Fall 10-24-2012

Keynote Talk Wednesday

Gil Bindewald
US DOE

Office of Electricity Delivery & Energy Reliability

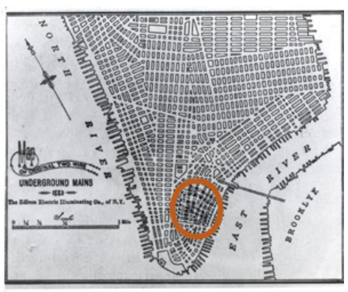
Modeling, Simulation and Optimization for the 21st Century Electric Power Grid

Gil Bindewald
US Department of Energy
Lake Geneva, WI Oct 21-25, 2012

Evolution of Reliability in the World's Most Complex Machine

- Interregional connections brought additional reliability
  - Back-up in times of equipment failure, unexpected demand, or routine maintenance.
  - Economics through reserve sharing and access to diverse energy resources.

Pearl Street Station



Vertically-Integrated Utilities

Isolated Generating Plants — Isolated Systems — Regional Systems — Interregional Systems — **How will reliability be achieved in the future?**

1885 *1910* *1935* *1960*

Complete interconnection of North America by 1964

Operational Challenges

- *The future generation resource mix is unknown*
- *The variability and uncertainty of wind and solar power require new ways to operate the power system (including the use of storage, natural gas, demand response, inter-hour scheduling; market impacts)*
- *Load profiles are uncertain as on-site renewable energy resources, demand response technologies, and EVs/PEVs are introduced to distribution systems*
- *Valuation of ancillary services is evolving*
- *Boundary seams are critical for effective integration*
- *New concerns (e.g., workforce; cybersecurity) are continually emerging*

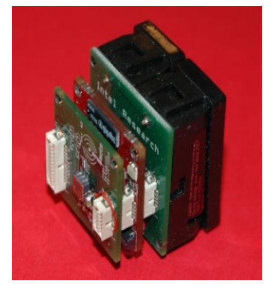
Addressing the Challenges…

- "Smart Grid" data sources enable real-time precision in operations and control to dynamically optimize grid operations to adapt to changing conditions
  - Real-time data from distribution automation and smart meter systems will significantly advance real-time operations of distribution systems and enable customer engagement through demand response, efficiency etc.
  - Time-synchronous phasor data, linked with advanced computation and visualization, enable advances in state estimation, real-time contingency analysis, and real-time monitoring of dynamic (oscillatory) behaviors in the system.

U.S. DEPARTMENT OF ENERGY | Office of Electricity Delivery and Energy Reliability

Smart Grid Investment Grant (SGIG)

Deploying technologies for immediate commercial use
supporting manufacturing, purchasing, and installation of smart grid technologies

Customer Systems	Advance Metering Infrastructure	Electric Distribution Systems	Electric Transmission Systems	Equipment Manufacturing
				
• Displays • Portals • Energy management • Direct load controls	• Smart meters • Data management • Back office integration	• Switches • Feeder optimization • Equipment monitoring • Energy storage	• Wide area monitoring and visualization • Synchrophasor technology • Energy storage	• Energy devices • Software • Appliances

99 projects, $3.4B Federal + $4.6B Private Investments

SMARTGRID.GOV RECOVERY ACT SMART GRID PROGRAMS

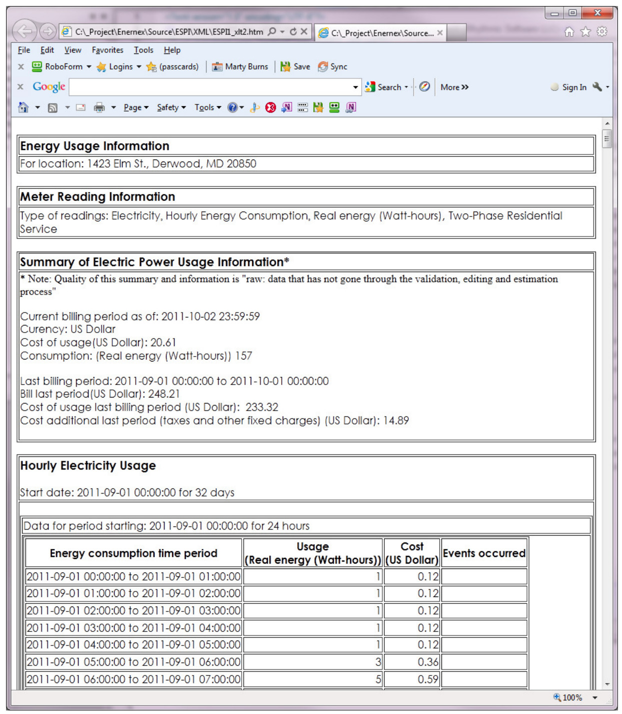
U.S. DEPARTMENT OF ENERGY | Office of Electricity Delivery and Energy Reliability

Green Button Data and Information Tools

Allow consumers to download standardized data file by clicking online "Green Button" to view their energy use information and transmit to third parties for value-added services

Green Button Download My Data

20 utilities committed to provide Green Button data access to 31 million customers (as of May 2012)



Energy Usage Information
For location: 1423 Elm St., Derwood, MD 20850

Meter Reading Information
Type of readings: Electricity, Hourly Energy Consumption, Real energy (Watt-hours), Two-Phase Residential Service

Summary of Electric Power Usage Information*
* Note: Quality of this summary and information is "raw: data that has not gone through the validation, editing and estimation process"

Current billing period as of: 2011-10-02 23:59:59
Currency: US Dollar
Cost of usage(US Dollar): 20.61
Consumption: (Real energy (Watt-hours)) 157

Last billing period: 2011-09-01 00:00:00 to 2011-10-01 00:00:00
Bill last period(US Dollar): 248.21
Cost of usage last billing period (US Dollar): 233.32
Cost additional last period (taxes and other fixed charges) (US Dollar): 14.89

Hourly Electricity Usage
Start date: 2011-09-01 00:00:00 for 32 days

Data for period starting: 2011-09-01 00:00:00 for 24 hours

Energy consumption time period	Usage (Real energy (Watt-hours))	Cost (US Dollar)	Events occurred
2011-09-01 00:00:00 to 2011-09-01 01:00:00	1	0.12	
2011-09-01 01:00:00 to 2011-09-01 02:00:00	1	0.12	
2011-09-01 02:00:00 to 2011-09-01 03:00:00	1	0.12	
2011-09-01 03:00:00 to 2011-09-01 04:00:00	1	0.12	
2011-09-01 04:00:00 to 2011-09-01 05:00:00	1	0.12	
2011-09-01 05:00:00 to 2011-09-01 06:00:00	3	0.36	
2011-09-01 06:00:00 to 2011-09-01 07:00:00	5	0.59	

Standard EUI File Format

Value-added Services

Did you know?

- Whirlpool, the world's largest manufacturer and maker of home appliances, has announced that it plans to make all of its electronically controlled appliances "smart grid-compatible" by 2015.

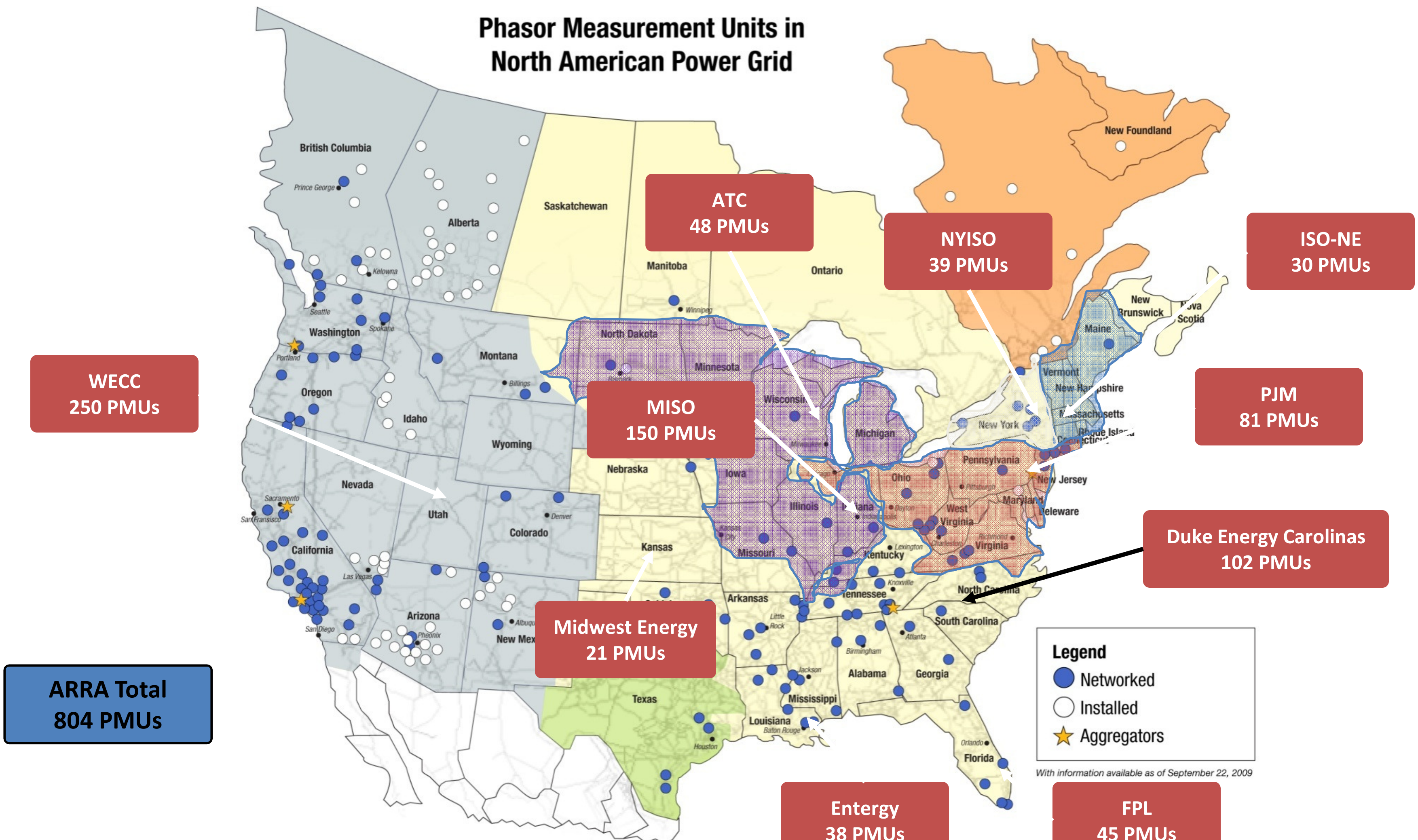
Peak and Overall Demand Reduction via AMI, Pricing and Customer Systems

