Economic Impacts of Advanced Weather Forecasting on Unit Commitment

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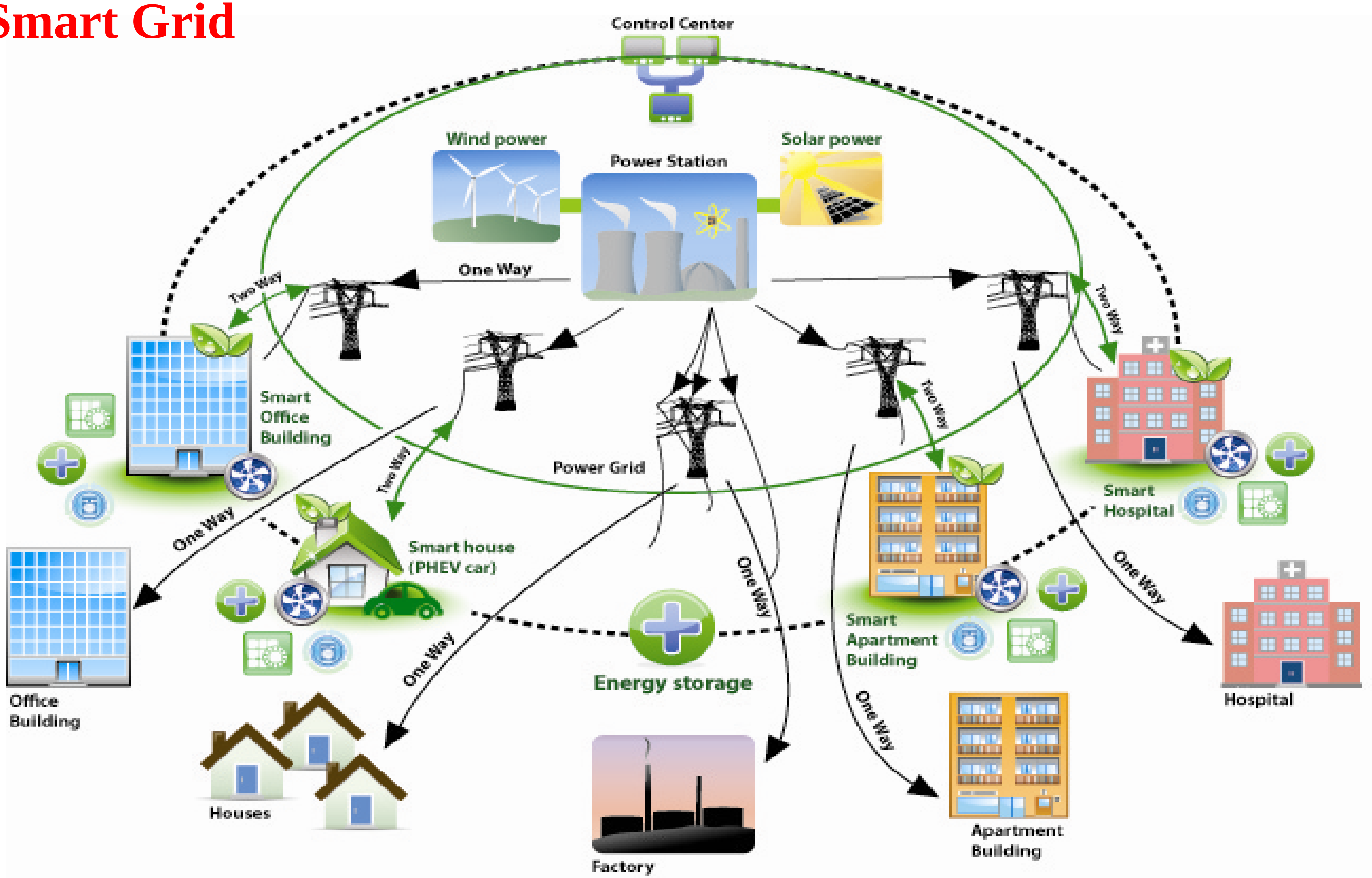
Motivation

