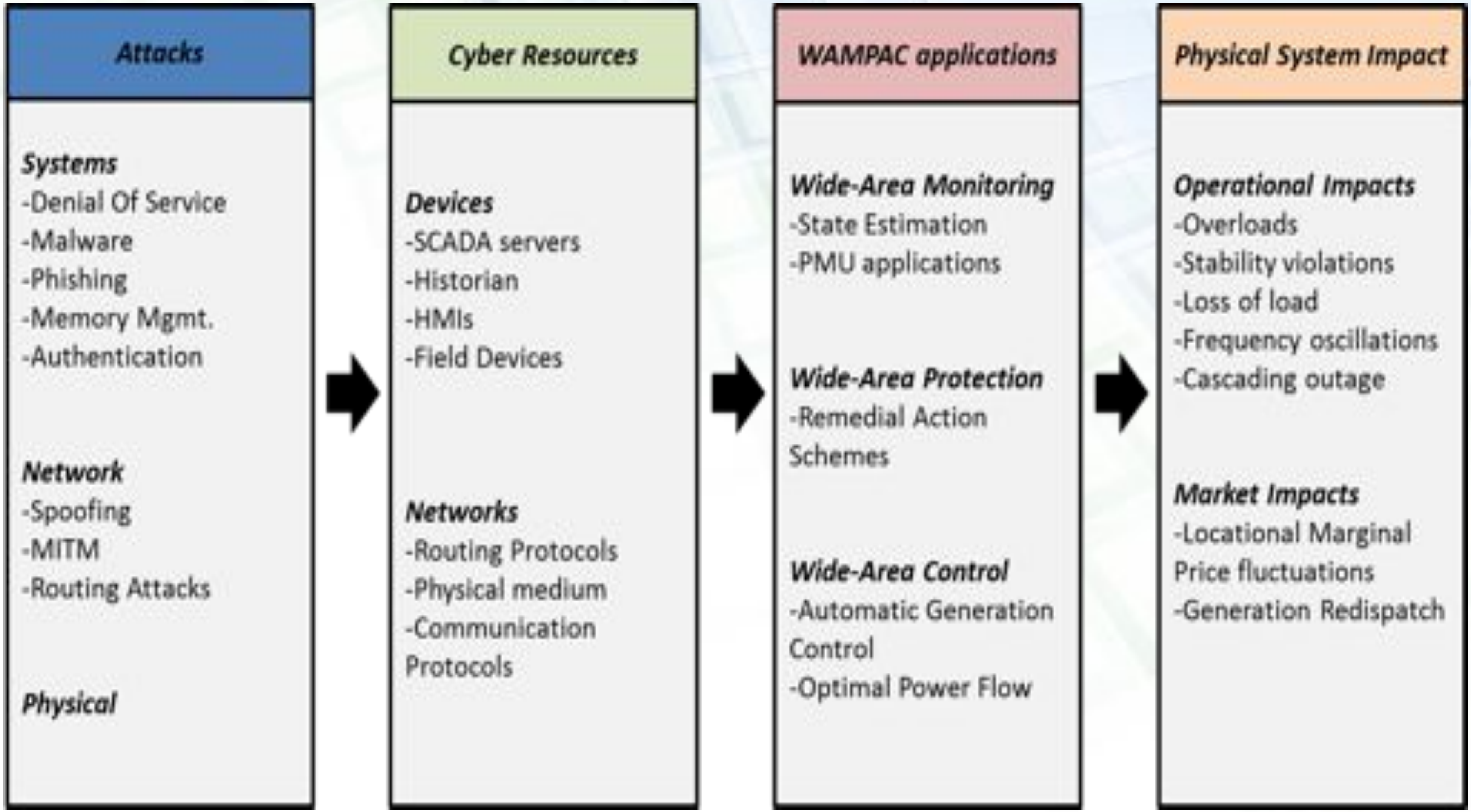
Comprehensive anomaly detection, control, and resilience methods

- Model-based control algorithms leveraging Cyber Physical System (CPS) properties
- Wide-area protection schemes that include the design of a hierarchical model-based MTD-inspired protection algorithm leveraging spatial-temporal properties of device/system operation
- Model-based anomaly detection methods for the Optimal Power Flow (OPF) algorithm though the use of Principal Component Analysis (PCA)

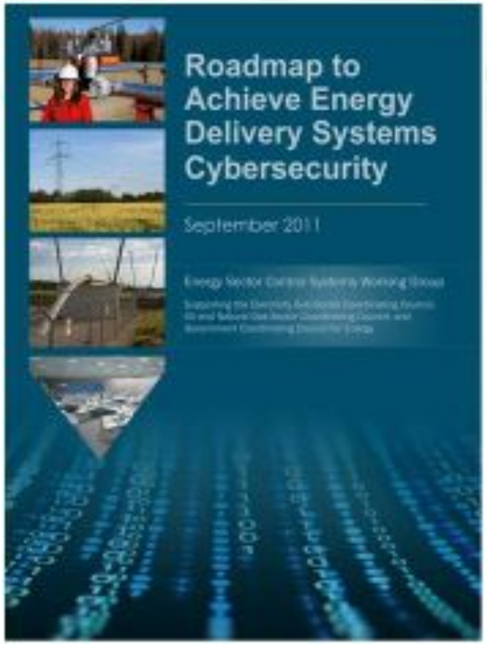
Addresses Roadmap Milestones: *2.3, 3.4, 3.5, 4.5*



Cyber-physical Mapping of Attacks to WAMPAC



Roadmap – Framework for Collaboration



- *Energy Sector's* synthesis of energy delivery systems security challenges, R&D needs, and implementation milestones
- Provides strategic framework to
  - align activities to sector needs
  - coordinate public and private programs
  - stimulate investments in energy delivery systems security