62 SGIG projects (pricing and customer systems offered mostly at pilot scales):

- **56 offering web portals; 46 offering (DLC, PCTs, and/or IHDs)**
- **32 offering pricing (TOU, CPP, CPR, VPP)**

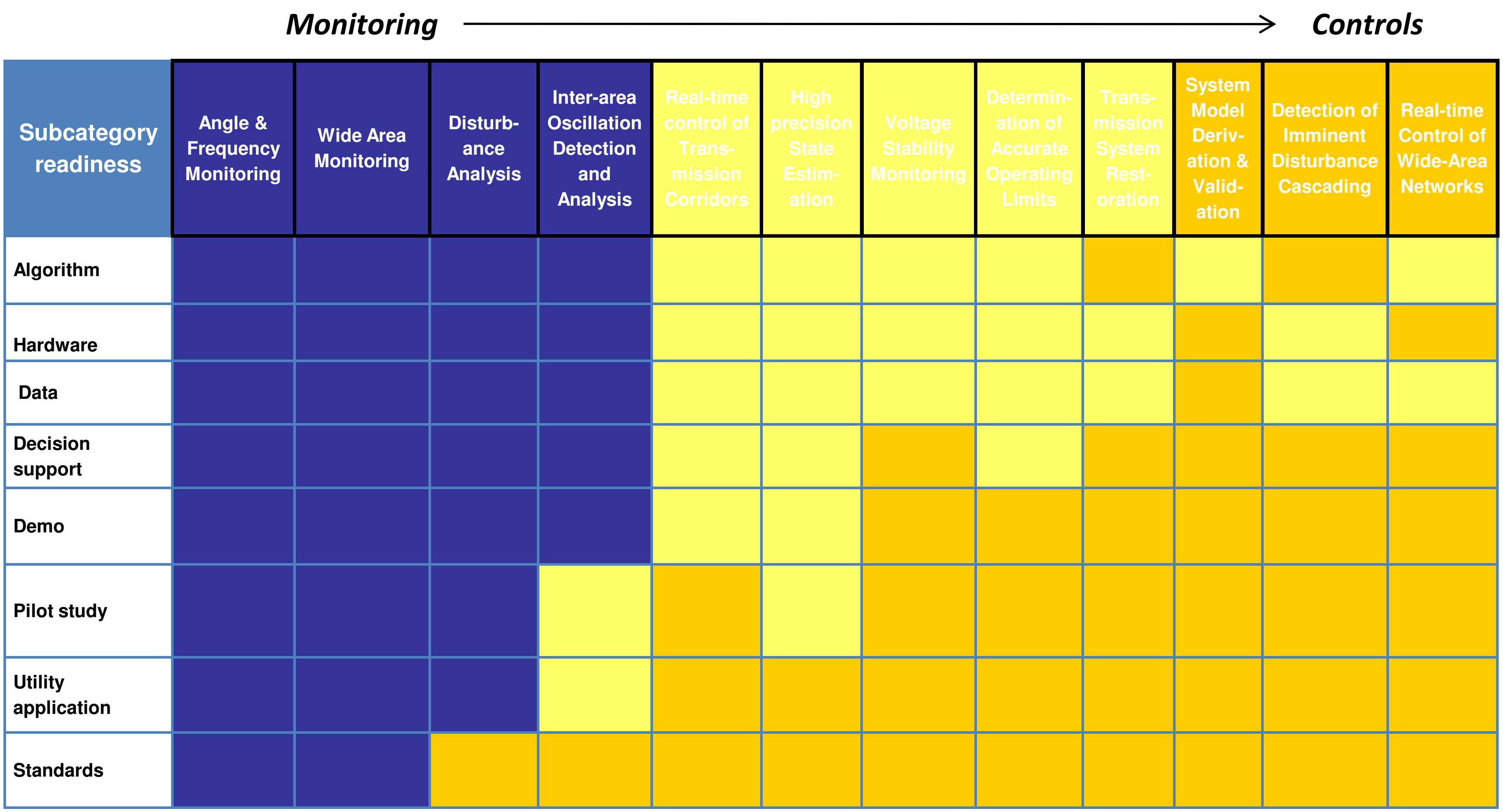
Project Elements	OG&E 770,000 customers	MMLD 11,000 customers	SVE 18,000 customers
Customers Tested	6,000 residential	500 residential	600 mostly residential
Time-Based Rate(s)	TOU and VPP, w/CPP	CPP	CPP
Customer Systems	IHDs, PCTs, and Web Portals	Web Portals	Web Portals
Peak Demand Reduction	Up to 30% 1.3 kW/customer (1.8 kW/customer w/CPP)	37% 0.74 kW/customer	Up to 25% 0.85 kW/customer
Outcome	Deferral of 210 MW of peak demand by 2014 with 20% participation	Lowers total purchase of peak electricity	Lowers total purchase of peak electricity
Customer Acceptance	Positive experience, many reduced electricity bills	Positive experience, but did not use the web portals often	Interested in continued participation, many reduced electricity bills

Synchrophasor Deployment

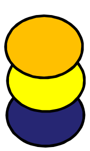


Source: Map from North American Synchrophasor Initiative, 2009

Emerging Real-Time Tools



Near-Term | 2-5 years | >5 years

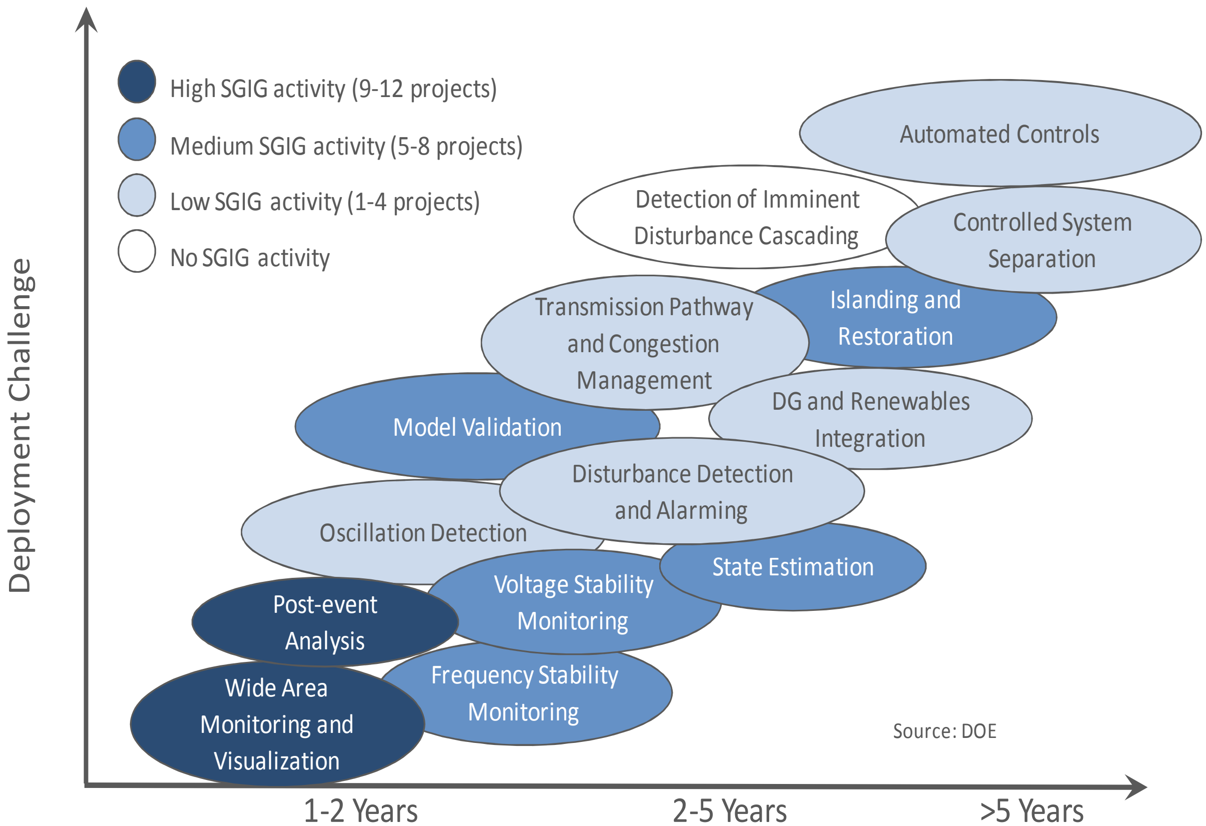


Requires Development and Pilots

Needs Moderate Development

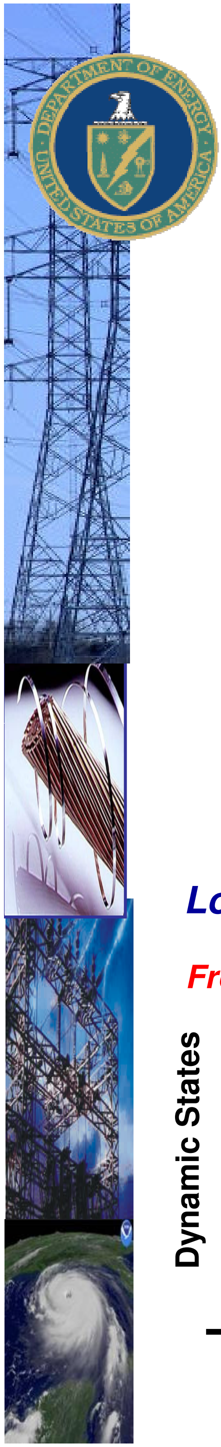
Available Now or Soon

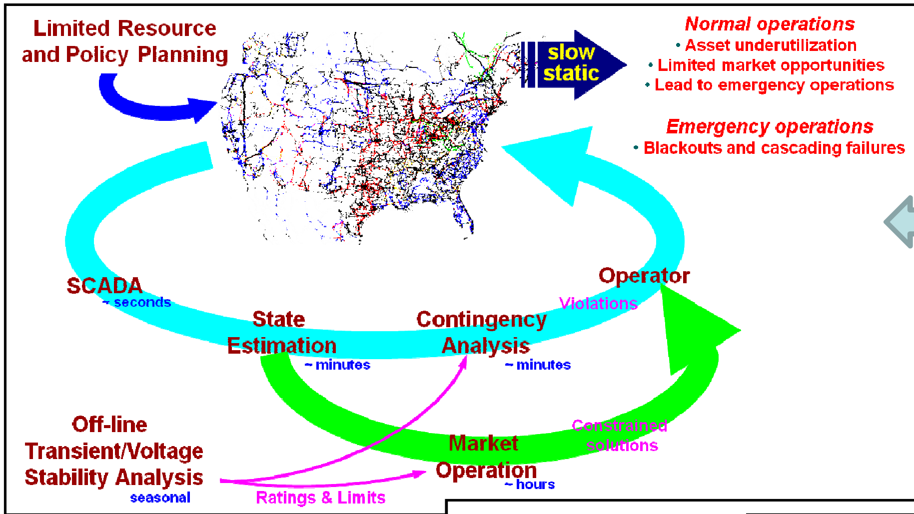
10 SGIG Synchrophasor Projects



Benefits:

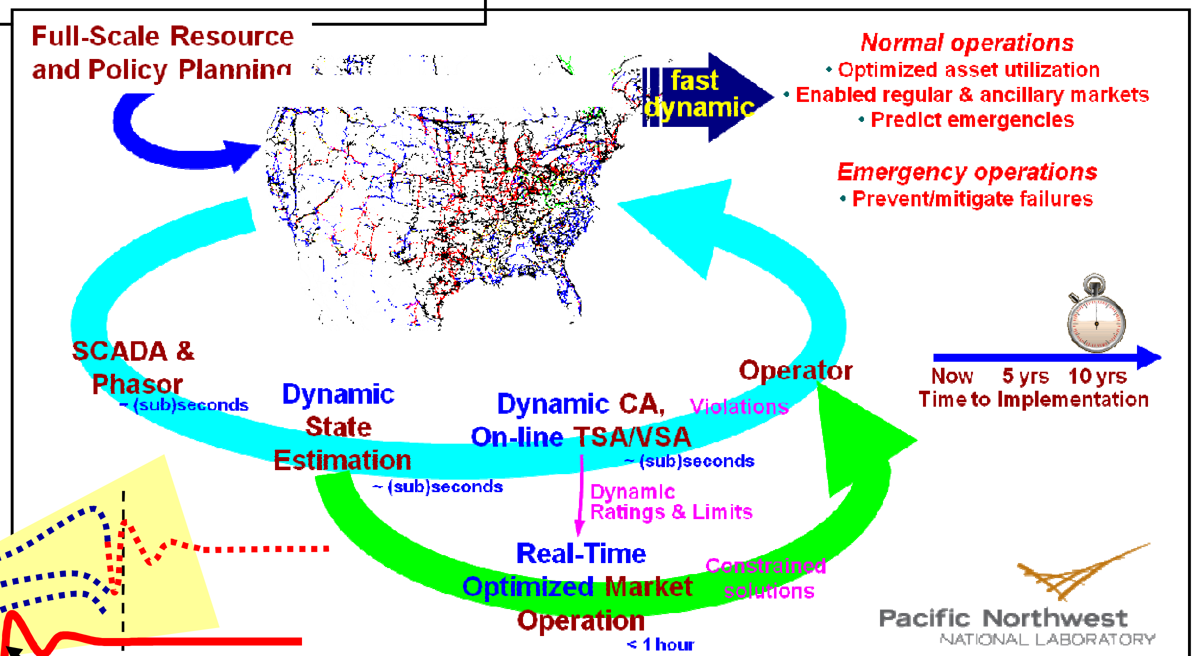
- **Improved reliability and resiliency**
- **Improved asset utilization**
- **Reduced transmission congestion**
- **Integration of distributed generation and renewables**





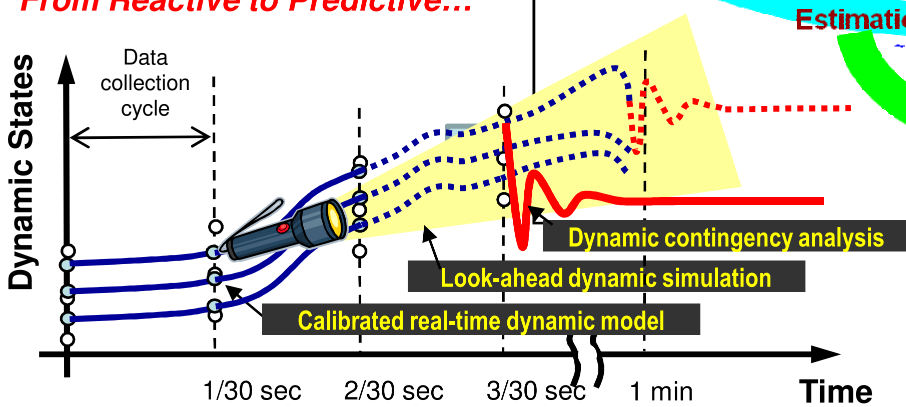
TODAY:

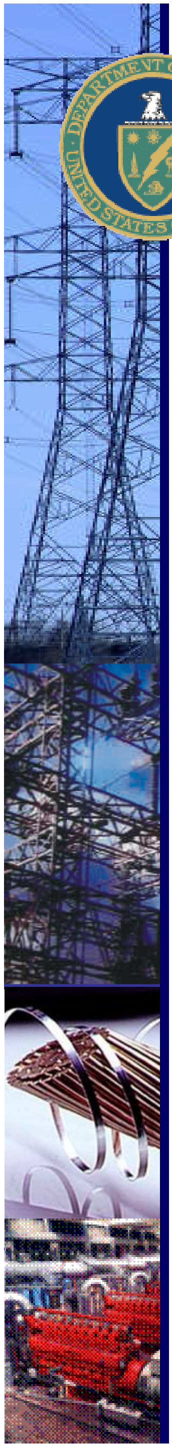
- Reliance on off-line analysis to set operating limits
- Operator trying to make control decisions, especially fast decisions during a disturbance, on incomplete data
- High reliance on local protection technologies to protect the grid if all else fails



Long-Term Vision

From Reactive to Predictive…



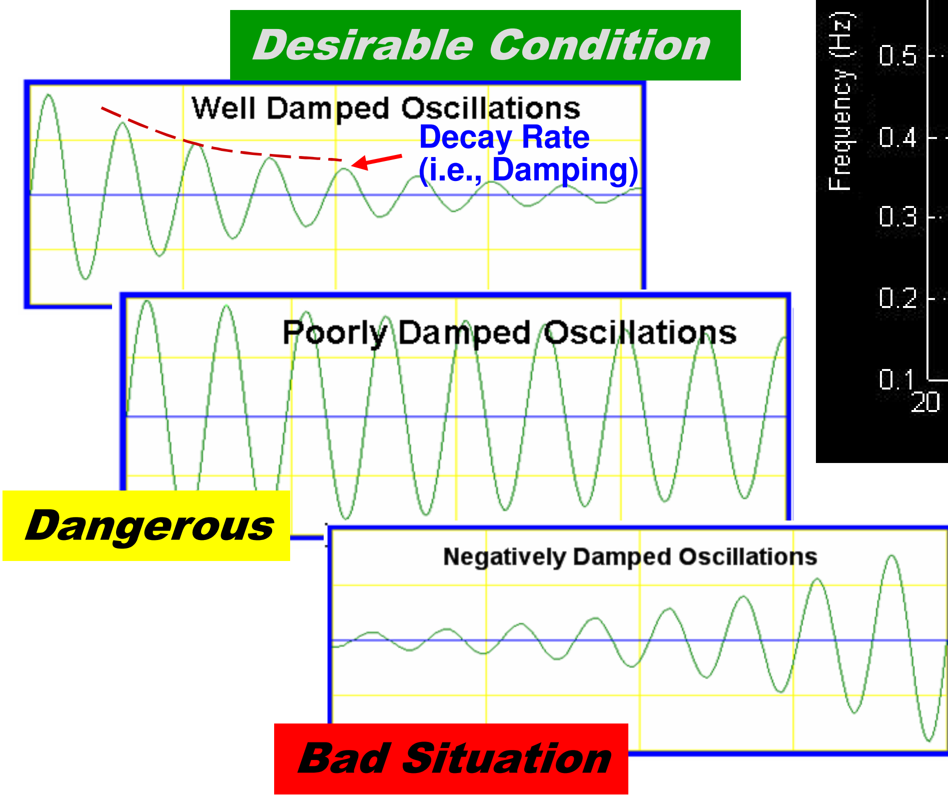


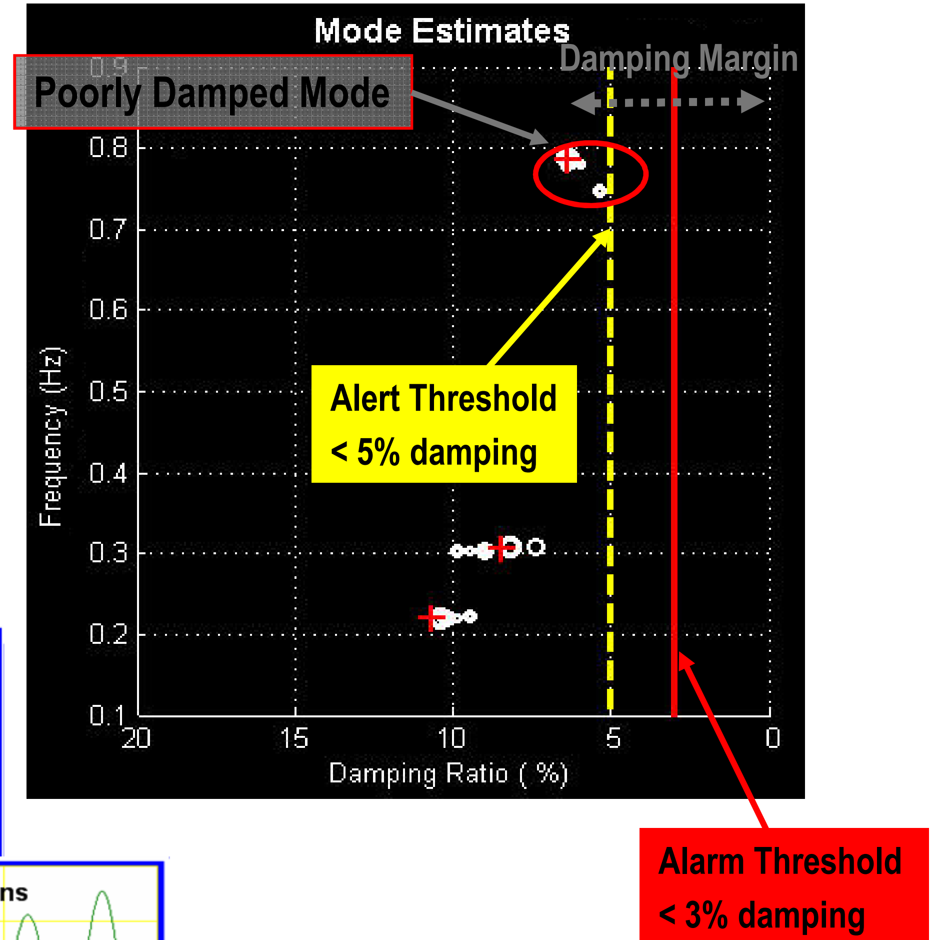
Grid Robustness:

Example of Development of New Tool Capabilities

Question: How well can the system withstand disturbances?

Damping (in %) is a measure of the grid's resilience to system events.