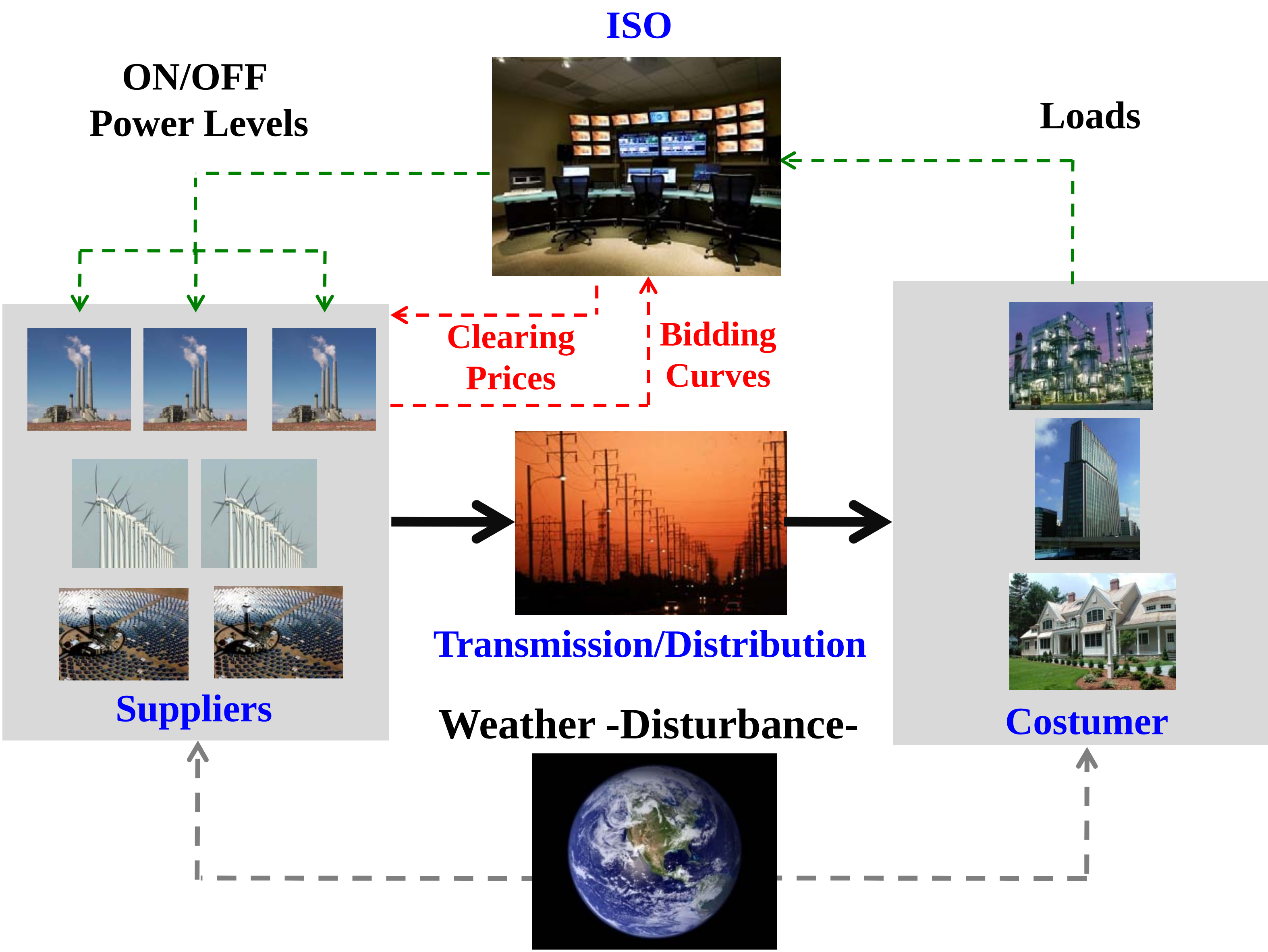
Smart Grid



Major Adoption of Renewable Resources (20-30%)