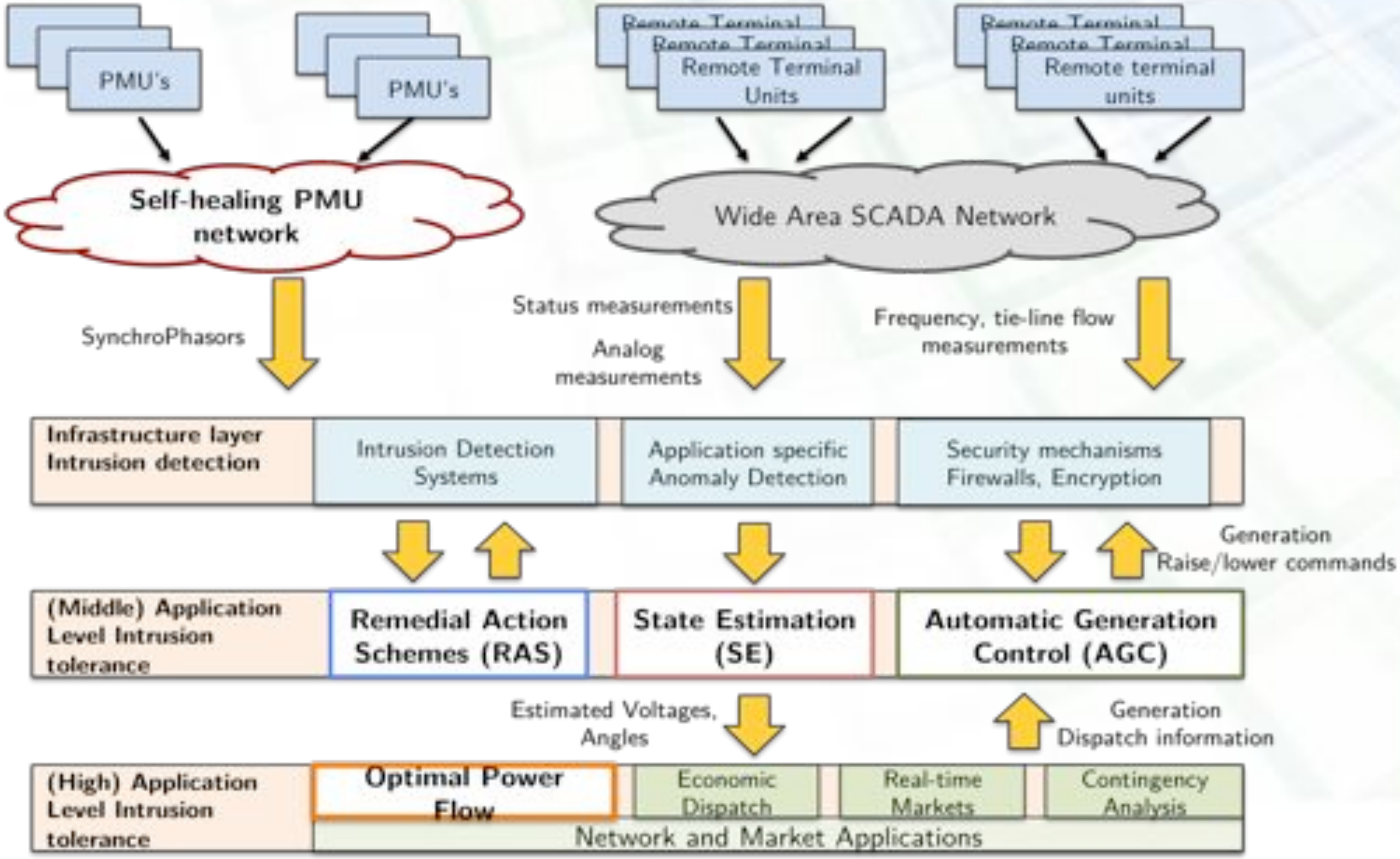
Roadmap Vision

By 2020, resilient energy delivery systems are designed, installed, operated, and maintained to survive a cyber incident while sustaining critical functions.

For more information go to:
www.controlsystemsroadmap.net

A Resilient Self-Healing Cyber Security Framework for the Power Grid

- The primary goal of the project is to develop an attack-resilient Wide-Area Monitoring, Protection, and Control (**WAMPAC**) framework, with associated computational algorithms and software tools, to prevent and mitigate cyber-attacks and achieve resilience of the bulk power system.



New Cybersecurity Projects

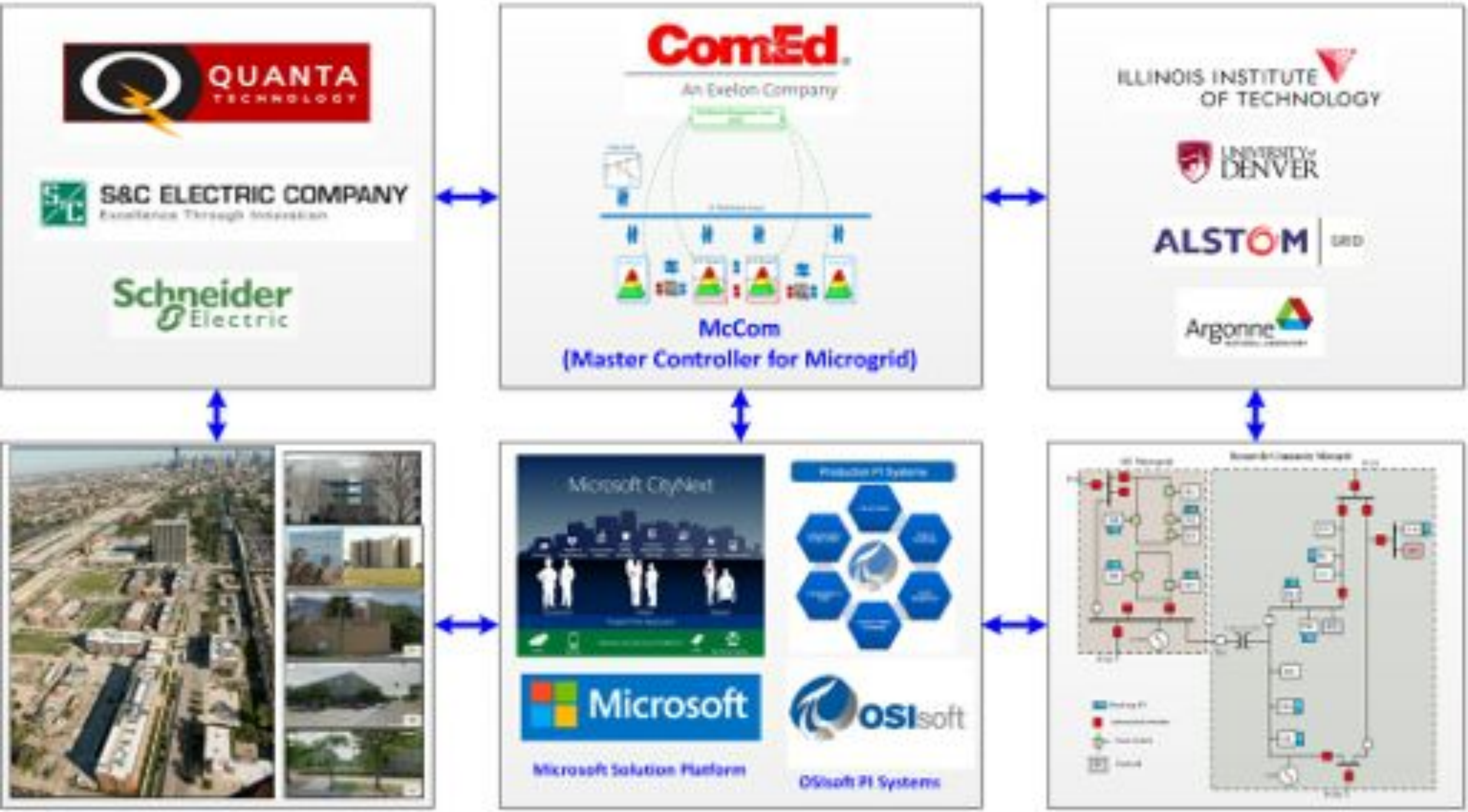
- ***A Resilient and Trustworthy Cloud and Outsourcing Security Framework for Power Grid Applications*** [Argonne (lead), Idaho National Laboratory, Illinois Institute of Technology, University at Buffalo, ComEd, PJM]
  - The primary goal of this effort is to develop a secure and trustworthy cloud computing and outsourcing security framework for power grid applications, with associated computational algorithms and software tools, to prevent and mitigate cyber-attacks and achieve resilience of cloud-based power grid applications.
- ***A Tool to Ensure Uninterrupted Energy Flow from Cyber Attacks Targeting Essential Forecasting Data for Grid Operations*** [Brookhaven National Laboratory (lead), Argonne National Laboratory, Idaho National Laboratory, Orange & Rockland]
  - The goal of this effort is to develop a tool to ensure uninterrupted energy flow from cyber-attacks targeting essential forecasting data for grid operations.
- ***University of Illinois Cyber Resilient Energy Delivery Consortium (CREDC)***
  - A $28.1 million DOE award that will develop cyber-resilient energy delivery systems for the electric power and oil & gas industries. The initiative is being led by the University of Illinois at Urbana-Champaign and includes 11 universities and national laboratories. The goals is to focus on improving the resilience and security of the cyber networks that serve as the backbone of the infrastructure that delivers energy to the nation, such as power grid, petroleum and natural gas pipeline systems.