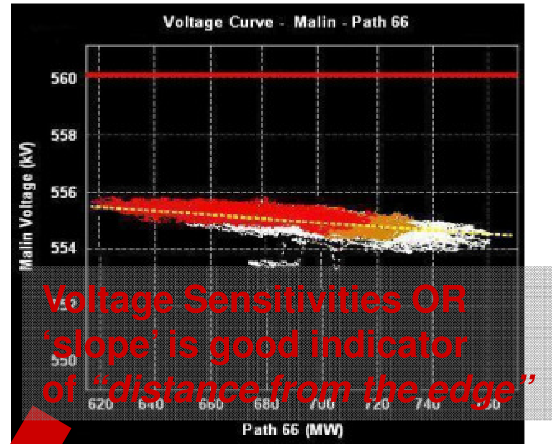


Source: CERTS

Reliability Margins :
Example of Development of New Tool Capabilities

Question: How far are we from the edge?

With PMUs, we can directly measure Voltage Sensitivities (kV/100MW) at critical interfaces or load pockets.



Voltage Stability

Higher Transfer Limits

Higher Energy Flows

Cliff!

When voltages drop too far, the entire power system can collapse

Large power flows over long distances increase the risk of voltage collapse

Source: CERTS

Advanced Modeling Grid Research Awards ($6.8M/FY12)

These projects will result in a new class of decision support tools that will simulate dynamic events and help inform operators on real-time conditions to maintain stability:

Electric Power Research Institute (EPRI) – Knoxville, TN

This project will develop a comprehensive set of innovative technical approaches and software tools to support operators' situational awareness and decision-making. The integrated tools will combine high-performance dynamic simulation results with synchrophasor measurement data to assess in real time the system dynamic performance and operational security risk.

Michigan State University (MSU) – East Lansing, MI

This project will develop a Lyapunov function based remedial action screening (L-RAS) tool that will use real-time data. This approach supports selection of appropriate remedial actions that are most likely to result in stabilizing trajectories.

Illinois Institute of Technology (IIT) – Chicago, IL

This project will accelerate performance and enhance accuracy of dynamics simulations, enabling operators to maintain reliability and steer clear of blackouts. This effort forms the backbone of a hybrid real-time protection and control architecture.

General Electric Global Research (GE) – Niskayuna, NY

This project will apply advanced computational techniques to the Positive Sequence Load Flow (PSLF) dynamic simulation software to demonstrate faster than real-time dynamic simulation. This will be coupled with expertise in small signal stability to develop a proof-of-concept for a fast contingency screening and control action engine.

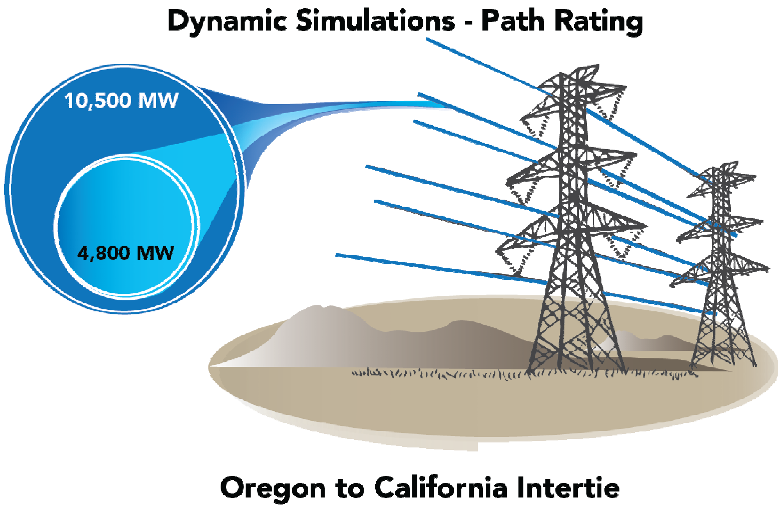
PowerWorld Corporation – Champaign, IL

This project will develop a faster than real-time dynamic simulation tool in the transient stability to short-term voltage instability or oscillatory stability time frame (from cycles to minutes) that can be used by operators of large, interconnected power grids for enhanced near real-time dynamic operational awareness and security decision-making.

Fast computation supports non-wire solution to congestion management

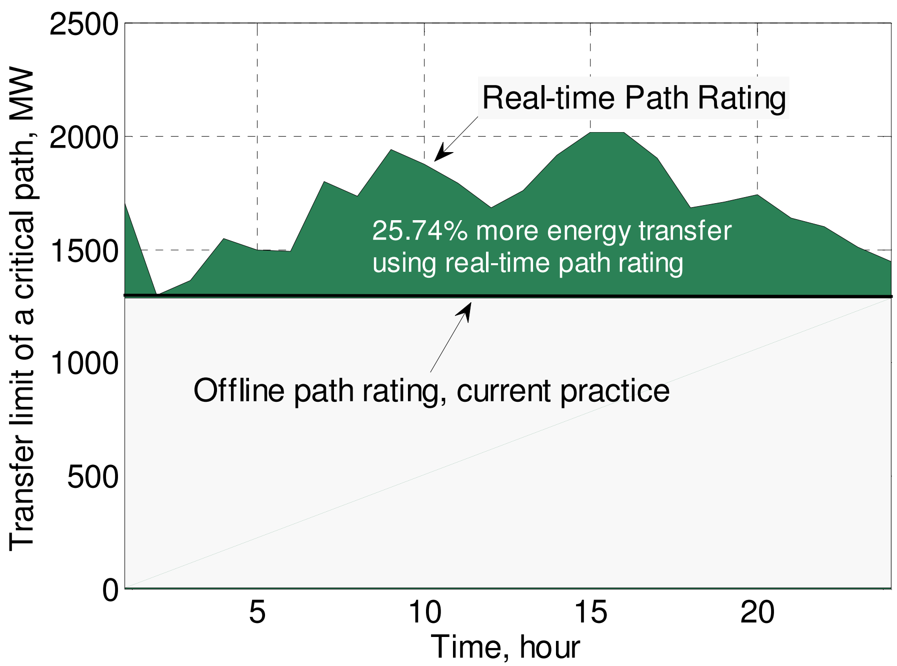
Fast Dynamic Simulation:

New simulation improving system efficiency

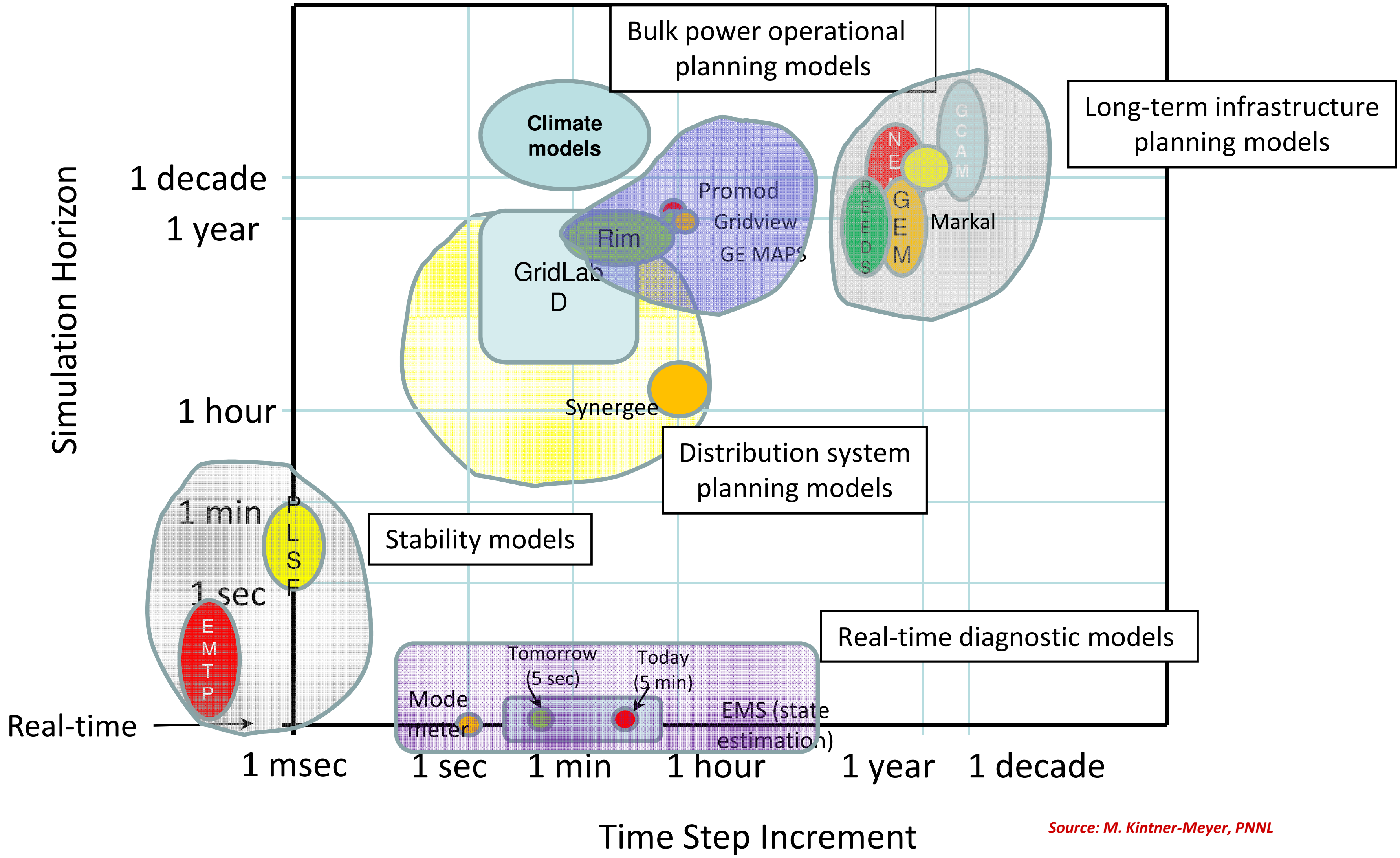


- 6x faster-than-real-time for interconnection-scale systems.
- Supports real-time rating for key assets and dramatically improves asset utilization: from off-line (weeks) to real-time (minutes):

- Real-time path rating: demonstration on an IEEE 39-bus power system model
  - 26% more capacity without building new transmission lines



Integrating Model Platforms



Source: M. Kintner-Meyer, PNNL

Technologies, Markets, and Policies are Intricately Linked

- Policies and regulations drive markets which drives technology
- When finding solutions to challenges, all aspects need to be considered simultaneously

The Grid

<u>Policies</u>
state RPS, federal CES, FERC, PUC's, environmental regulations, siting, etc.

<u>Markets</u>
business models, cost allocation, wholesale power trading, utilities, vendors, etc.

<u>Technologies</u>
generation, infrastructure, smart grid, electric vehicles, storage, etc.

