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Advances in Power Grid Research in the Pacific Northwest

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Pacific Northwest National Laboratory

SusTech, Portland, OR, July 26, 2014

Overview

I will talk about the contributions of three major projects at PNNL to the power grid in the Pacific Northwest:

- Pacific Northwest Smart Grid Demonstration Project
- PNNL Future Power Grid Initiative
- Multifaceted Mathematics for Complex Energy Systems (M2ACS)

Overview

- Pacific Northwest Smart Grid Demonstration Project
- PNNL Future Power Grid Initiative
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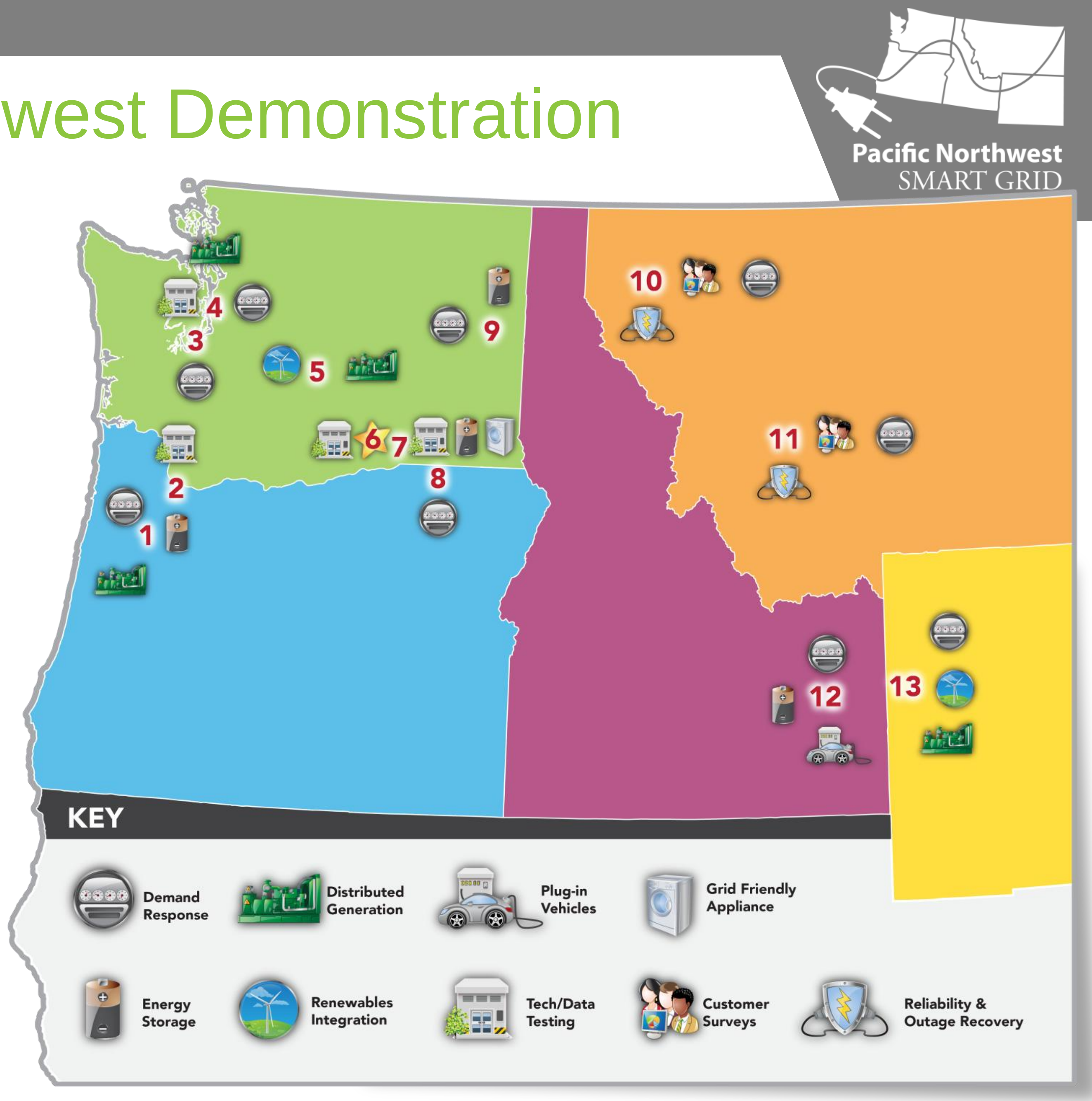
Pacific Northwest Demonstration Project

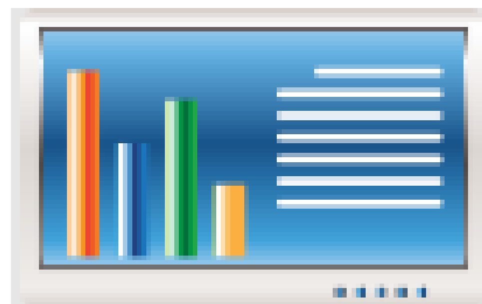
- **What:**
  - $178M ($89M private, $89M ARRA-funded), 5-year demonstration
  - 60,000 metered customers in 5 states
- **Why:**
  - Quantify costs and benefits
  - Develop communications protocol
  - Develop standards
  - Facilitate integration of wind and other renewables
- **Who:**
  - Led by Battelle and partners including BPA, 11 utilities, 2 universities, and 5 vendors



Slide thanks to Ron Melton

How?