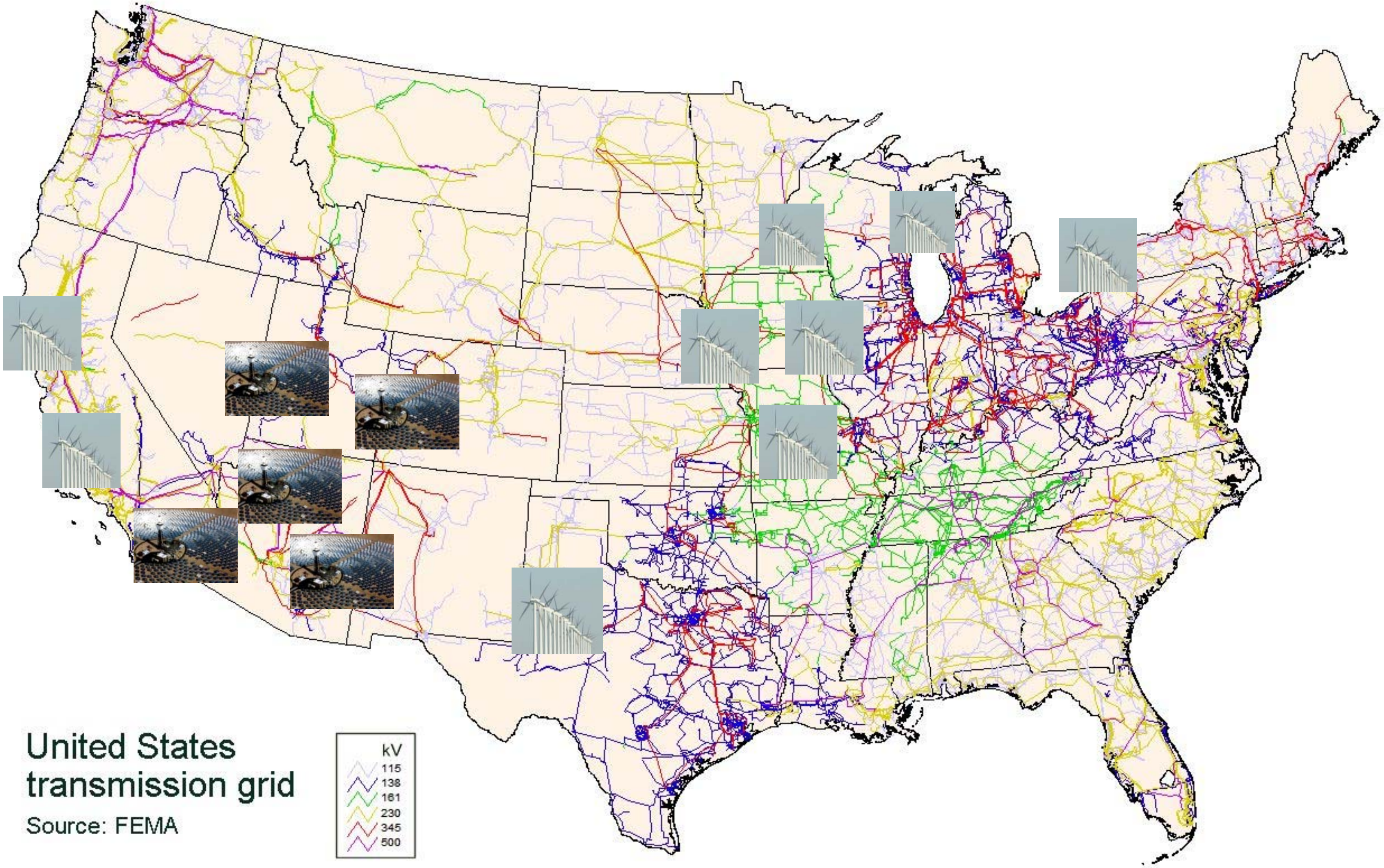
Highly <u>Distributed</u> Generation and Demand-Response = Increasing Uncertainty