Emerging Areas of Model Research

Develop and test new approaches for operations and planning that incorporate…

Uncertainty
- *Wind, other generation*
- *Load*
- *Contingencies (discrete, low probability/high consequence)*

Spatiotemporal dimension
- *Storage, load shifting*
- *Ramping constraints and costs*
- *Unit commitment; economic dispatch*
- *New generation and transmission infrastructure – dynamic effects*

Environmental costs/drivers

Infrastructure Inter-dependencies

Pricing
- *Co-optimize, avoiding sequential optimization*
  (avoid proxy contraints)
- *Capture consumer behavior*
  (as enhanced by smart grid technologies)

Operator Interface

Framework for Data Integration

Advanced Grid Modeling Strategy

GOAL: Develop the computational, mathematical, and scientific understanding needed to transform the tools and techniques (e.g. mathematical formulations) that underpin the planning and operation of the electric system.

STRATEGY: Support mathematically-based power systems research to:

- ***Accelerate Performance –*** improving grid resilience to fast time scale phenomena that drive cascading network failures and blackouts
- ***Enable Predictive Capability –*** relying on real-time measurements and improved models to represent with more fidelity the operational attributes of the electric system, enabling better prediction of system behavior and thus reducing $ inefficiencies
- ***Integrate Modeling Platforms (across the system) –*** capturing the interactions and interdependencies that will allow development (and validation) of new operational and planning approaches

What is needed?

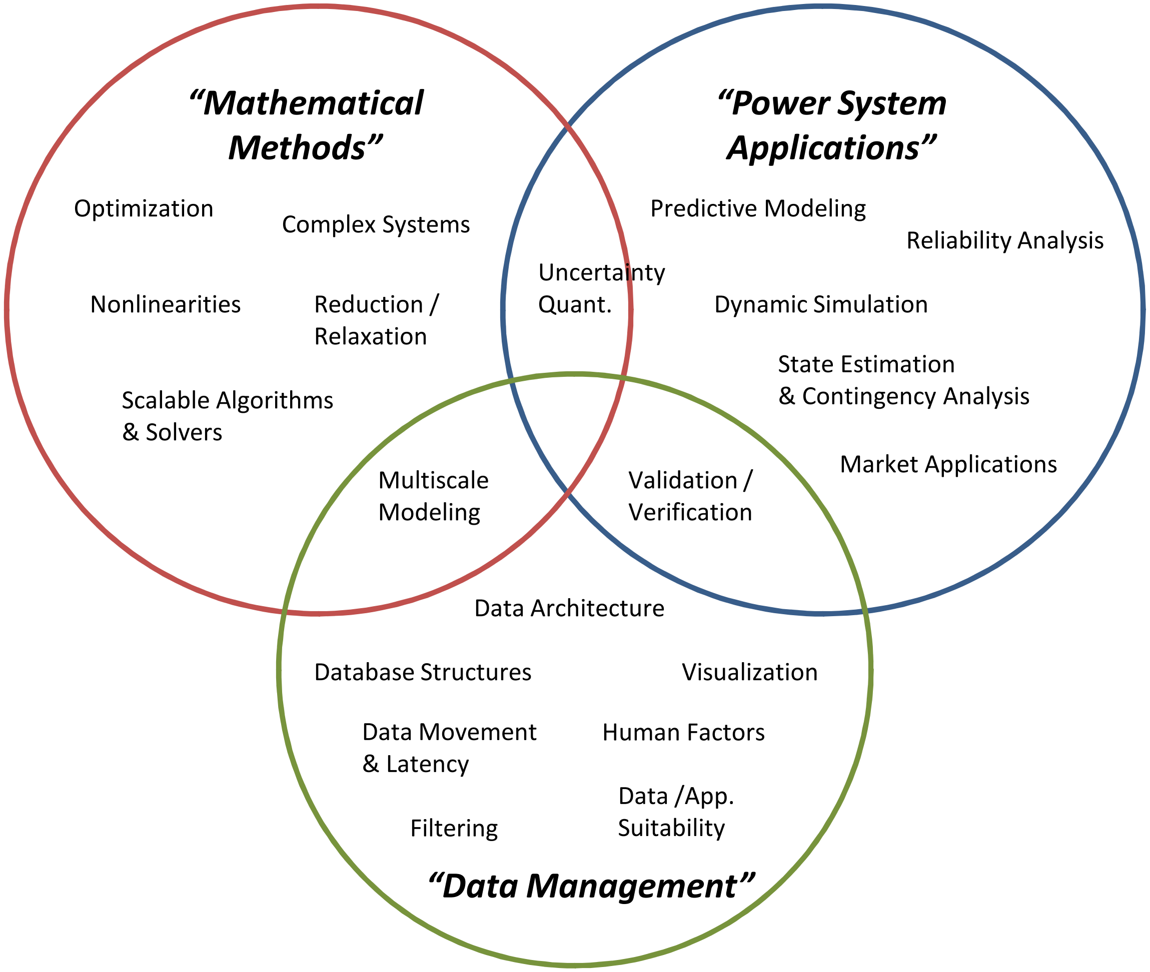
- New algorithms that are scalable and robust for solving large nonlinear mixed-integer optimization problems and methods for efficiently (real-time) solving large sets of ordinary differential equations with algebraic constraints, that include delays, parameter uncertainties, and data as input.

- A new mathematics for characterizing uncertainty in information created from large volumes of data and for characterizing the uncertainty in models used for prediction.

- New methods to enable efficient use of high bandwidth networks by dynamically identifying only the data relevant to the current information need and discarding the rest. This would be especially useful for wide area dynamic control where data volume and latency are barriers.

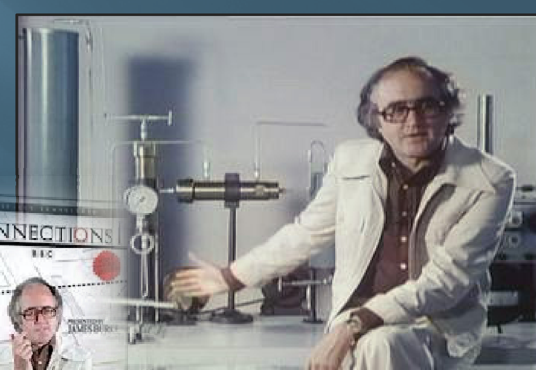
- New software architectures and new rapid development tools for merging legacy and new code without disrupting operation. Software should be open source, modular, and transparent. Security is a high priority.

What is needed?



Connections

- One cannot consider development of any particular piece of the modern world in isolation.
- The history of science and invention has demonstrated how various discoveries, scientific achievements, and historical world events were built from one another successfully in an interconnected way to bring about particular aspects of modern technology.



James Burke (Connections, 1979)

Advanced Modeling

Accelerate existing functions (faster)

- Fast state Estimation
- N-k Contingency Analysis
- Look ahead dynamic simulation
- Financial trans right

Develop new functions (better)

- Dynamic State Estimation
- Stochastics and UQ
- Multi-scale Modeling

Integrated functions

- Operation + Planning
- Trans + Distribution
- Physical + Cyber (Data)

- **Basic Research**
  - multi-scale modeling, optimization, stochastic simulations, uncertainty quantification, large-scale data analysis and data management, and visualization
- **Transformational energy research**
  - innovative control software and control architectures
- **Applied research**
  - accelerate performance and enhance predictability of power systems operational tools; development of new software platforms and capabilities using time-synchronized data, e.g. phasors; reliability modeling in support of regional and interconnection planning
  - development of non-proprietary models of wind generators and inverter technologies for use in transmission planning/interconnection studies
  - use of stochastic simulations for generation dispatch

Coordinated Examples

- **Improved Power System Operations Using Advanced Stochastic Optimization**
  - Parallel algorithms and software for solving stochastic optimization problems (SC)
  - New commitment/dispatch/ pricing formulation and models that uses probabilistic inputs to account for uncertainty (ARPA-E, SC, OE)
  - Real-time tools and platforms for balancing demand-side flexibility and supply-side variability (OE, EERE, ARPA-E)
  - Renewable integration model (RIM) for multi-timescale power-flow analysis (OE, EERE)

- **Fusing Models and Data for a Dynamic Paradigm of Power Grid Operations**
  - Calibrated real-time dynamic model (SC)
  - Look-ahead dynamic simulation (OE)
  - Dynamic contingency analysis (OE, ARPA-E)

- **Exploring Power Systems Models using Nonlinear Optimization Techniques**
  - New toolkit for solving nonlinear optimization problems (SC)
  - Modular suite of test problems using either DC or AC (linear or nonlinear) transmission models (OE)
  - Explore effect of AC & DC models for transmission switching (OE, ARPA-E)

GENI Program

Green Electricity Network Integration

Objectives

- Enable 40% intermittent non-dispatchable generation penetration
- Mitigate challenges for implementation of “real-time” electricity markets
- Greater than 10x reduction in power flow control hardware (target < $0.04/W)
- Greater than 4x reduction in HVDC terminal/line cost relative to state-of-the-art

Motivation

- The intermittency of wind and solar stresses existing transmission resources and is a significant obstacle to expanded integration
- Blackouts resulted in an estimated $79B in lost revenue annually
- Nearly 1/3 of the electricity infrastructure in the USA is approaching or has passed end-of-life