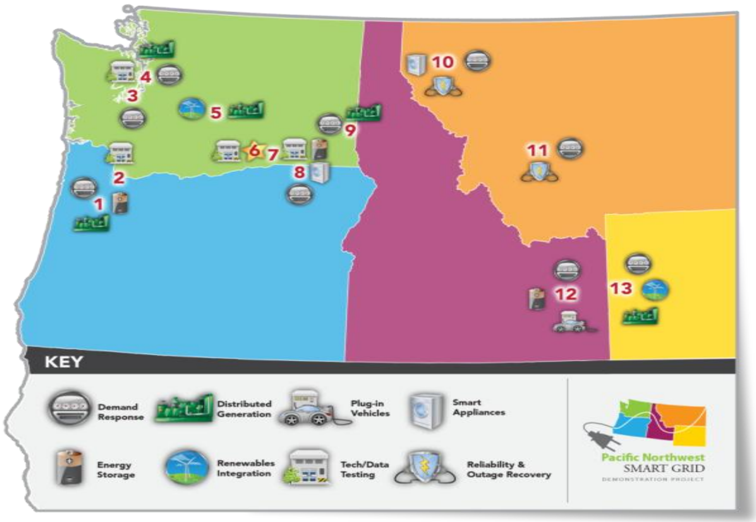
- Testing technology which …
  - Informs when energy is cheaper
  - Sends signals to distribute decision making
  - Integrates renewable energy
- In order to …
  - Keep costs down
  - Save energy
  - Boost reliability
  - Shorten outages



PNWSG Demo Status Update

Pacific Northwest SMART GRID DEMONSTRATION PROJECT

- Viewed by DOE as top tier performer and strategic
- Utility install lagged schedule; data still adequate for core analytics
- Gathered 300M records to date in EIOC
- BPA PNW SG business case drafted, positive
- Preliminary Observations:
  - Avista saw 3x higher benefits from AMI and DA
  - Fox Island leverage for cable outage
  - BPA key events detected by transactive model



Post-FY15 Completion

- ~$77M of smart grid assets installed and in use in participating regional utilities
- Transactive control technology developed, documented and tested
- Transactive control theory – development needed
- Operational use of transactive control – specific monetized operational use yet to be defined
- IP captured – commercialization is critical for utility adoption

Slide thanks to Ron Melton

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The Grid Challenge

- Over the next 15 years, we expect
  - 15% of electricity coming from intermittent renewable power
  - Generation changing from centralized to distributed, two way model
  - Millions of smart meters and sensors, plug-in hybrid vehicles, and electricity storage coming online

- New challenges
  - How can we manage large-scale data in real time?
  - How do we safeguard high reliability and security?
  - How will we run such a complex grid?

➔ We need new concepts and tools that transform grid operation and planning

Slide thanks to Henry Huang

Data and Computational Complexity

	Today – SCADA data	Tomorrow – Phasor data	Improvement
Variety	voltage + current	+ phase angle	more information
Velocity	1 sample/4 seconds	30-120 samples/second	~200x faster
Volume	8 terabytes/year	1.5 petabytes/year	~200x more data*
Veracity	unseen ms-oscillations	oscillations seen at ~10ms	greater accuracy

* Transmission level only

	0-2 years	3-5 years	6-10 years +
Model Size	**10^4** (major transmission elements)	**10^5** (+ major renewable and major loads)	**10^6** (+ renewable, loads, DGs)
Simulation Time to Solution	**2-4 minutes**	**2-4 seconds**	**10 msec – 1 sec**
• State Estimation	100 MFLOPS	10 GFLOPS	10 ExaFLOPS
• Contingency Analysis	100 MFLOPS	1 TFLOPS	10 PFLOPS
• Dynamic Simulation	1 MFLOPS (10x slower than real-time)	100 GFLOPS (10x faster than real-time)	10 TFLOPS (10x faster than real-time)
• Small Signal Stability	10 GFLOPS	100 TFLOPS	1 ExaFLOPS

Slide thanks to Henry Huang

Our answer - Future Power Grid Initiative

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- **The Future Power Grid Initiative (FPGI)**
  - A multi year, multi million dollar, interdisciplinary initiative
  - Funded through PNNL's Laboratory Directed Research and Development Program
  - Led by Henry Huang, Ph.D., P.E., and Jeff Dagle, P.E.

- **Approach**
  - Combining PNNL's distinctive capabilities in power systems, data-intensive high-performance computing and visual analytics
    - Designing computational approaches to deliver a new class of real-time tools for grid modeling and simulation
    - Expanding power grid networking to support large scale and secure real-time data flow
    - Advancing state-of-the-art visual analytics to convert very large volumes of multi-domain real-time data into actionable information

Slide thanks to Henry Huang

Focus Area 1 – Networking and Data Management

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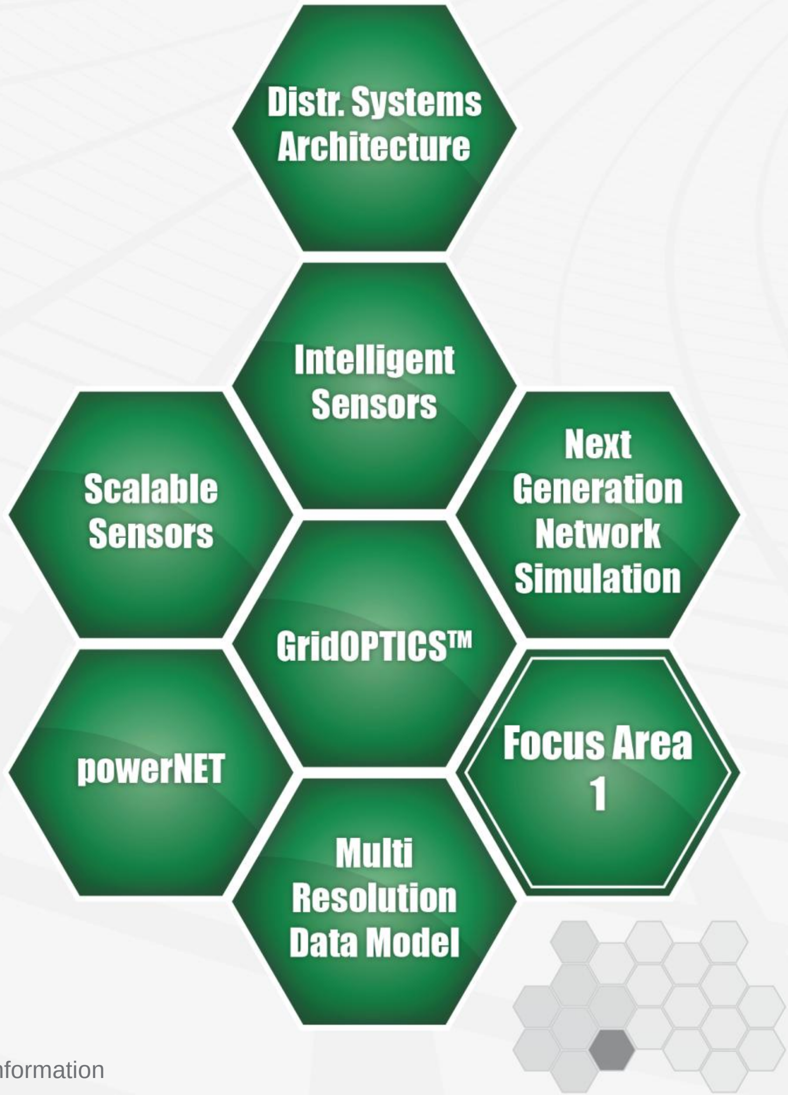
- Identify, filter, and reduce data to ensure real-time performance
- Enable large-scale information network modeling and simulation environments
- Develop operational sensor prototypes that allow adaptive autonomous operation supporting new distributed control paradigms