New York State Reforming Energy Vision (REV) Initiative

- Increasing requirements for grid resilience after Hurricane Sandy
- Distribution – level electricity market
- Diverse participants/resources (DR, DG, microgrids, storage, etc.)
- Distribution System Platform (DSP)
- Market platform and market rules
- Challenges exist – distribution OPF, market clearing, etc.

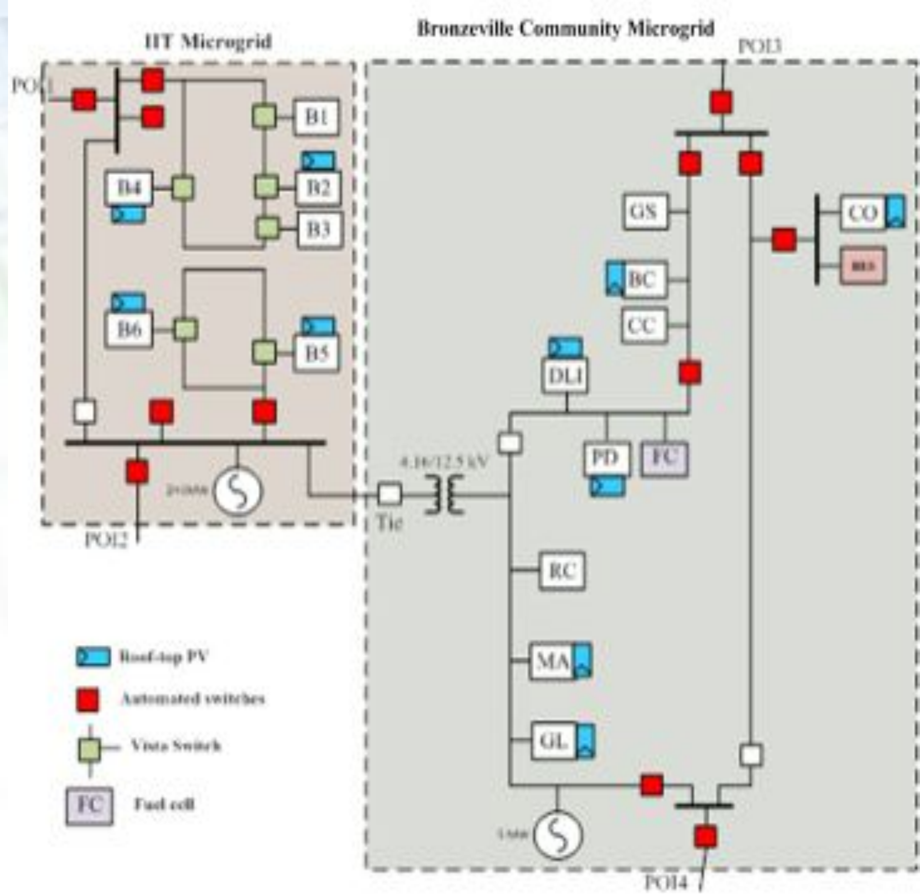
Argonne is supporting NY REV initiative

DOE FOA 997 - Research, Development, and Testing of a Master Controller with Applications to the Bronzeville Community Microgrid System



DOE FOA 997 - Research, Development, and Testing of a Master Controller with Applications to the Bronzeville Community Microgrid System

- **Goal**: Develop a Master Controller for a Community (McCom) with applications to the Bronzeville Community Microgrid (BCM), and develop an interconnected microgrid system design and test plan in the Chicago's Bronzeville community.
- **Tasks**: (1) a microgrid testbed; (2) autonomous microgrid clusters; (3) cost/benefit analysis of alternatives for microgrids; (4) new reliability and power quality standards based on customer needs; (5) new rates and tariffs to correlate microgrids costs/benefits and customer payments; (6) terms and conditions of service for microgrid customers; (7) market mechanism; (8) service differentiation and rates
- **Impact**: McCom will help meet the DOE targets: (1) 98% reduction in outage time of critical loads, (2) 20% reduction in emissions, and (3) 20% improvement in system energy efficiencies.

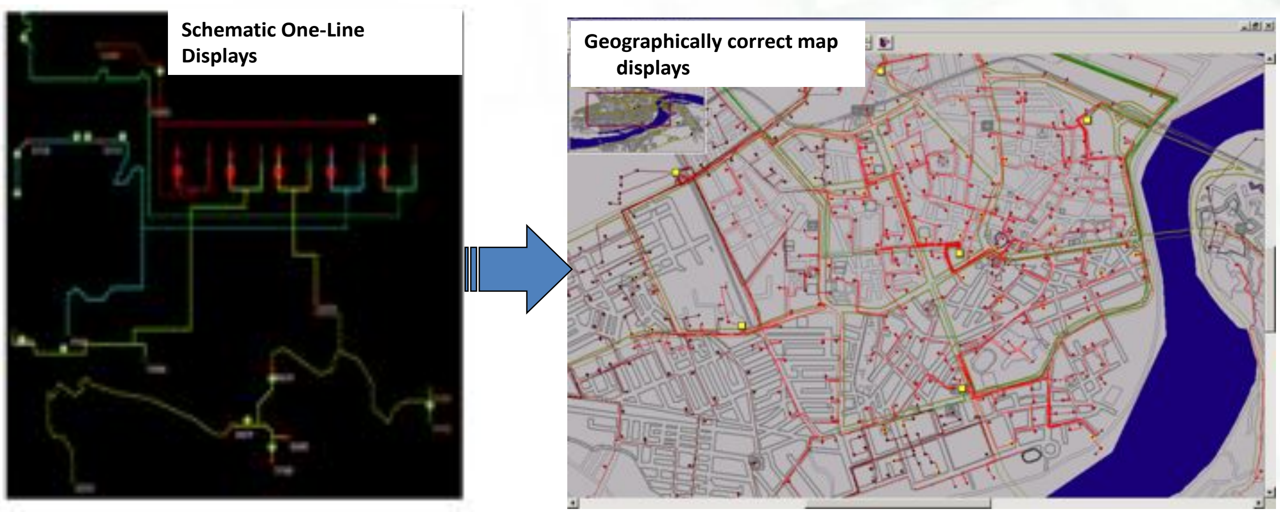


DMS – Current Status and New Challenges

- What is a DMS?