Program Dir.: Tim Heidel

Kick-off: 12/15/2011

No. Projects: 15

Investment: $39.4M

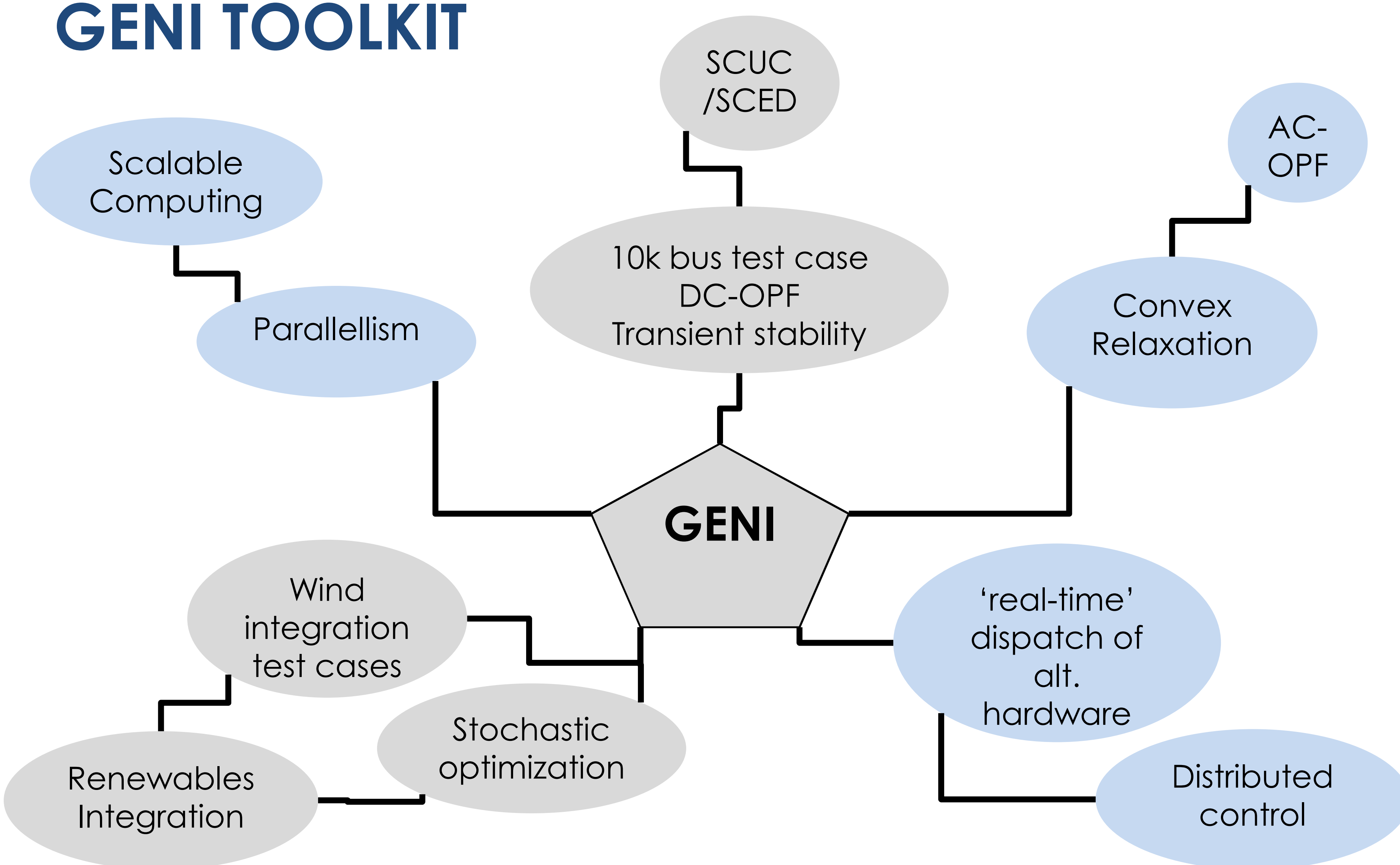
Approach 1: Control Architectures (scalability demonstrated with > 10,000 node simulations)

- Develop control architectures that are resilient, reliable, cost-optimizing and are capable of managing distributed intermittent resources

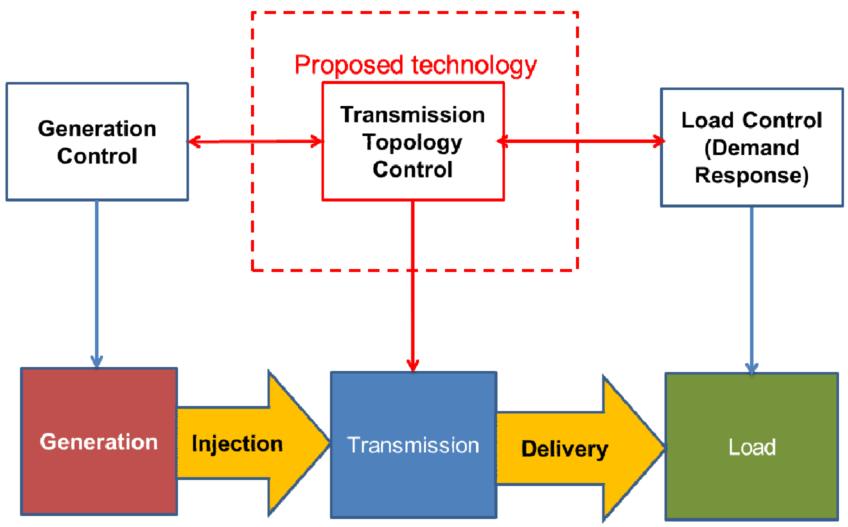
Approach 2: Transmission Controllers (> 3 controllers/terminals connected with > than 5 nodes)

- Hardware demonstration of resilient, reliable power flow control

GENI TOOLKIT



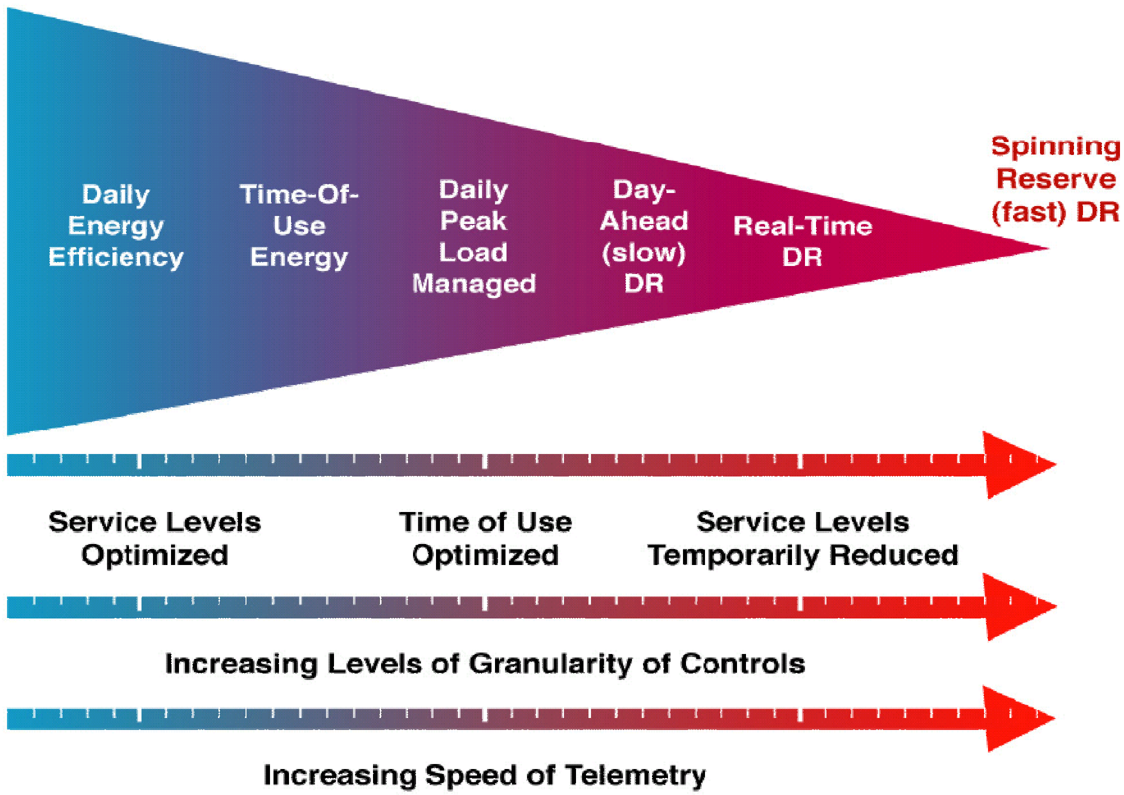
Transmission Topology Optimization

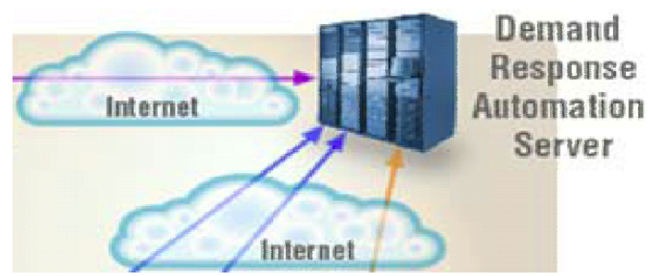


Charles River Associates	Project management, algorithms, impact assessments, integration, commercialization
Boston University	Optimization algorithms, market design issues
Tufts University/ Northeastern University	Express algorithms for voltage and transient stability analysis
Polaris Systems Opt./ Paragon Decision Technology	Software implementation
PJM Interconnection	Operation and implementation consulting and review

Estimates indicate that implementation of TC in the entire US electrical grid would save of $1-2 billion in generation costs and would reduce the needs for transmission investments

Highly Dispatchable and Distributed Demand Response for Integration of Distributed Generation

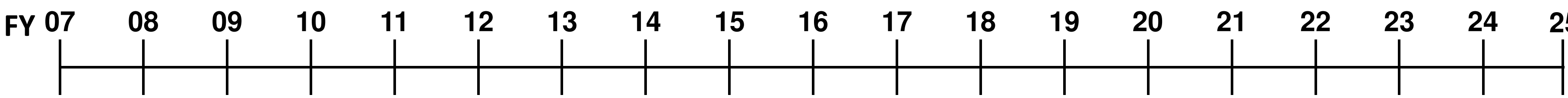




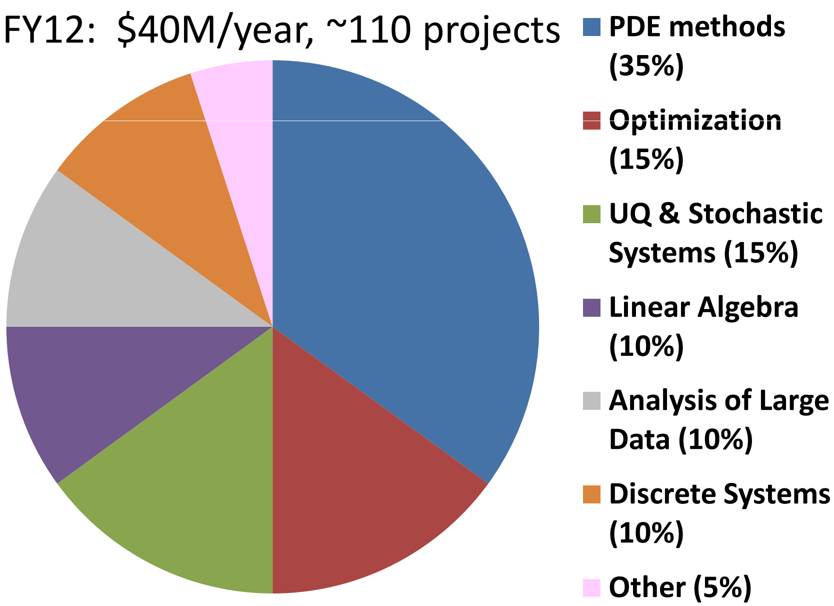
• OpenADR, IP-based telemetry solutions, and intelligent forecasting and optimization techniques to provide "personalized" dynamic price signals to millions of customers in timeframes suitable for providing ancillary services to the grid

DOE Applied Mathematics FY09 – FY12

The DOE Applied Mathematics program supports basic research leading to fundamental mathematical advances and computational breakthroughs across DOE and Office of Science missions; analysis and development of robust mathematical models, algorithms and software for enabling predictive scientific simulations of DOE-relevant complex systems.