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Focus Area 2 – Modeling, Simulation, and Analysis

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- Expand power grid models to include smart consumer devices and intermittent energy sources
- Develop new modeling approaches for integrated, multi-scale transmission and distribution analysis
- Develop new algorithms and computational platforms for real-time power grid analysis
- Design computational tools for power grid planning

Slide thanks to Henry Huang

Focus Area 3 –
Visualization and Decision Support

- Visualization and Decision Support projects focus on creating computational methods and software tools to aid human-in-the-loop analysis and decision making for grid operations and strategic planning.
- Research directed towards *the interface* between the operators, planners and policy-makers and the future power grid.

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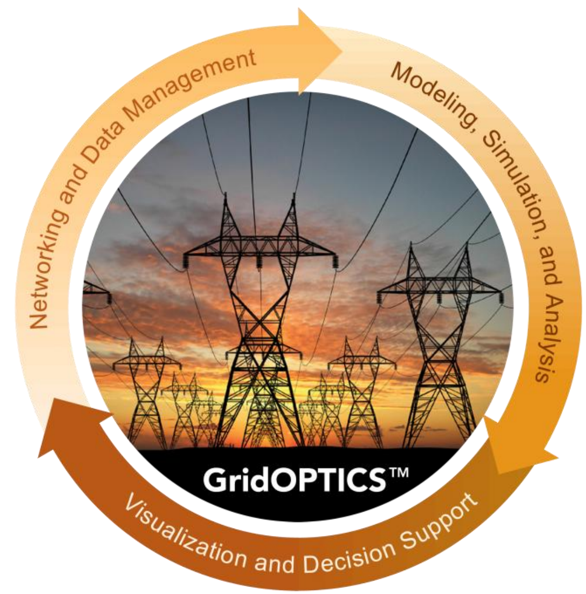
FPGI (journey) leads to GridOPTICS™ (product)

Integrated view of FPGI elements

GridOPTICS™

Grid Operation and Planning Technology Integrated Capabilities Suite



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Our end-goal – product of the FPGI

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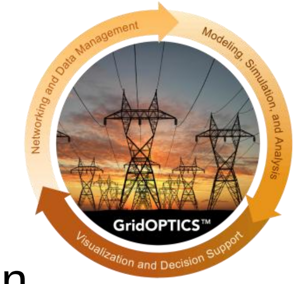
GridOPTICS™ – a suite of tools to enable three fusions:



- Bridging **operation** and **planning** to enable more seamless grid management and control
  - Remove overhead involved in communication between operation and planning
  - Improve response when facing emergency situations
- Integrating **transmission** and **distribution** in end-to-end grid modeling and simulation capable of handling 10^9 devices with uncertainty
  - Understand the emerging behaviors in the power grid due to smarter loads, mobile consumption, and intermittent generation
- Managing interdependency between power **grid** and **data** network (a test lab for power grid data networking is being set up)
  - Enable "all-hazard" analysis
  - Prepare grid operators and planners with the knowledge of data network impact on the power grid

Slide thanks to Henry Huang

Progress highlights

- Capabilities Developed
  - Launched powerNET, a research laboratory and testbed for power grid data networking, equipment, and technology
  - Developed models for large number of distributed energy resources
- Technical Leadership
  - More than 30 papers, one book chapter published
  - Four patent applications & five copyrights and open source licenses
  - Hosted the first HPC power grid workshop in conjunction with SC11 and SC12, ICSE Workshop in Zurich and organized SC13 workshop in Denver, Colorado.
- Impact Examples
  - Early success of the Initiative resulted in DOE and DHS funding support to further develop the technology
  - Strengthened relationships with national and regional power grid organizations. Major ISO stated FPGI's approach to Decision Support was "changing the paradigm of the power industry."

Slide thanks to Henry Huang

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Complex energy systems share common challenges that motivate new math