As accepted by the IEEE PES DMS Task Force,

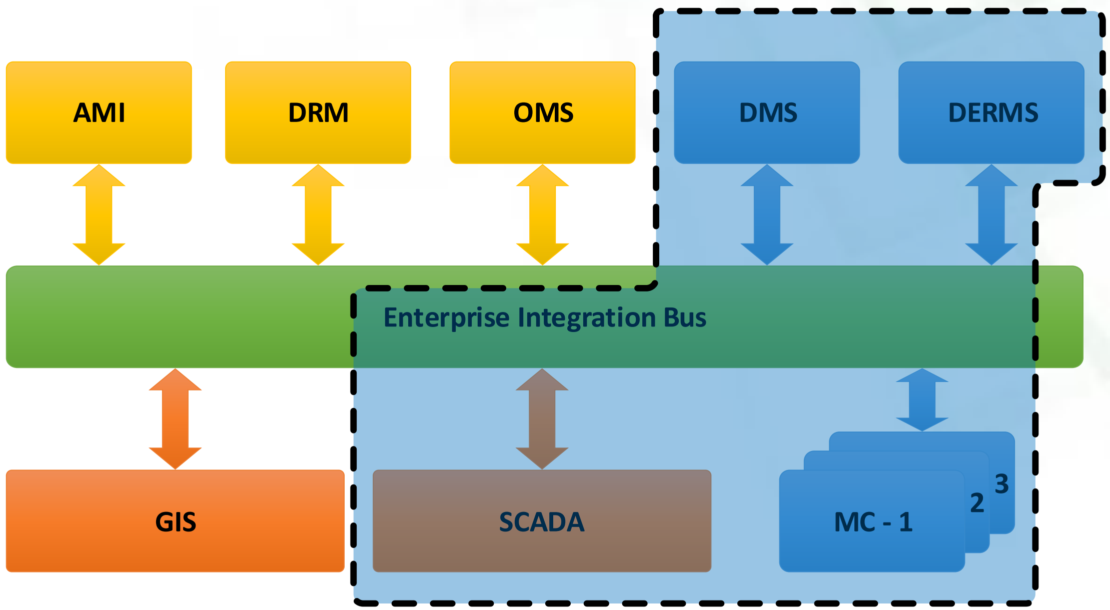
"A DMS is a decision support system that is intended to assist the distribution system operators, engineers, technicians, managers and other personnel in monitoring, controlling, and optimizing the performance of the electric distribution system without jeopardizing the safety of the field workforce and the general public and without jeopardizing the protection of electric distribution assets."



Graphical interface of DMS to display the physical connection of a regional distribution system

DMS – Current Status and New Challenges

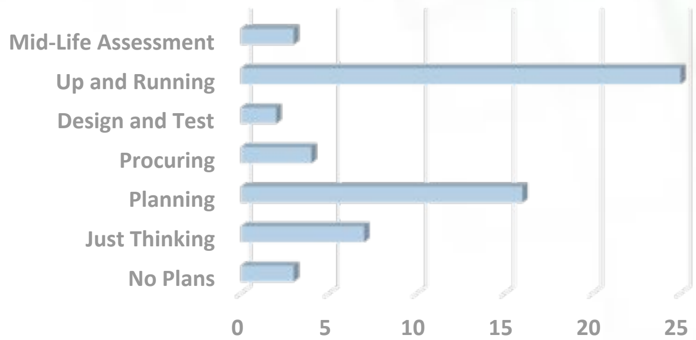
- Distribution management system (DMS) plays a critical role in control and management of distribution systems
- Increasing penetration of distributed energy sources (DERs) challenges the conventional DMS
- Existing technologies for control and management of DERs include microgrid controller (MC) and DER management system (DERMS)
- An advanced distribution management system (ADMS) should be developed with the integration of MC and DERMS



Integrated approach to achieve an ADMS

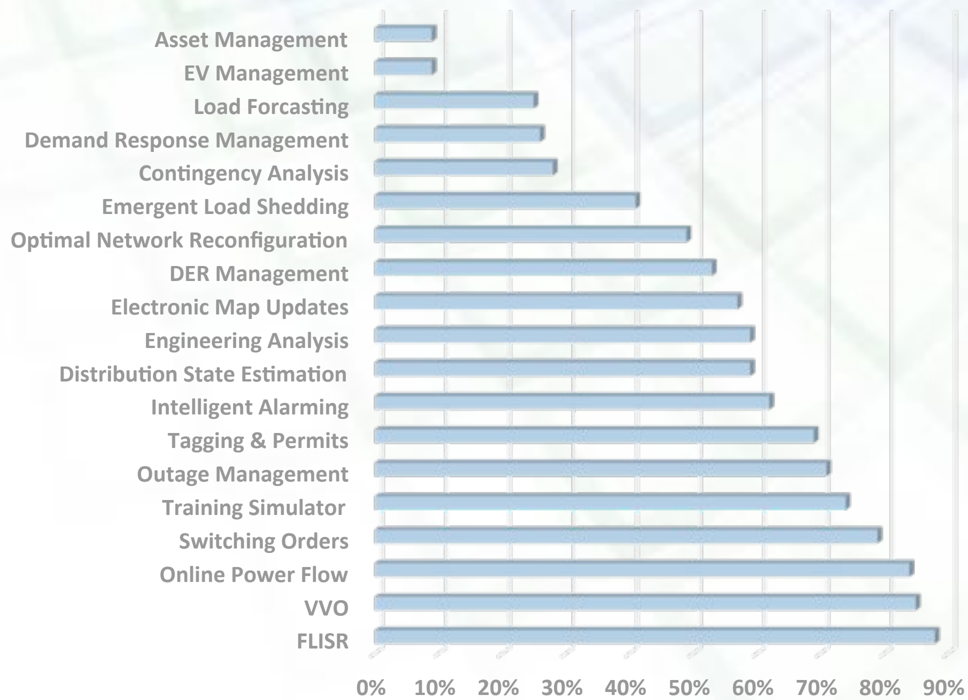
DMS – Current Status and New Challenges

- Current status of DMS development
  - Based on the information gathered from an industry survey, DMS has been widely implemented in existing distribution systems
  - Only some of the DMS functions have been realized by utilities



Status of DMS implementation

Source: IEEE industry survey, April 2015.



DMS applications being implemented

A DOE Initiative of $6 million/year for the next three years

Guidelines for Implementing Advanced Distribution Management Systems – Requirements for DMS Integration with DERMS and Microgrids

Argonne NATIONAL LABORATORY

ANL/ESD-15/15

Guidelines for Implementing Advanced Distribution Management Systems

Requirements for DMS Integration with DERMS and Microgrids

Energy Systems Division

This report describes research sponsored by the U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability.