Motivation



Weather Drives Markets and Operations – Forecasting is Critical

Motivation



Weather, Loads, and Generation Exhibit <u>Complex Spatio-Temporal</u> Correlations
-Correlations <u>Must Be</u> Captured in Forecasting-

Outline

1. Uncertainty Quantification and Weather Forecasting

2. Stochastic Optimization - Unit Commitment

3. Conclusions and Research Challenges

Contribution of the Talk:

New Insights on Uncertainty Management and High-Performance Computing For Power Grid Operations

1. Uncertainty Quantification and Weather Forecasting

Uncertainty Quantification

Major Advances in Meteorological Models (WRF)

Highly Detailed Phenomena

High Complexity 4-D Fields (10^6- 10^8 State Variables)

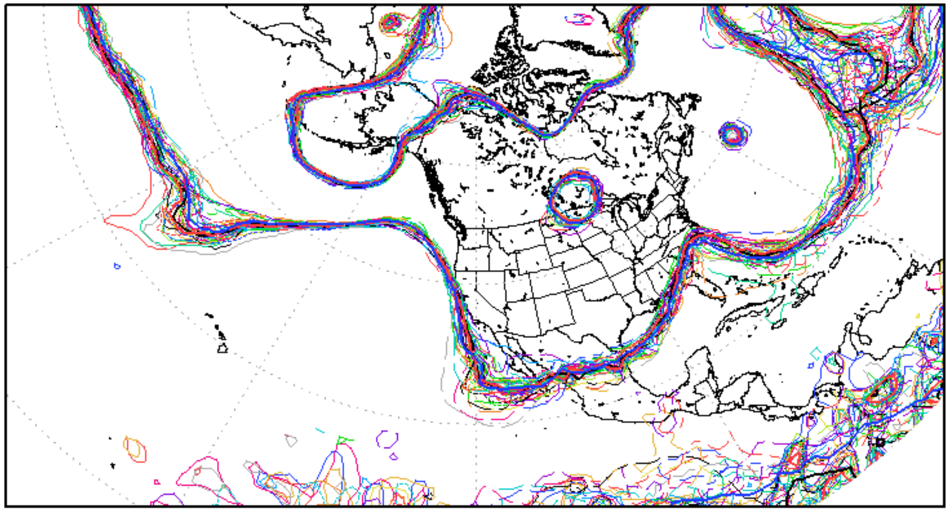
Model Reconciled to Measurements From Meteo Stations

Data Assimilation Techniques:

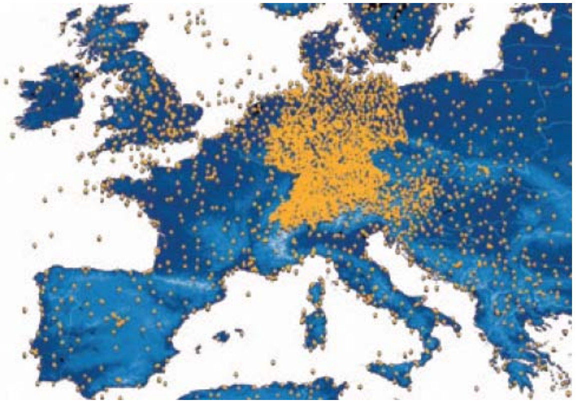
3-D Var *Courtier, et.al. 1998*

4-D Var *Navon et.al., 2007*

Extended and Ensemble Kalman Filter *Eversen, et.al. 1998*



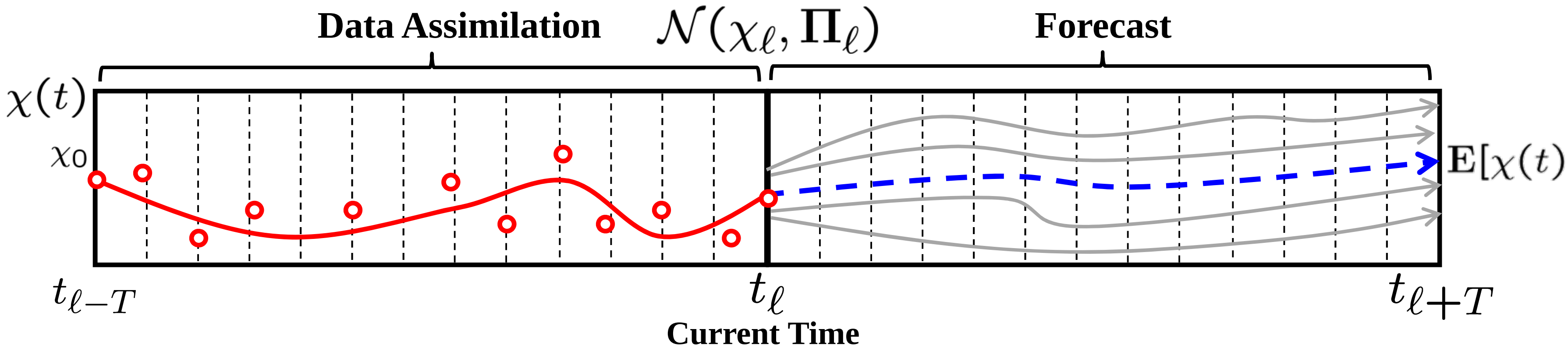
http://www.emc.ncep.noaa.gov/gmb/ens/



http://www.meteomedia.com/

Is WRF Computationally Practical Enough for Real-Time Operations?

Uncertainty Quantification



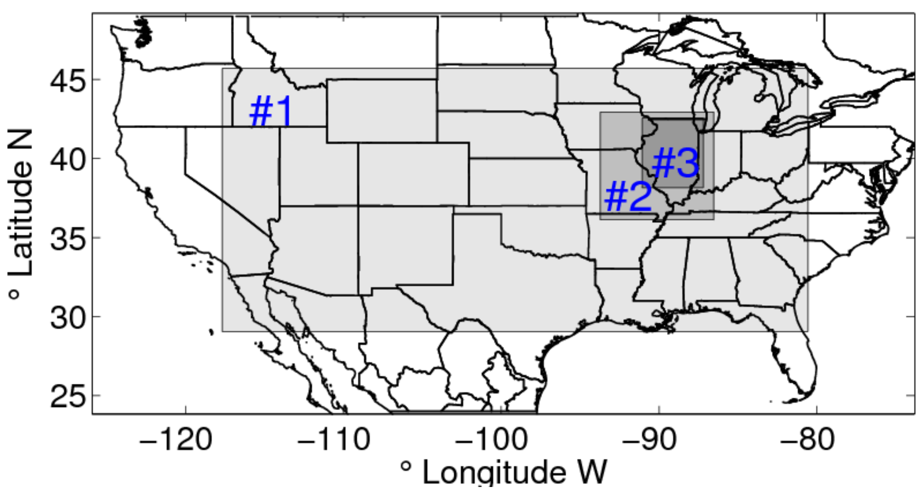
Computing and Storing Exact Covariance Matrix is <u>Impractical</u>:

1) **Create Empirical Distribution of Current Atmospheric State**
2) **Propagate Samples through WRF Model**

ID	Size	Grid
#1	130×60	$32\,\text{km}^2$
#2	126×121	$6\,\text{km}^2$
#3	202×232	$2\,\text{km}^2$

Making WRF Feasible:

Grid-Targeted Resolutions and Computational Resources



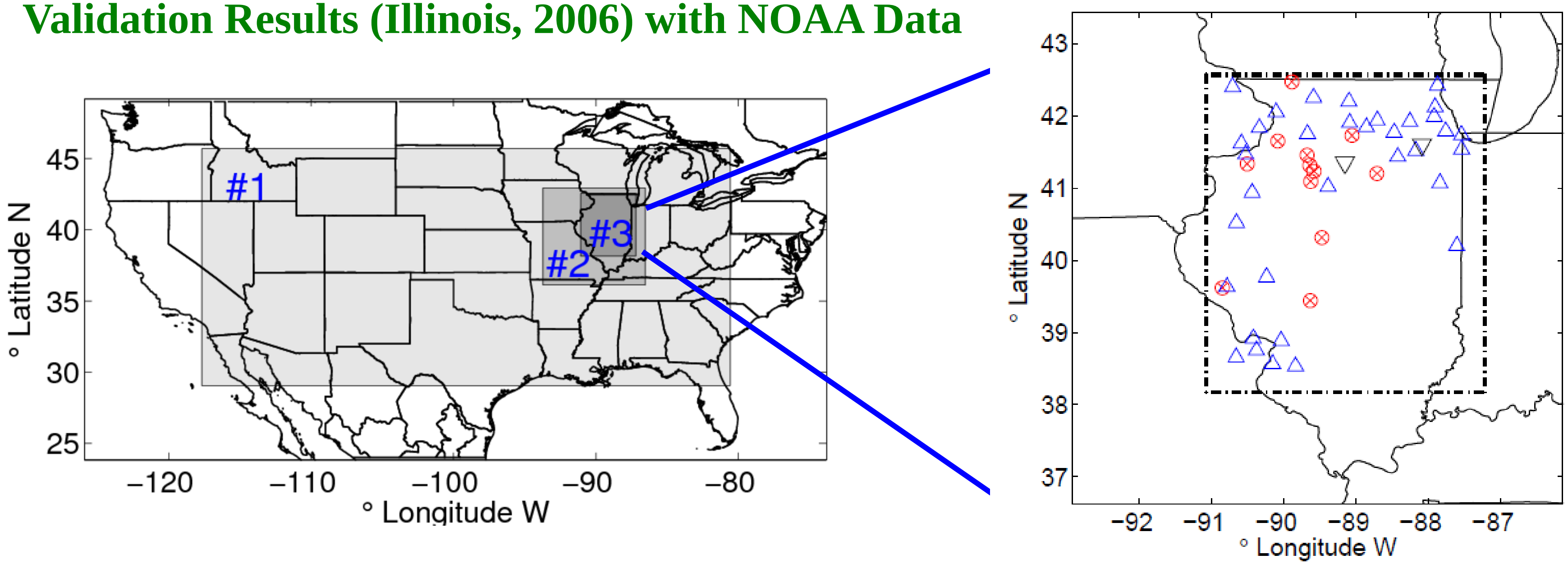
CPUs	Wall-time [hr]
4	50
8	28
16	17
32	10

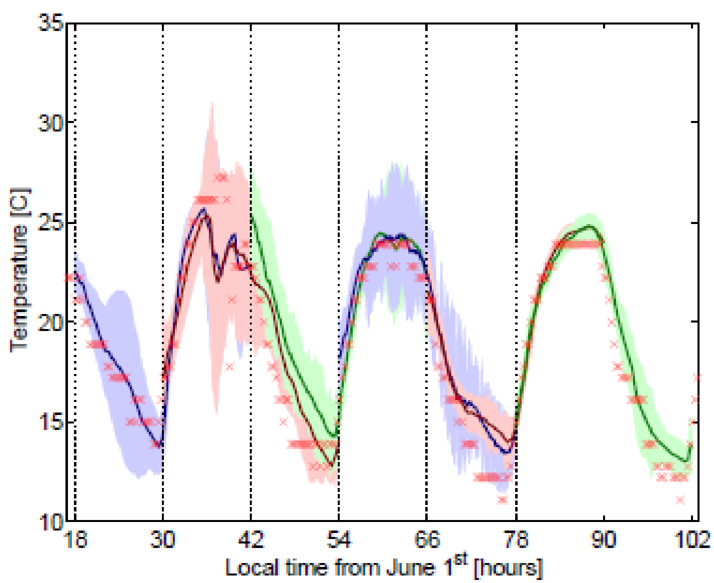
Jazz Cluster at Argonne National Laboratory