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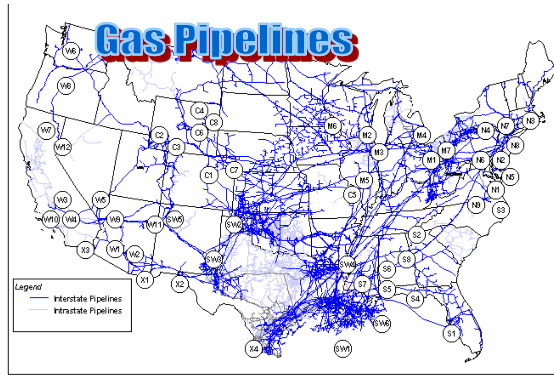
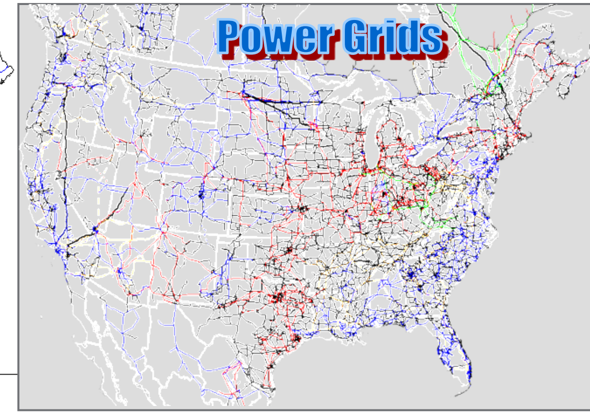
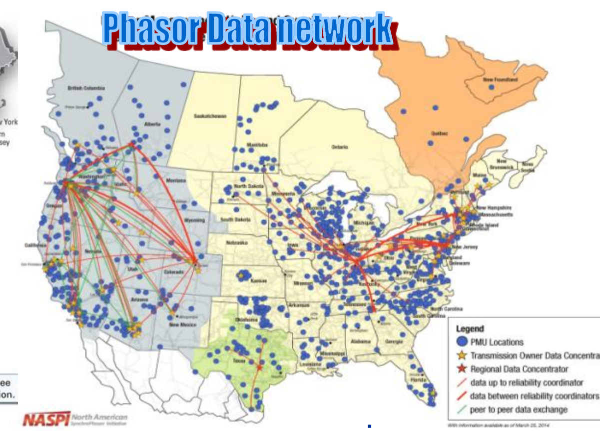
- Complex graphs
- Unique Randomness
- Multi-spatial-temporal-scale modeling
- Model vs. observations: neither is perfect
- Many possible futures: a control challenge
- Interdependency: gas bubble, cyber security, …



Source: Energy Information Administration, GasTran Gas Transportation Information System, Natural Gas Pipeline Construction Database



Source: Time Warner Telecom



www.naspi.org

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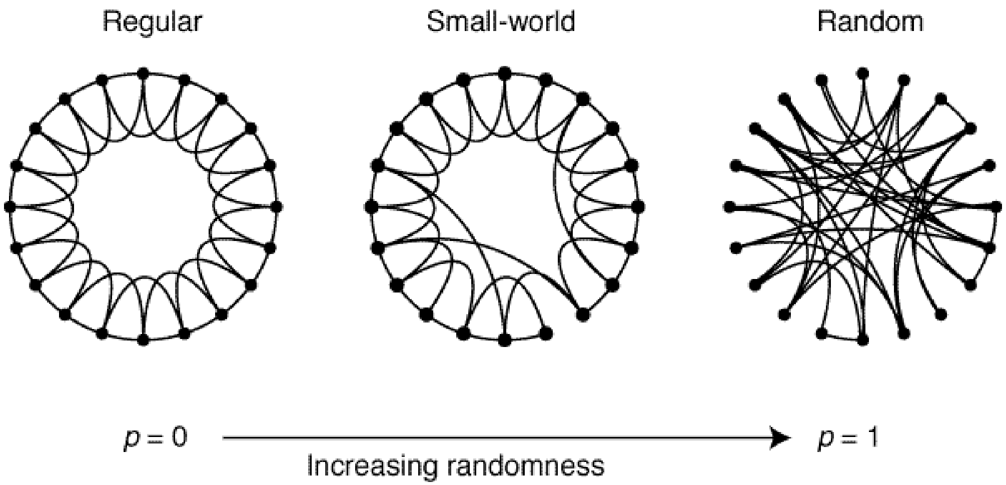
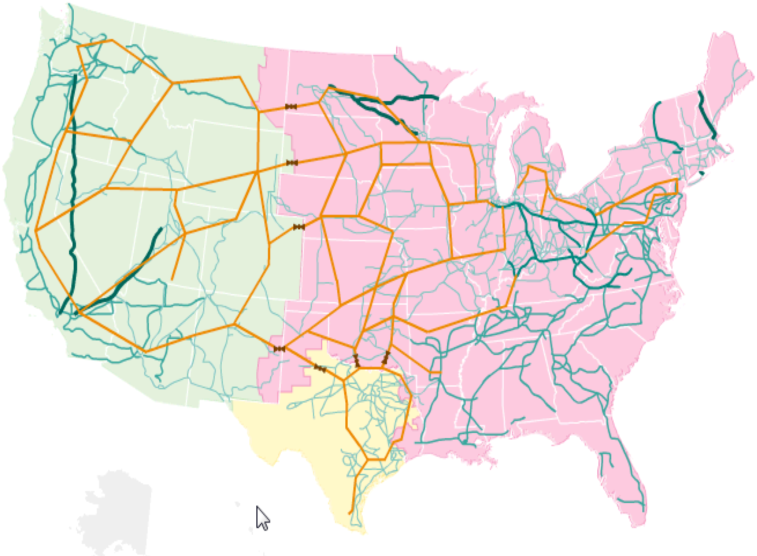
M2ACS Argonne NATIONAL LABORATORY Pacific Northwest NATIONAL LABORATORY Sandia National Laboratories THE UNIVERSITY OF CHICAGO WISCONSIN

How to model graph evolution when the graph is neither random nor small-world?

- Power grids do not resemble random or small-world graphs.
- It is local clusters connected through regional and global layers.
  - It is a great challenge to capture such unique graph features.





Source: Duncan J. Watts and Steven H. Strogatz, "Collective dynamics of 'small-world' networks", Nature 393, 440-442(4 June 1998)

Source: NPR, http://www.npr.org/2009/04/24/110997398/visualizing-the-u-s-electric-grid

How to construct data assimilation problems when noises are not Gaussian?