- Chapter 1: Introduction
- Chapter 2: DMS – Current Status and New Challenges
- Chapter 3: Microgrid Operation
- Chapter 4: Distributed Energy Resources
- Chapter 5: Distributed Energy Resources Management Systems
- Chapter 6: DMS Integration with Microgrid
- Chapter 7: DMS Integration with DERMS
- Chapter 8: DMS Design Principles for Integration with DERMS and Microgrids
- Chapter 9: Summary and conclusion

Upcoming Foundational DMS Report Series

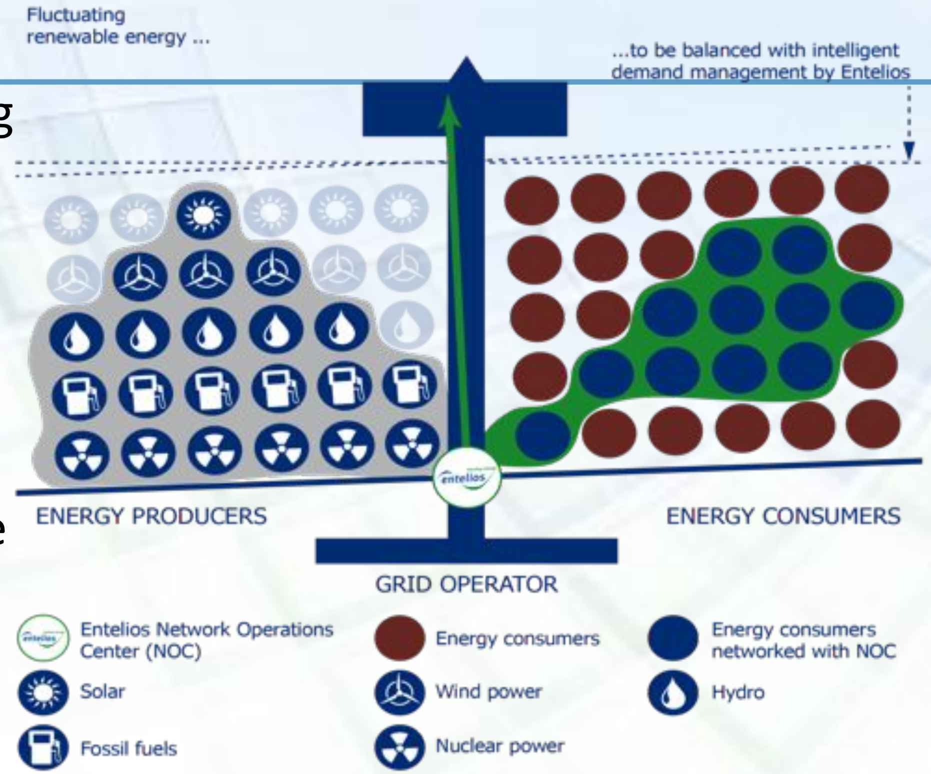
1. Importance of DMS for Distribution Grid Modernization (ANL/ESD-15/16)
2. DMS Functions (ANL/ESD-15/17)
3. High-Level Use Cases for DMS (ANL/ESD-15/18)
4. Business Case Calculations for DMS (To Be Published)
5. Implementation Strategy for DMS (To Be Published)
6. DMS Integration of Microgrids and DER (To Be Published)
7. DMS Industry Survey (To Be Published)

Follow-on projects:

- Interconnection, Integration and Interactive Impact Analysis of µGrids and the Distribution Systems
- Structuring a demonstration project to Integrate DER, Microgrid EMS, DERMS, and DMS

Distributed Load Control

- Why demand response (DR)? increasing demand, expensive generation investment, reliability enhancement, renewable integration, etc.
- Goals
  - Decentralized reliable direct load control of residential appliances while taking full advantage of their operational flexibilities
- How?
  - Two-layer communication based control architecture
  - Upper-layer: distributed target allocation using average consensus algorithm
  - Lower-layer: Load information update and admission control



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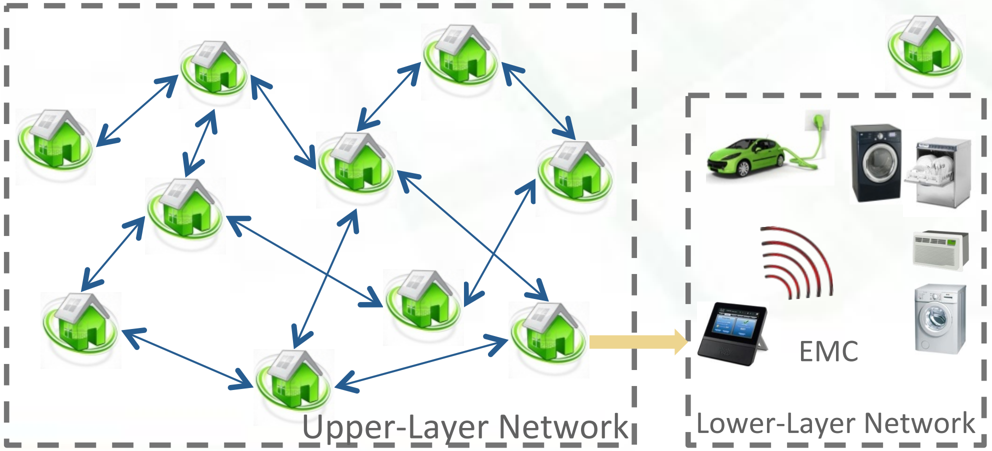
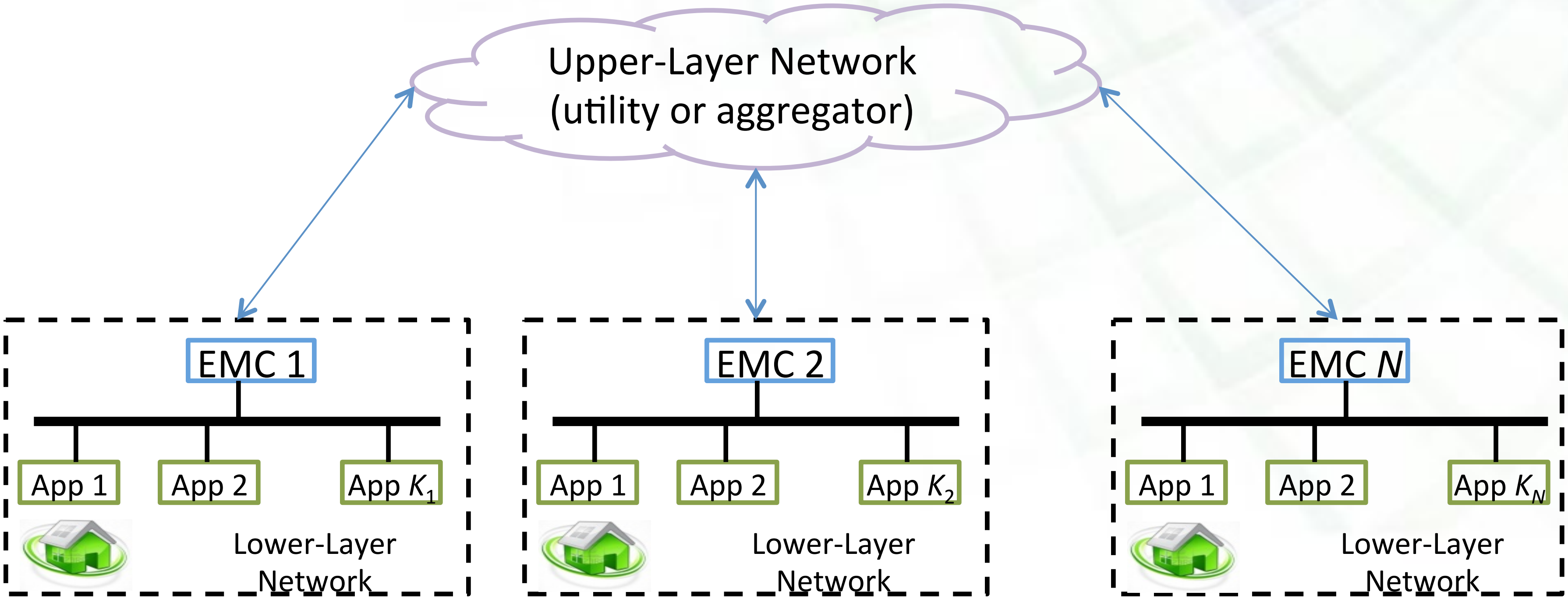