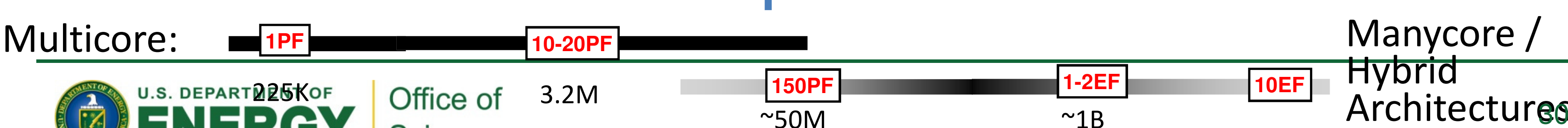


FY12: $40M/year, ~110 projects

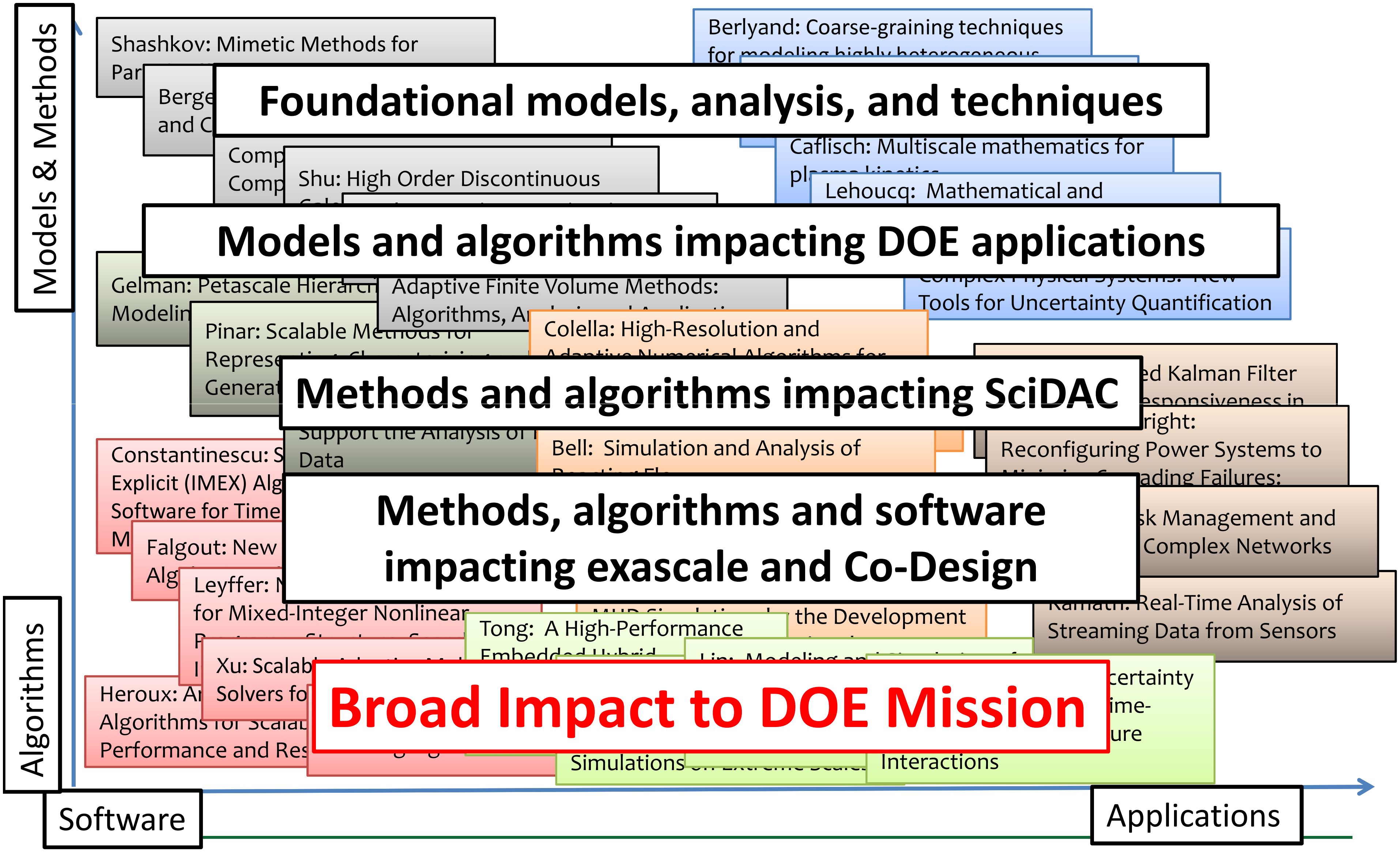


Future: Modeling, analysis, and algorithms for simulation of DOE complex systems:

- Increase fidelity: develop new multi-scale, multi-physics models, analysis of coupled systems
- Uncertainty Quantification and V&V
- Approaches for systems that are inherently stochastic
- Methods that integrate data and simulation
- Novel analysis of algorithms for large data / streaming data
- Solvers and optimization methods with reduced global communication
- Higher-order methods; accuracy, stability of methods that move away from bulk synchronous programming models
- Algorithms resilient to machine errors
- Analysis of algorithms for emerging architectures



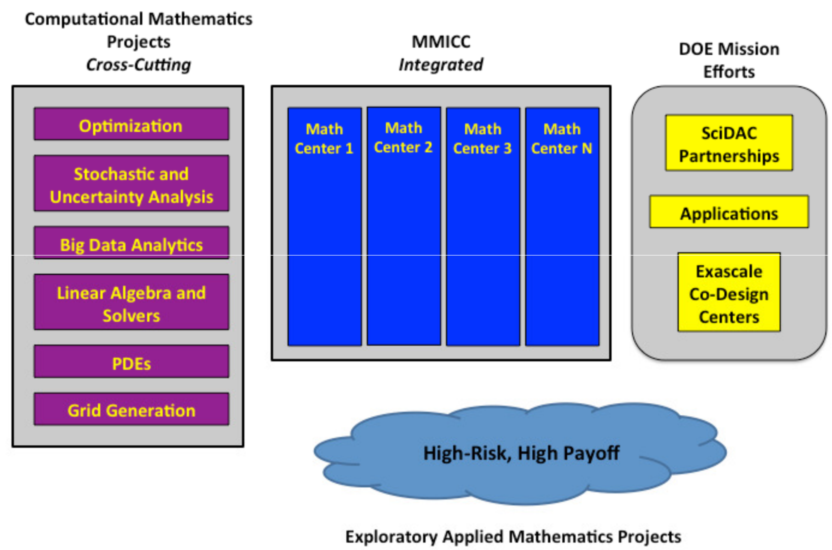
Applied Mathematics research has broad impact



New DOE Applied Mathematics paradigm

Support the research and development of applied mathematical models, methods and algorithms for understanding natural and engineered systems related to DOE's mission.

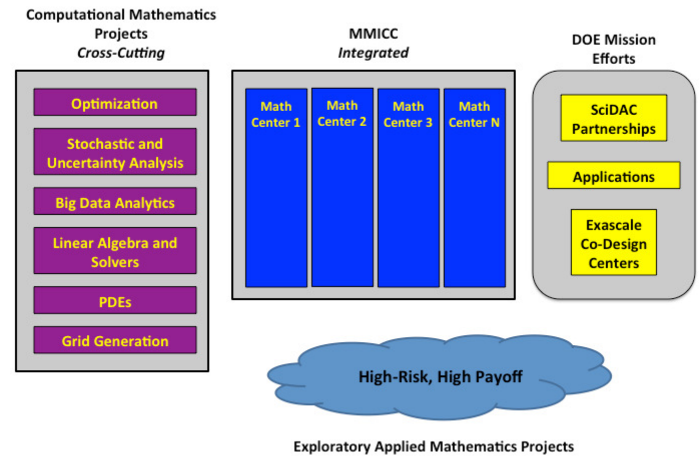
Long-term goals:



- Mathematics research that 5-10+ years out will impact DOE mission efforts: DOE Applications, SciDAC Partnerships, and Exascale Co-Design
- New Mathematical Multifaceted Integrated Capability Centers (MMICCs) directly enhances impact of applied math on DOE mission
- Cross-cutting mathematics projects: addresses foundational, algorithmic and extreme-scale mathematical challenges
- High-risk, high-payoff: new mechanism to bring in highly innovative research

Mathematical Multifaceted Integrated Capability Centers (MMICCs)

- <u>Background</u>
  - 2005 Multiscale Mathematics solicitation
  - 15 projects awarded under Multiscale Mathematics and Optimization of Complex Systems (ending 8/2012)
  - 7 projects awarded under Mathematics for Complex Distributed Interconnected Systems (ending 8/2012)
  - 7 projects awarded under ARRA Multiscale Mathematics and Optimization of Complex Systems (ending 8/2012)



  - Workshop: Sept 13-15, 2011; Workshop report, *"A Multifaceted Mathematical Approach for Complex Systems"* March 2012.
  - Applied Math Summit 3/7/2012.
- <u>New Paradigm</u>
  - Holistically address mathematics for increasingly complex DOE-relevant systems for scientific discovery, design, optimization and risk assessment.
  - Broader view of the problem as a whole, and devise solution strategies that attack the problem in "its entirety" by building fundamental, multidisciplinary mathematical capabilities
  - Enable applied mathematics researchers to work together in large, collaborative teams to more effectively address science problems earlier in the problem solving process.

M2ACS: Multifaceted Mathematics for Complex Energy Systems

AN ASCR MMICCS project, PI Anitescu (ANL), $3.5M/yr FY12-FY16

Participants: ANL, PNNL, SNL, U Wisconsin, U Chicago

- Focuses on the grand challenges of analysis, design, planning, maintenance, and operation of electrical energy systems and related infrastructure in the presence of rapidly increasingly complexity of the systems.
- Four mathematical areas identified:
  - Predictive modeling that accounts for uncertainty and errors
  - Mathematics of decisions that allow hierarchical, data-driven and real-time decision making
  - Scalable solution algorithms for optimization and dynamic simulation
  - Integrative frameworks leveraging model reduction and multiscale analysis
- Mathematical aspects include: discrete and continuous optimization, dynamical systems, multi-level techniques, data-driven methods, graph-theoretical methods, and stochastic and probabilistic approaches for uncertainty and error.
- Mathematics addresses a broad class of complex energy systems challenges including planning for power grid and related infrastructure; analysis and design for renewable energy integration; real-time broad-scale system monitoring and prediction; and predictive control of cascading blackouts.