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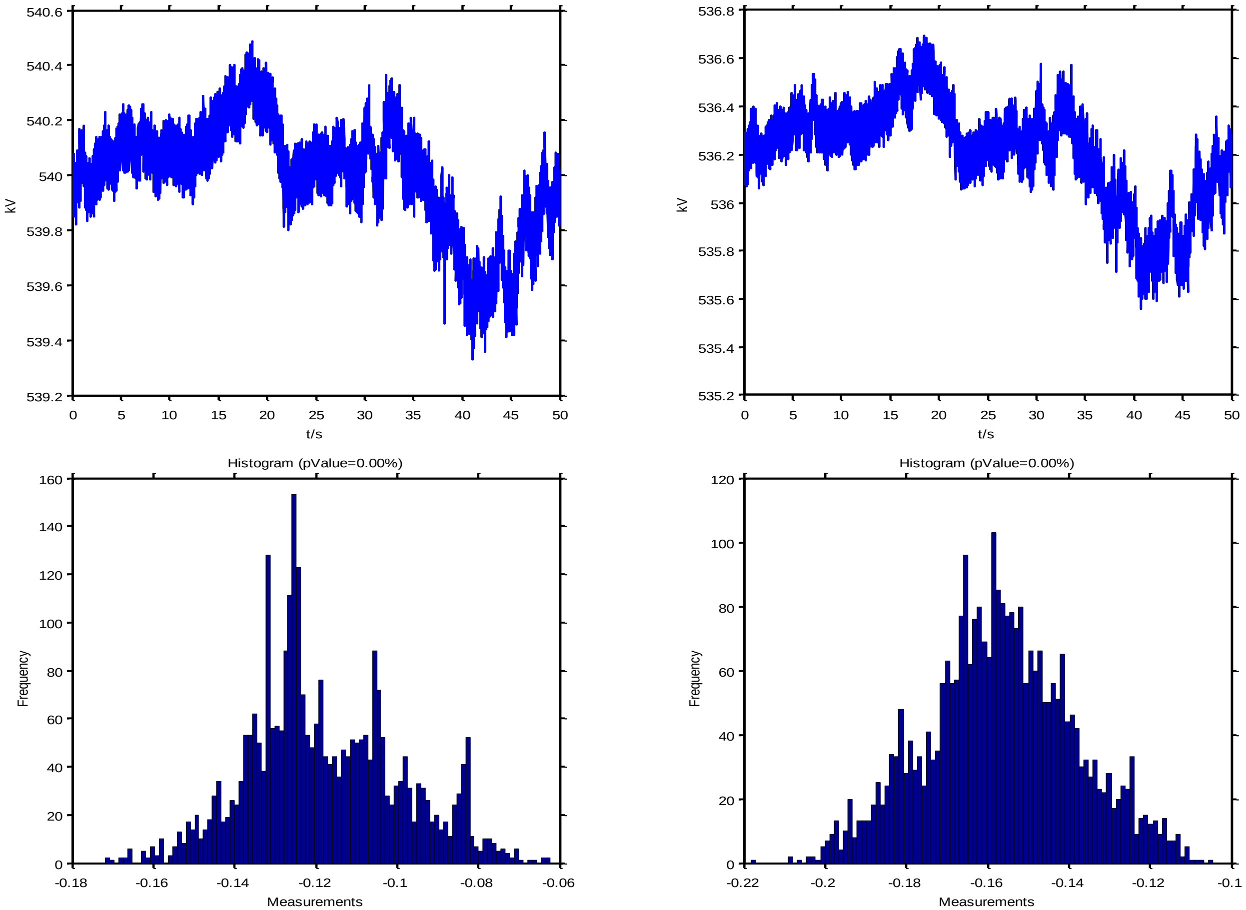
- Non-Gaussian noise properties determined from actual phasor measurements



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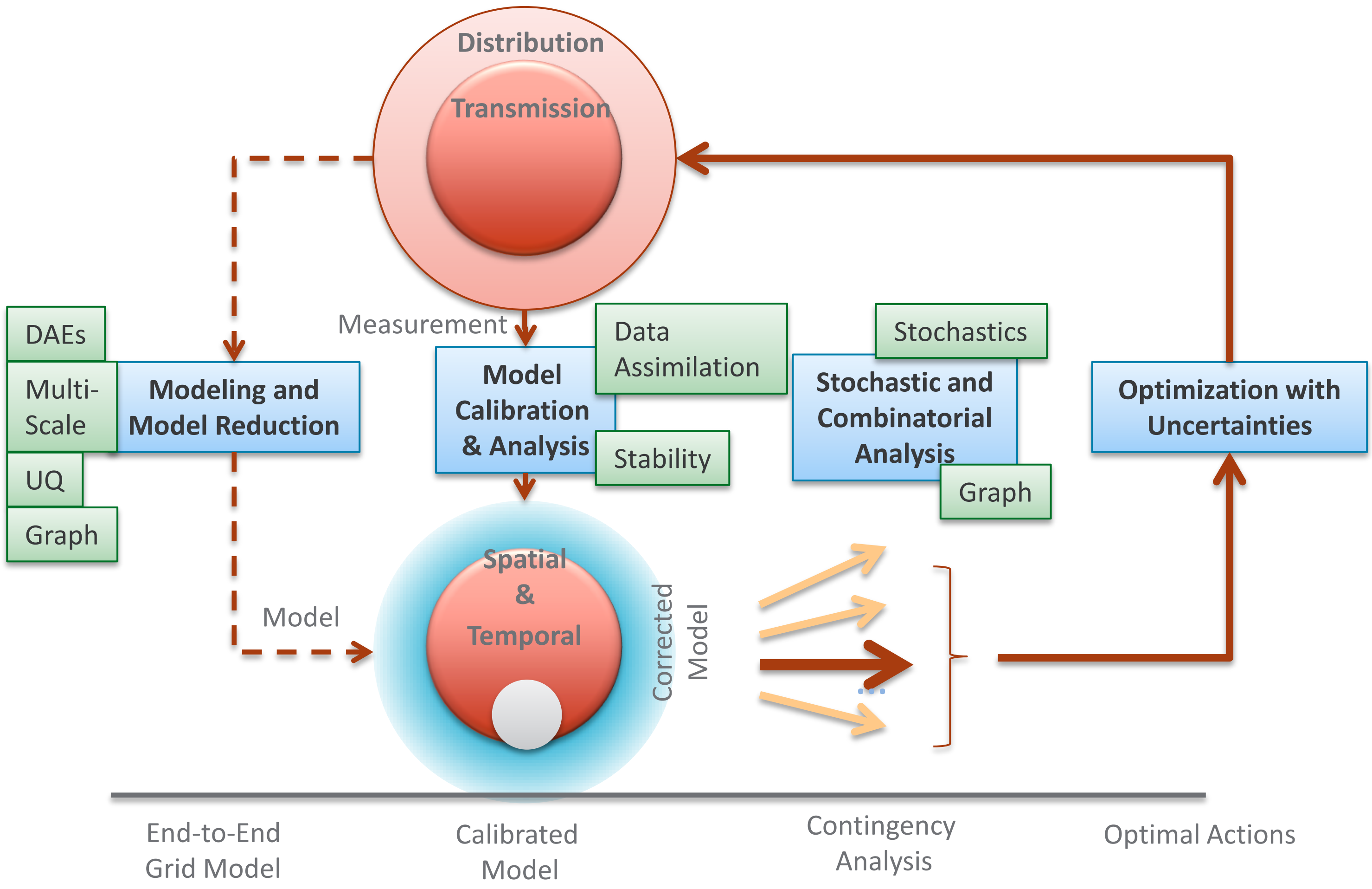
Integrative math to address these challenges for better energy systems