Reference: C. Chen, J. Wang, S. Kishore, A Distributed Direct Load Control Approach for Large-Scale Residential Demand Response, *IEEE Transactions on Power Systems*, Vol. 29, No. 5, pp. 2219 - 2228, September 2014

A Two-layer Communication based Control Architecture

- Advantages of our approach
  - ***Low requirements for computation***: Distributed control
  - ***Low communication complexity:*** Limited data communication requirements
  - ***Reliable and robust***: No central controller for the aggregator needed
  - ***Privacy protection***: Individual appliance usage not exposed to others
  - ***Fair***: Unbiased for any individual customer
  - ***Non-intrusive***: Override option provided and little impact on appliances



Distributed Direct Load Control for Large-Scale Residential Demand Response (Cont'd)

- Upper-layer Design
  - A desired overall demand Z_τ for the aggregator serving the area
  - Allocate this demand to local power consumption target θ_i^τ for each building
  - Each EMC communicates to its neighboring EMCs for the local power consumption target computation in a fully distributed fashion
  - Local power consumption target computation

$$\theta_i^\tau = \hat{q}_i^\tau + \eta_\tau \cdot \tilde{q}_i^\tau, \qquad \eta_\tau = \frac{Z_\tau - \sum_{i\in\mathcal{B}} \hat{q}_i^\tau}{\sum_{i\in\mathcal{B}} \tilde{q}_i^\tau}$$

$\hat{q}_i^\tau$: fixed demand
$\tilde{q}_i^\tau$: flexible demand

  - Average values $\hat{q}_i^{\tau *}$ and $\tilde{q}_i^{\tau *}$: consensus agreement by all nodes; the ratio can be computed indirectly

$$\sum_{i\in\mathcal{B}} \tilde{q}_i^\tau = B \cdot \tilde{q}^{\tau *} \qquad \sum_{i\in\mathcal{B}} \hat{q}_i^\tau = B \cdot \hat{q}^{\tau *}$$

  - Average consensus algorithm

$$\hat{q}_i^\tau(k+1) = \hat{q}_i^\tau(k) + \varepsilon \cdot \sum_{j\in\mathcal{N}_i} \left[\hat{q}_j^\tau(k) - \hat{q}_i^\tau(k)\right]$$

$$\tilde{q}_i^\tau(k+1) = \tilde{q}_i^\tau(k) + \varepsilon \cdot \sum_{j\in\mathcal{N}_i} \left[\tilde{q}_j^\tau(k) - \tilde{q}_i^\tau(k)\right]$$

$\mathcal{N}_i$: set of neighboring nodes of i
ε: step size
k: iteration index

  - Convergence is guaranteed: scalable to network size

Distributed Direct Load Control for Large-Scale Residential Demand Response (Cont'd)

- Lower-layer Design
  - Load information update
    - Appliances send power-on/power-off requests to the EMC
    - EMC tracks the different states of appliances with different sets
    - Media access control with acknowledge for the packets transmission
  - Admission control mechanism: approach the local demand target

$$
\begin{aligned}
\max_{x_j, v_{i,j}^{\tau}} \quad & \sum_{j \in \mathcal{R}_i^{\tau}} x_j \cdot P_{i,j}^{\tau} + \sum_{j \in \mathcal{Z}_i} v_{i,j}^{\tau} \\
\text{s.t.} \quad & \hat{q}_i^{\tau} + \sum_{j \in \mathcal{R}_i^{\tau}} x_j \cdot P_{i,j}^{\tau} + \sum_{j \in \mathcal{Z}_i} v_{i,j}^{\tau} \leq \theta_i^{\tau} \\
& \xi_{i,j}^{\tau} \cdot v_{i,j}^{\tau,\min} \leq v_{i,j}^{\tau} \leq \xi_{i,j}^{\tau} \cdot v_{i,j}^{\tau,\max}, \ j \in \mathcal{Z}_i \\
& x_j \in \{0,1\}, \ j \in \mathcal{R}_i^{\tau}
\end{aligned}
$$

x_j: On/Off decision for Type I appliance *j*

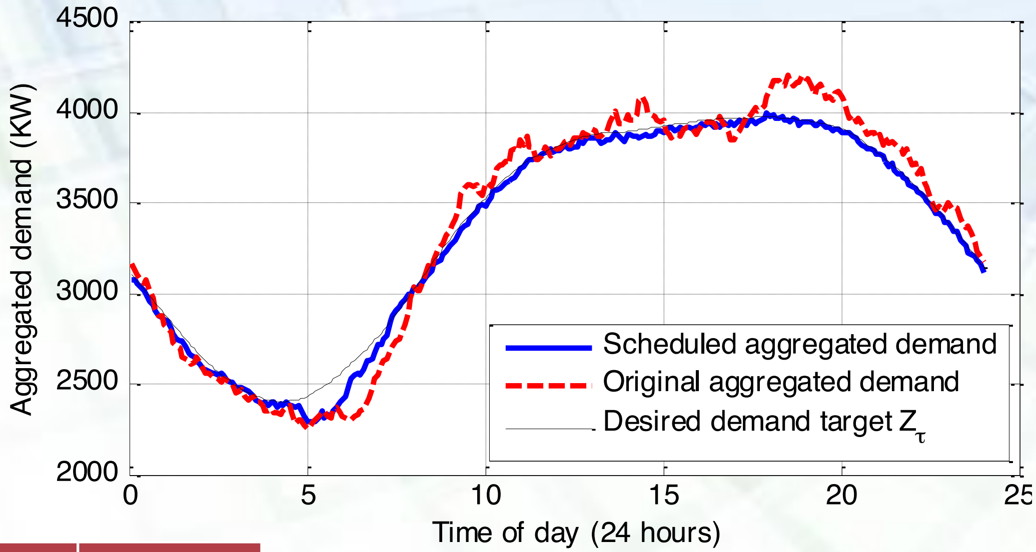
$P_{i,j}^{\tau}$: Power consumption for Type I appliance *j* (constant)

$v_{i,j}^{\tau}$: Power consumption decision for Type II appliance *j*

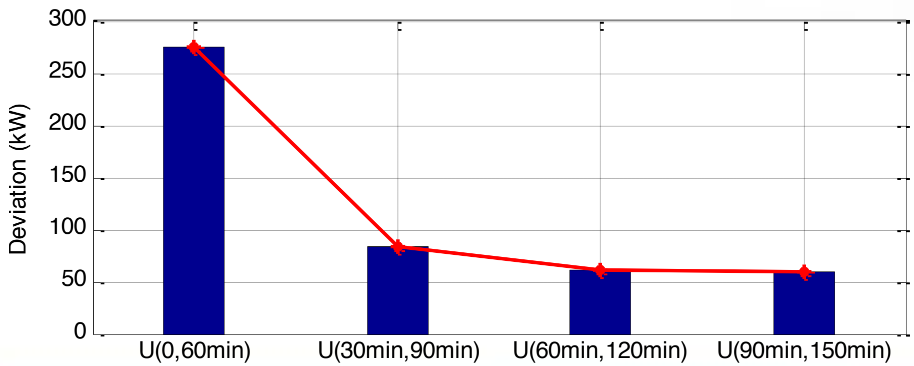
  - Non-intrusiveness design for appliances: customer override options; preventing frequent ON-OFF switches; operation deadline

Distributed Direct Load Control for Large-Scale Residential Demand Response (Cont'd)

- One day scheduling results
  - Scheduled aggregated demand is closer to the desired demand than the original demand
  - Deviation decreases by 35.6%



% of flexible apps	100%	75%	50%	25%
Deviation (kW)	80.2	84.2	97.1	101.9



- Effects of operation flexibilities on deviation
  - More flexible appliances, lower deviation
  - Larger delay tolerance, lower deviation

Power Grid Resilience

- PRESIDENTIAL POLICY DIRECTIVE/PPD-21

  The Presidential Policy Directive (PPD) on Critical Infrastructure Security and Resilience advances a national unity of effort to strengthen and maintain secure, functioning, and resilient critical infrastructure.