M2ACS Team: Topic Structure

Predictive modeling
Huang/Tartakovsky

- **Dynamics and stochastics** — Constantinescu, Huang, Lin, Tartakovsky
- **Hamiltonian & Lyapunov structure** — DeMArco
- **Stability** — DeMarco, Lee
- **Graph tools** — Halappanavar, Hovland,Huang

Math. of decision
Wright/Leyffer

- **Hierarchical Decision Making** — Birge, Ferris, Munson
- **Data-driven decisions** — Anitescu, Wright
- **Equilibrium problems** — Birge, Ferris, Leyffer, Munson
- **Realtime** — Zavala

Integrative frameworks
Ferris/Watson

- **Approximation** — Leyffer
- **Multiscale reduction** — Lin, Lu
- **Rare event sampling** — Weare
- **Relaxation** — Luedtke,Lesieutre
- **Integrative modeling** — Ferris, Smith, Watson, Hovland

Scalable algorithms
Smith/Linderoth

- **Scalable dynamic simulation** — Constantinescu
- **Decomposition algorithms** — Linderoth,Watson, Munson, Anitescu
- **Multilevel algorithms** — Lee, Smith
- **Infrastructure for scalable alg.** — Anitescu, Munson

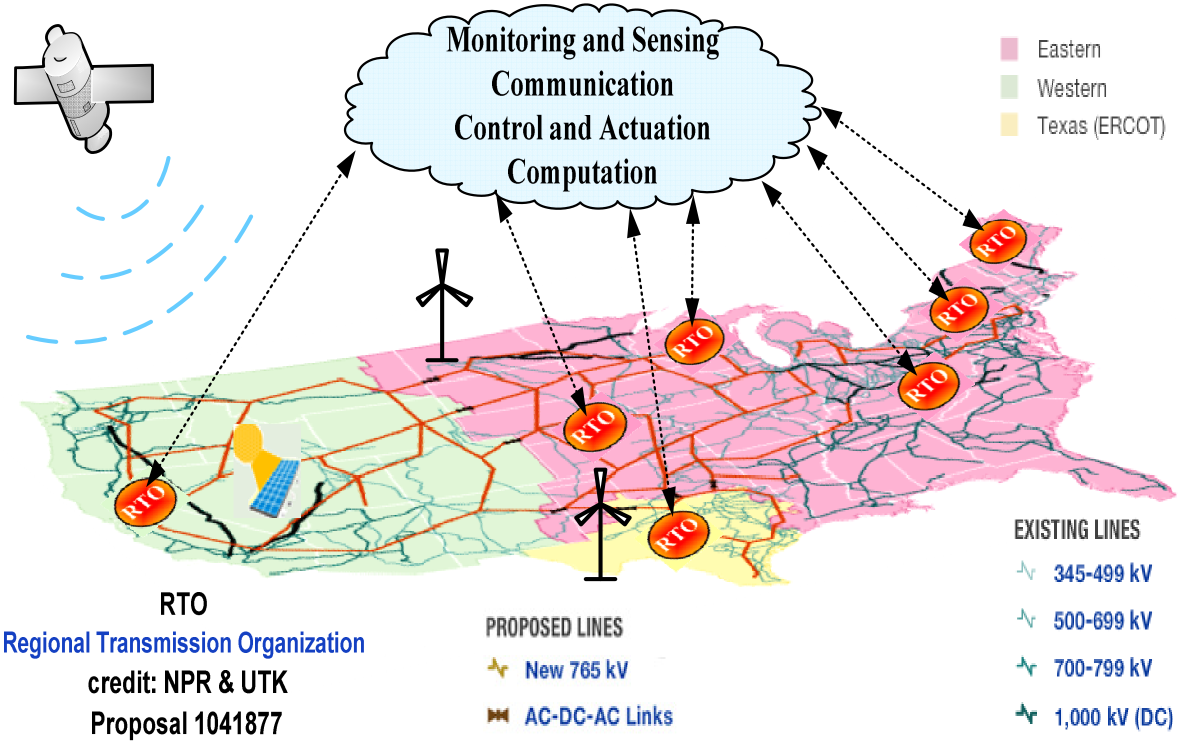
Systems Challenges
DeMarco / Huang

- **Planning under sustainability** — DeMarco
- **Monitoring and prediction** — Huang
- **Delivery architecture** — Lesieutre
- **Contingency analysis** — Lu

Center for Ultra-wide-area Resilient electric Energy Transmission networks (CURENT)

- A nation-wide transmission grid that is fully monitored and dynamically controlled for high efficiency, high reliability, low cost, better accommodation of renewable sources, full utilization of storage, and responsive load.
- A new generation of electric power and energy systems engineering leaders with a global perspective coming from diverse backgrounds.

- University of Tennessee
- Northeastern University



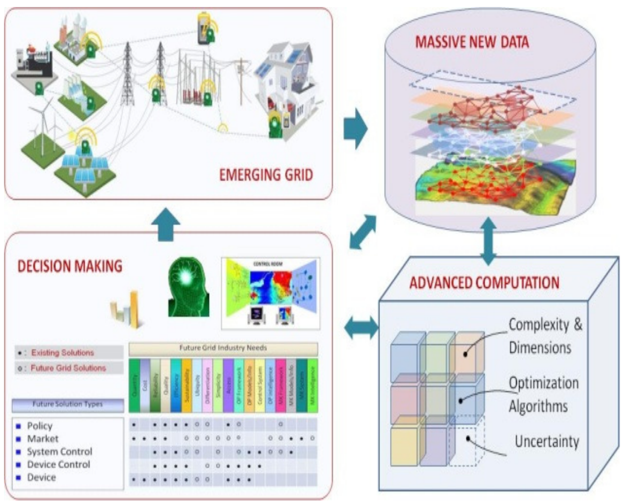
RTO
Regional Transmission Organization
credit: NPR & UTK
Proposal 1041877

- Tuskegee University
- Rensselaer Polytechnic Institute

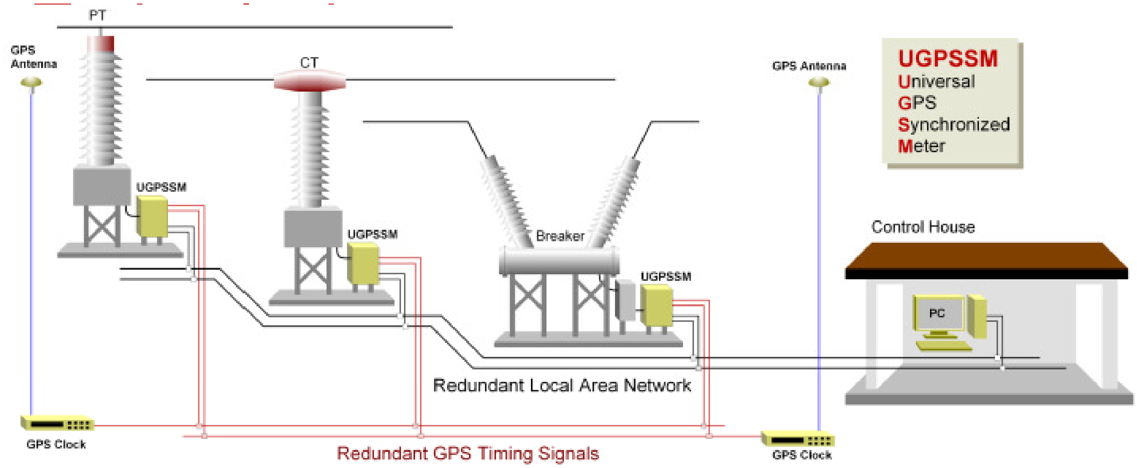
Power Systems Engineering Research Center

Empowering minds to engineer the future electric energy system

Power Systems



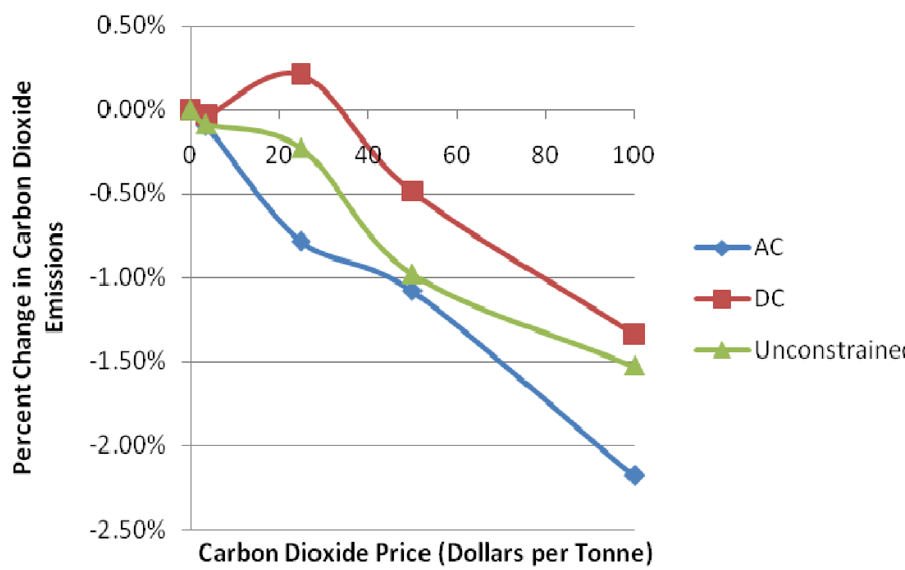
Transmission & Distribution



Organization in Brief

- NSF I/UCRC
- 37 Industry Members
- 13 Universities
- 14 on-going industry projects
- Supporting ~50 grad students
- U.S. DOE projects (Future Grid Initiative, CERTS)

Markets and Policies



Advanced Modeling for Electric Power Systems

SC · OE · EERE · ARPA-E

What's the challenge?

- The field relies on mathematical constructs, physical models, and computational algorithms.
- Cursed by dimensionality and often by lack of scalability in the tools (approximations are rampant and necessary).
- Improving the reliability or efficiency of a single component is *not sufficient* to enhance the reliability or cost of delivery by the interconnected system

Where are we today?

- Real-time system monitoring by operators is supported by offline engineering analysis (high latency)
- Operator trying to make control decisions, especially fast decisions during a disturbance, on incomplete data
- Inconsistencies in planning and operations assumptions/models

Need for coordination?

- A strategic modeling approach for the holistic understanding and design of a complex system of grid systems
- New algorithms, mathematical techniques, and computational approaches
- Validation and verification of tools, techniques and models on actual power system problems (and data)

Where are we going?

- New models, planning, and operational tools that are well integrated and used by industry for real-time system control
- Improved flexibility and reliability through better system understanding
- Refined markets; increased engagement (services and roles)

Advanced Modeling for Electric Power Systems
Future Opportunities for Coordination

- **Accelerate Performance:** improving grid resilience to fast time scale phenomena that drive cascading network failures and blackouts
- **Enable Predictive Capability:** relying on real-time measurements and improved models to represent with more fidelity the operational attributes of the electric system, enabling better prediction of system behavior and thus reducing $ inefficiencies
- **Integrate Modeling Platforms (across the system):** capturing the interactions and interdependencies that will allow development (and validation) of new operational and planning approaches

- What characteristics are necessary for new model (or operator tool) development for the future electric grid?
- How do we foster a community of mathematic, computational, and power systems expertise to address these technical challenges?
- How can this community work together to facilitate model validation and verification?