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We have made great progress in building predictive modeling capabilities

- Predict uncertainty due to model reduction
- Predict uncertainty propagation
- Predict system states with measurements
- Predict future power grid topology

Predict uncertainty due to model reduction through graph theory and principle component analysis

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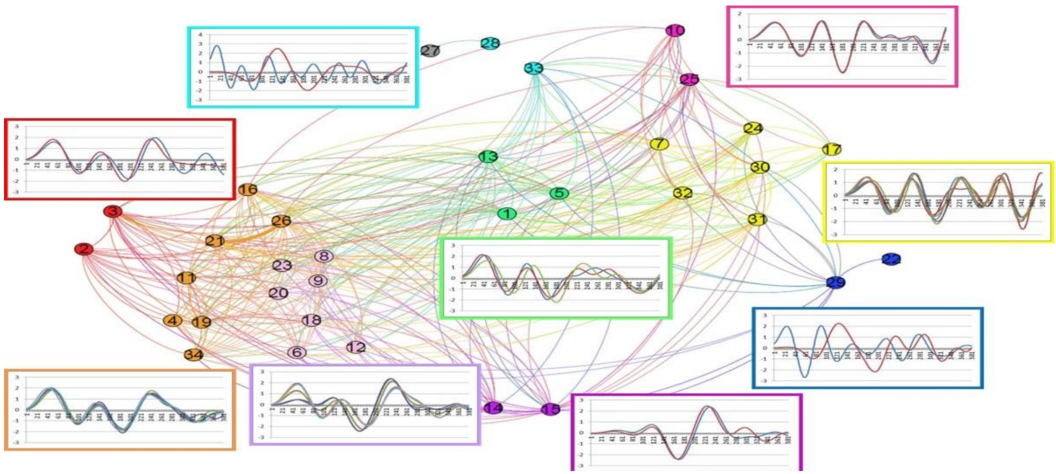
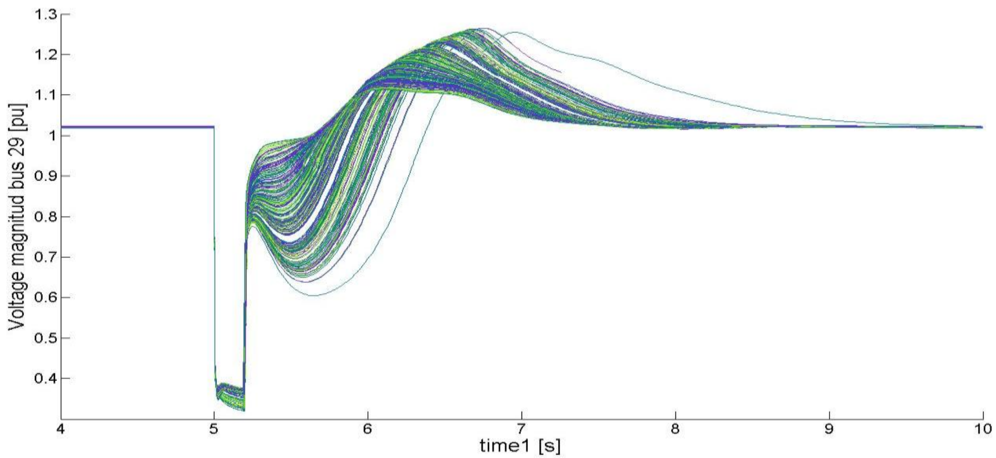
Work by Emilie Hogan, Mahantesh Halappanavar, Eduardo Cotilla-Sanchez (OSU)

- Model reduction using spectral clustering with a Fourier transform based pseudo distance



Work by Guang Lin

- Modeled effect of randomness in wind speed and direction on dynamic response of a wind farm



- Dynamic-feature Extraction, Attribution and Reconstruction (DEAR) Method for Power System Model Reduction, IEEE Transactions on Power Systems, 99:1-11, 2014.
- Dynamic Response of Large Wind Power Plant Affected by Diverse Conditions at Individual Turbines, 2014 IEEE Power & Energy Society General Meeting, National Harbor, MD, July 2014.