- Bulk Power System Restoration
  - Integrated Restoration Model
  - Restoration Solution Refinement
  - Solution Algorithms
  - Optimal Black-Start Resource Procurement
- Distribution System Restoration
  - Microgrid formation
  - Network reconfiguration
- Working closely with FEMA, MISO and PJM
- Tied to Smart Cities

Argonne's Comprehensive Set of resilience tools

Prepare

- Self-assessment (**ERAP-D**)
- Emergency planning (**onVCP/ SyncMatrix, SpecialPop, LPAT**)
- EP/PSR exercise/ drill (**Scenarios, Threat-Damage, Impact Models**)

Mitigate

- Mitigation assessment (**EPfast, NGfast, POLfast**)
- Resource mitigation measures, dependencies (**IST-RMI**)
- Power system restoration planning (**EGRIP**)
- Blackstart resource planning (**EGRIP**)

Respond

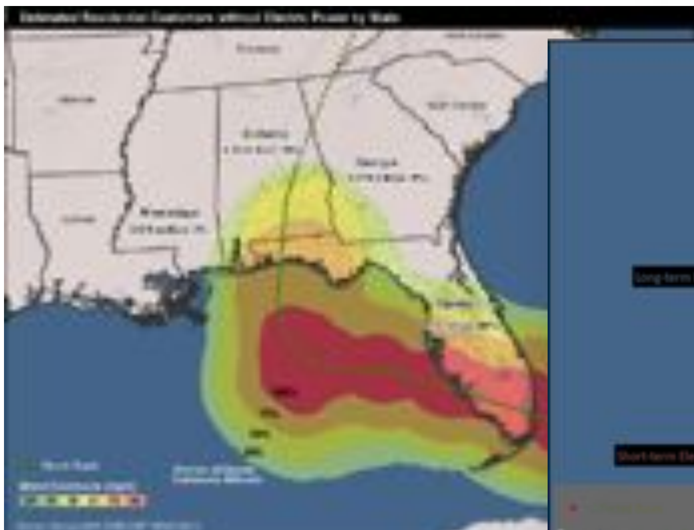
- Impact assessment (**Threat-Damage, Impact Models**)
- Hurricane assessment (**HEADOUT**)
- Emergency management/ response (**onVCP, vBEOC**)

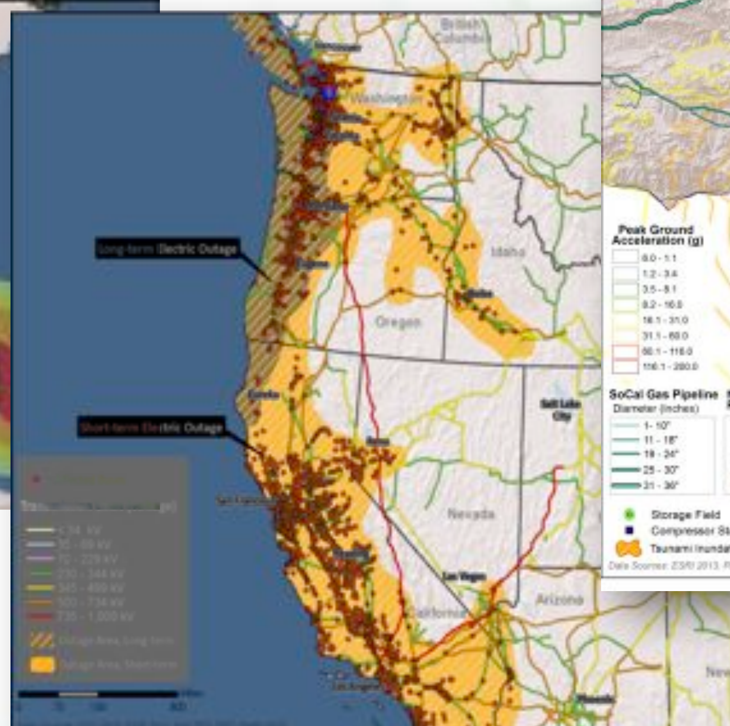
Recover

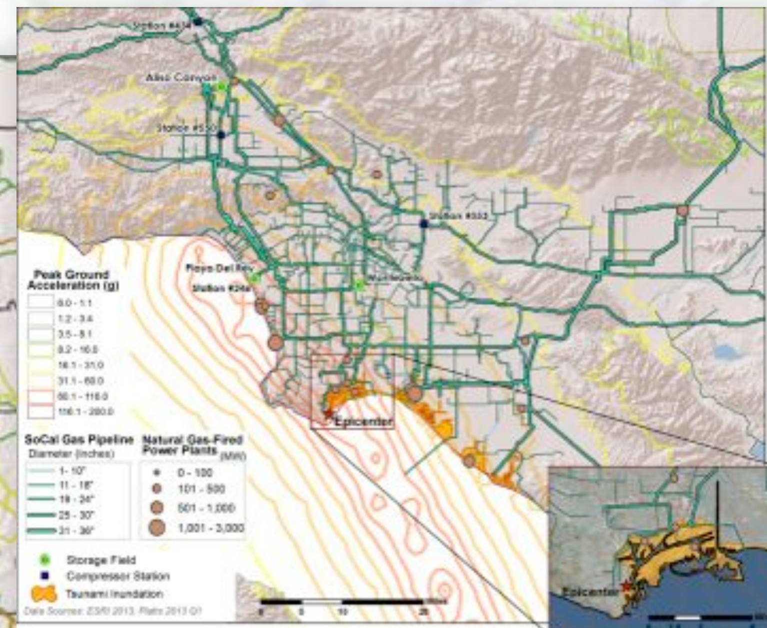
- Real-time PSR analysis (**EGRIP**)
- Emerge-Manage., Communication, Collaboration (**onVCP/vBEOC**)

Experience: Regional infrastructure resilience

- Regional Resilience Assessment Program identifies critical infrastructure security and resilience gaps to all hazards; dependencies; interdependencies; cascading effects
- Includes multiple infrastructure assessment tools (oil, gas, electric, water, service restoration)
- Argonne completed 56 RRAPs (2009-2015) and supported various table-top exercises for DOE