Slide thanks to Henry Huang

Predict uncertainty propagation using probability density function (PDF) method

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Work by Alexandre Tartakovsky, David Barajas-Solano, Peng Wang

- Formulate power grid model as a set of stochastic Differential Algebraic Equations → Langevin equations with colored noise

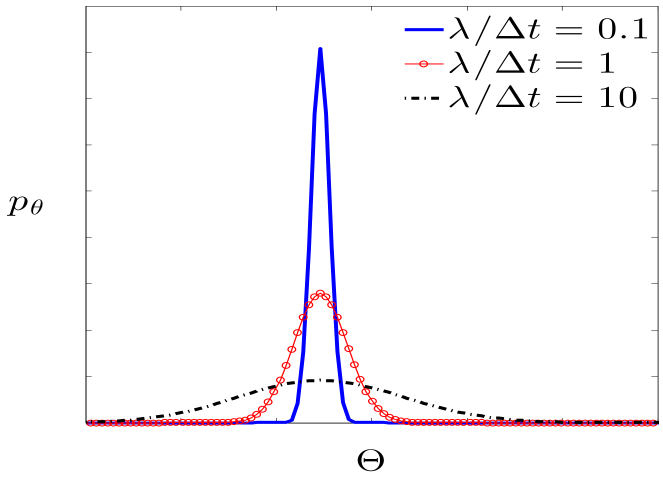
$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega_{\mathrm{B}}(\omega - \omega_{\mathrm{s}}),$$

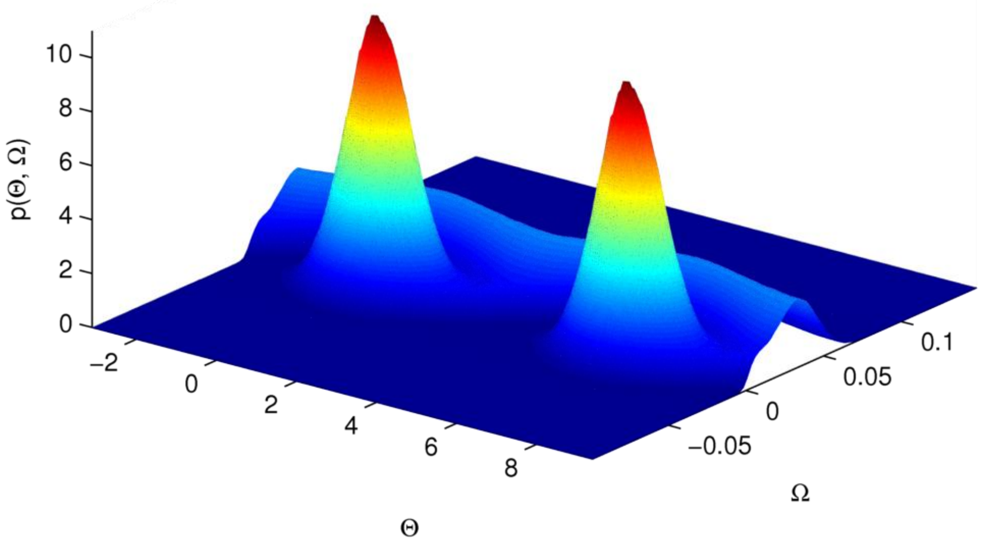
$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{\omega_{\mathrm{s}}}{2H}\left[P_{\mathrm{m}} - P_{\mathrm{e}} - D\left(\omega - \omega_{\mathrm{s}}\right)\right],$$

$$P_{\mathrm{e}} = \frac{EV}{X}\sin\theta.$$

→

$$\frac{\mathrm{d}X_i}{\mathrm{d}t} = h_i(\mathbf{X}, t) + \sum_{j=1}^{N} g_{ij}(\mathbf{X}, t)\xi_j(t), \quad i = 1, \ldots, N$$





- "Probabilistic Density Function Method for Stochastic ODEs of Power Systems with Uncertain Power Input", in review for SIAM/ASA Journal on Uncertainty Quantification, 2013.

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Predict system states with measurements through data assimilation with non-Gaussian noises

Work by Henry Huang

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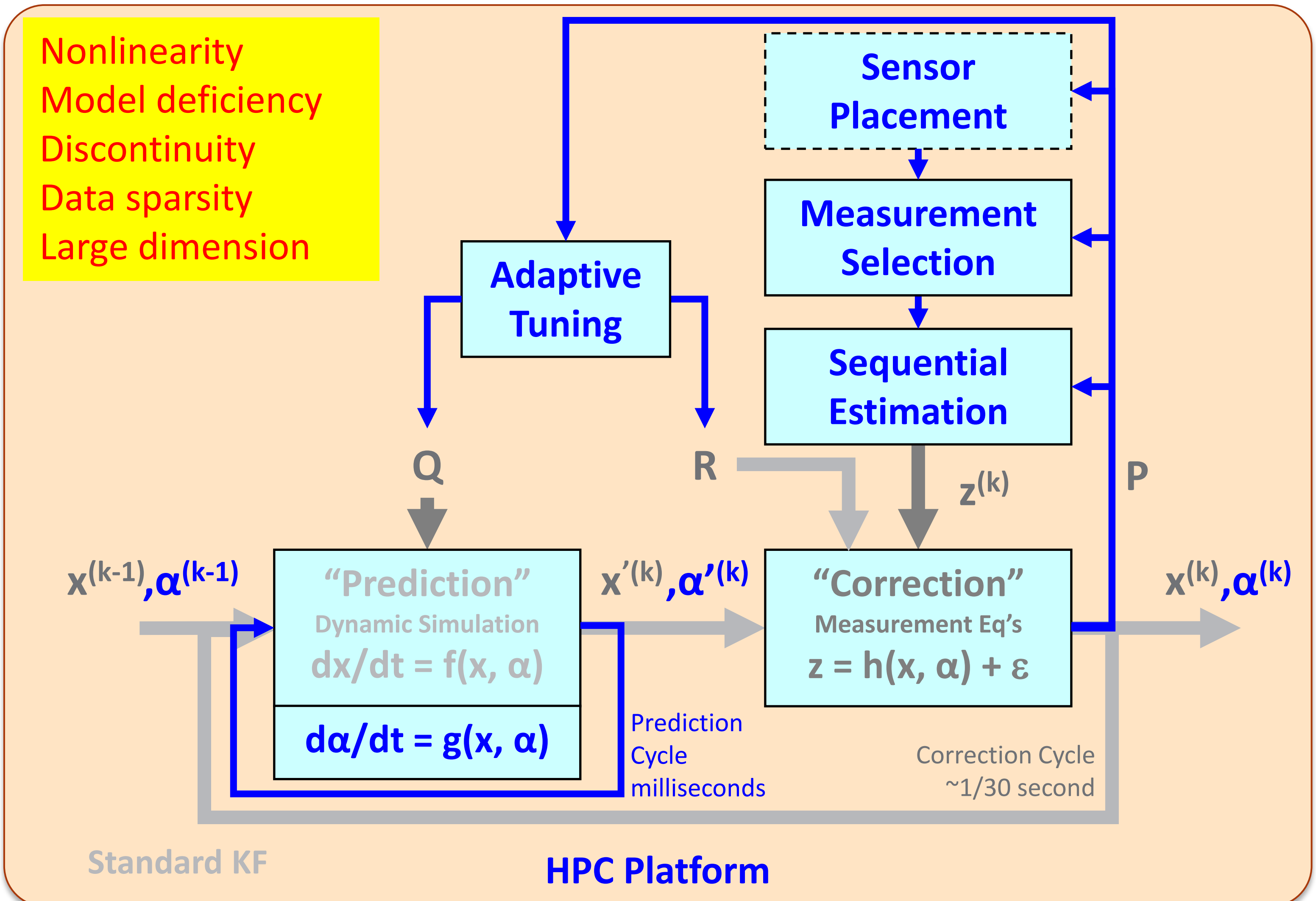


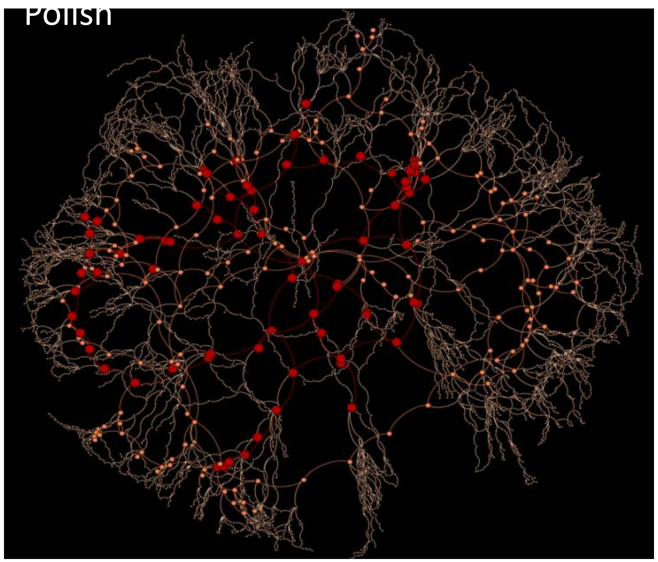
- "Noise Properties of Power Grid Measurements", SIAM Annual Meeting, Chicago, IL, July 7-11, 2014

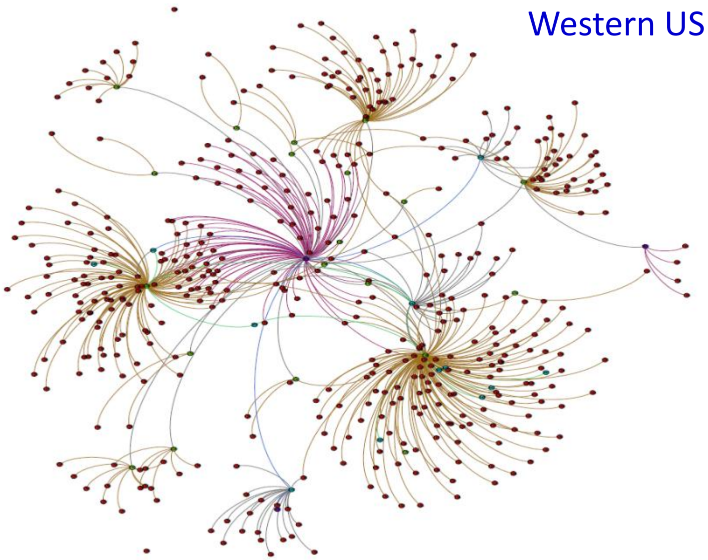
Slide thanks to Henry Huang

Predict future power grid topology using graph theory

Work by Emilie Hogan, Mahantesh Halappanavar, Eduardo Cotilla-Sanchez (OSU), Daniel Duncan (OSU), Paul Hines (U of VT)

- Projection of topology per graph properties: degree, diameter, centrality, …
- Graph representation of the full Polish and Western US power systems, showing layered structures.





- “Towards Effective Clustering Techniques for the Analysis of Electric Power Grids”, Proc. 3rd Workshop on High Performance Computing, Networking and Analytics for the Power Grid, 2013
- “Parallel heuristics for scalable community detection”, Proc. International Workshop on Multithreaded Architectures and Applications (MTAAP), IPDPS Workshops, May 23, 2014, Phoenix, AZ.
- "Scaling Graph Community Detection on the Tilera Many-core Architecture". Under review (conference).
- "Parallel Heuristics for Scalable Community Detection". Under review (journal).

Slide thanks to Henry Huang

Math is needed to answer some of the key energy questions of national interest

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- Predictive modeling enables high-fidelity real-time grid analysis for new methods to manage the emerging challenges in the power grid. It can help to answer key questions such as:
  - How much wind generation can a system afford without losing stability?
  - Is the system stable in the near future given predicted uncertainties in generation and load?
  - How to optimize the power grid to mitigate uncertainties?
  - At what level loads should be aggregated in models?
  - How to quantify the impact of stochastic distributed energy resources on grid reliability?
  - How would the power grid and other energy system evolve? And what is the policy implications of such evolution?

Summary

- PNNL is a major player in many research projects for advancement of power grid technologies
- In the SmartGrid Demonstration Project we are helping to advance technologies allowing for consumer-in-the-loop interaction in order to use more renewables and keep costs down
- The Future Power Grid Initiative is making strides in real-time analysis and visualization of power grid data
- The M2ACS project is focused on technical research questions in the area of mathematics which are inspired by real power grid problems
  - Significant math development is required in order to understand and manage emerging behaviors in complex energy systems.
  - Such math development leverages other domain’s work but also has unique aspects that requires new math.
- At PNNL, we have a great opportunity to link the fundamental math development with applied research – a necessary pathway to make real impact.

Questions?