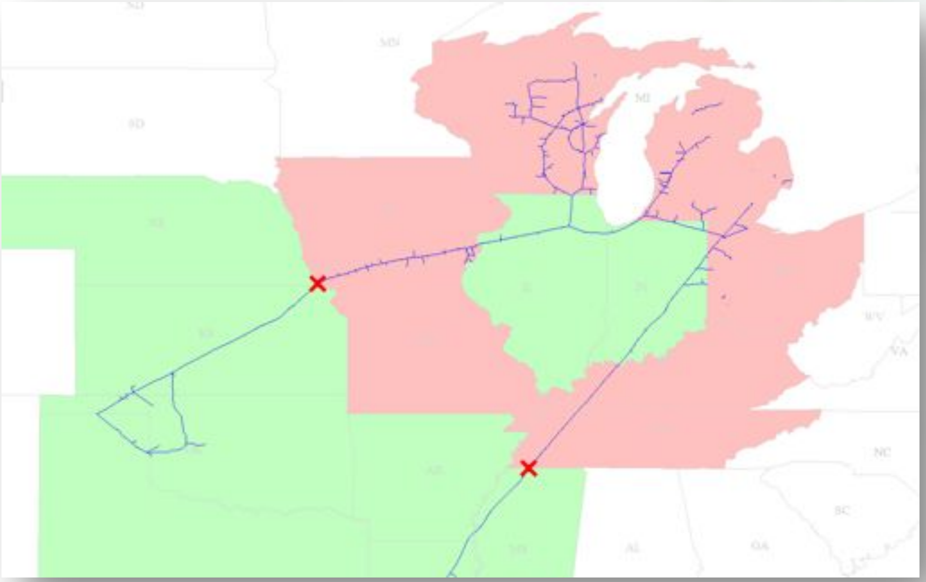






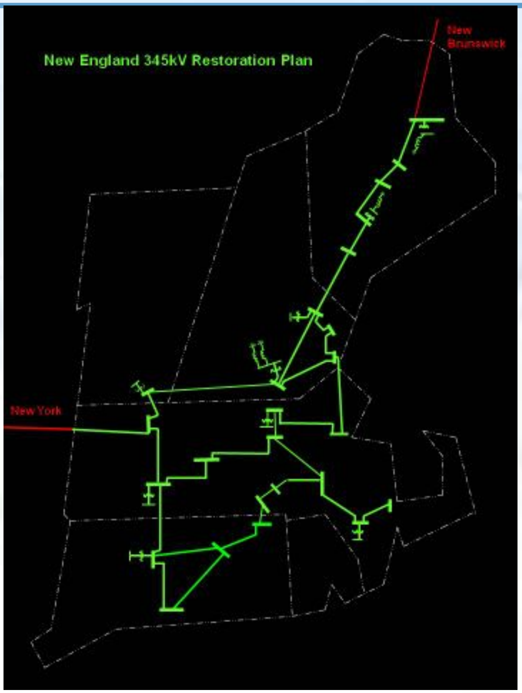
Experience: Support for EP/PSR drills for MISO

- Trained over 300 grid operators in Midcontinent Independent System Operator (MISO) footprint on electric/gas interdependencies as part of 2015 EP/PSR training cycle
- Support MISO's working group for Emergency Preparedness and Power System Restoration (EP/PSR) in upcoming 2016 drills (spring and fall)



NGfast Graphical Results—States Affected

Bulk Power System Restoration – Highlights of Our Modeling and Analysis Approach



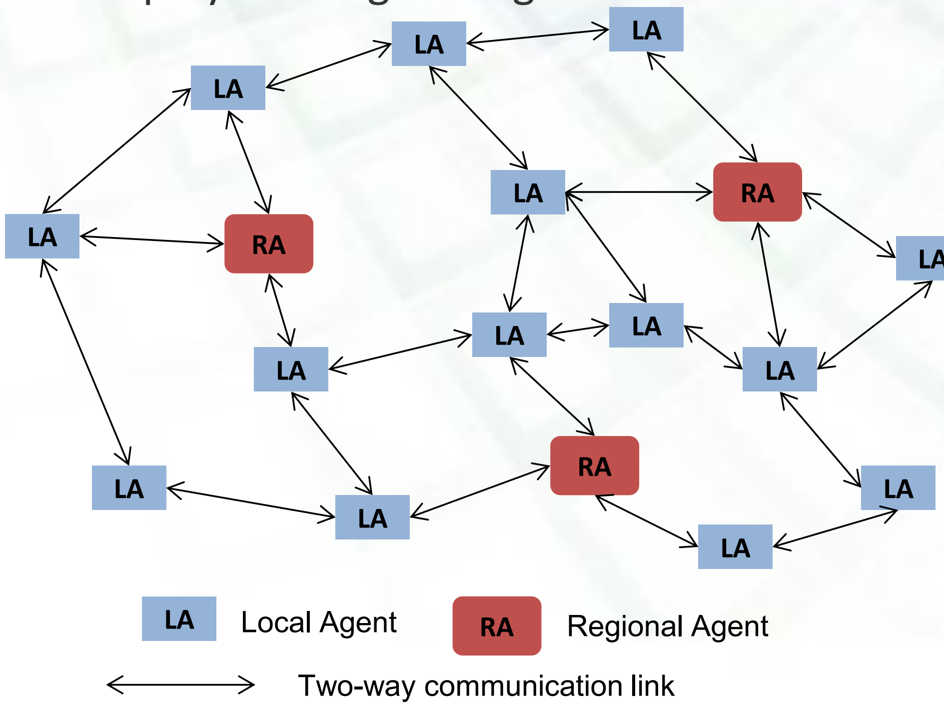
- Integrated model that simultaneously optimizes system sectionalization and generator startup leading to a global optimal solution
  - Maintain load-generation balance
  - Minimize overall restoration time
- Advanced simulator that validates restoration plans (e.g., line overloading, frequency excursion, voltage limits, etc.)
- Integrated restoration of both bulk power and distribution systems

Bulk power system restoration
- Integrated optimization model (produces an initial restoration plan)
- Power system simulator (checks restoration plan feasibility)

Distribution system restoration
- Distributed multi-agent coordination scheme for global information discovery
- Dynamic microgrid formation using distributed generation

Distribution System Restoration - Our Approach

- Utilize distributed generators (DGs) and automatic switches to form several microgrids after a large natural disaster
- Continue supplying critical loads, after major grid faults
- Use distributed multi-agent coordination scheme for global information discovery: increased resilience over centralized communication schemes (single point of failure)
- Objective: maximize the total weighted load picked up by forming microgrids energized by DGs
- Mixed integer linear programming (MILP) formulation considering both topology and operational constraints
  - Decision variables: ON/OFF status of remotely controlled automatic switches (binary); output of DG (continuous)
  - Constraints: Topology constraints, power flow constraints, voltage range constraints, distribution condition constraints
- Leads to more resilient distribution system



Reference: C. Chen, J. Wang, F. Qiu, D. Zhao, Resilient Distribution System by Microgrids Formation After Natural Disasters, *IEEE Transactions on Smart Grid*, in press.

Conclusions

- Our electric power industry experiences unprecedented changes at a stunning pace
- Significant supply side changes that include continued rapid growth of renewables and changes in our thermal power generation mix may lead to changes in markets, system operations, and system planning
- New consumers and new technologies may alter our demand situation significantly and lead to more uncertainty in demand forecasts
- Smart grid offers both opportunities and challenges
- New approaches to data management, analysis, and modeling will be needed

Questions?

THANK YOU!

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