- ✔ Illinois [2km]: 500 processors
- ☐ US [2 km]: ~50,000 processors
- ☐ US [1 km]: ~400,000 processors

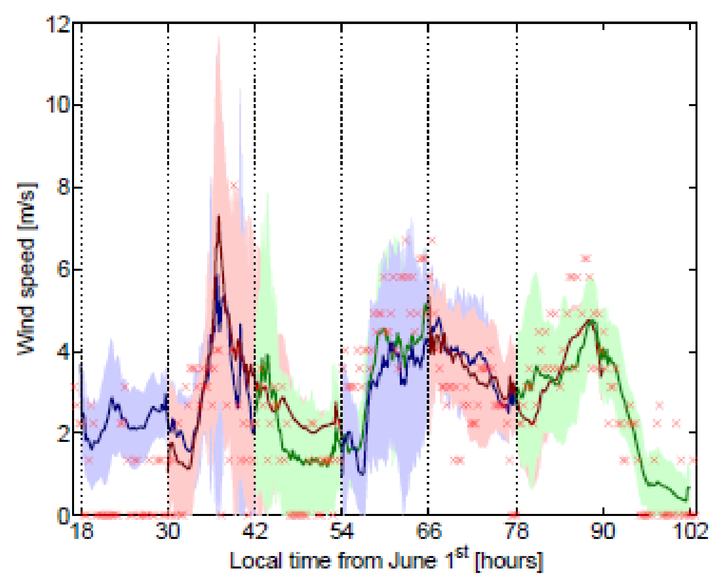
Uncertainty Quantification

Validation Results (Illinois, 2006) with NOAA Data





Temperature [ºC]

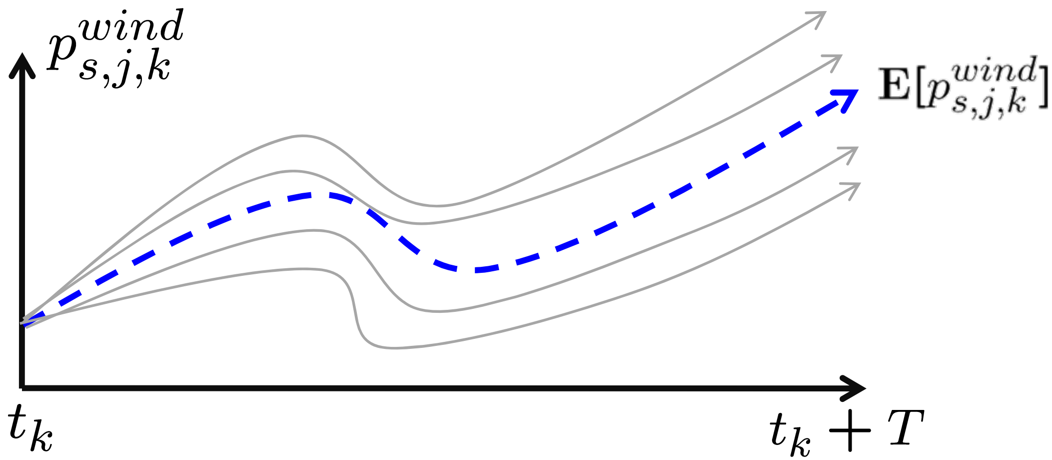


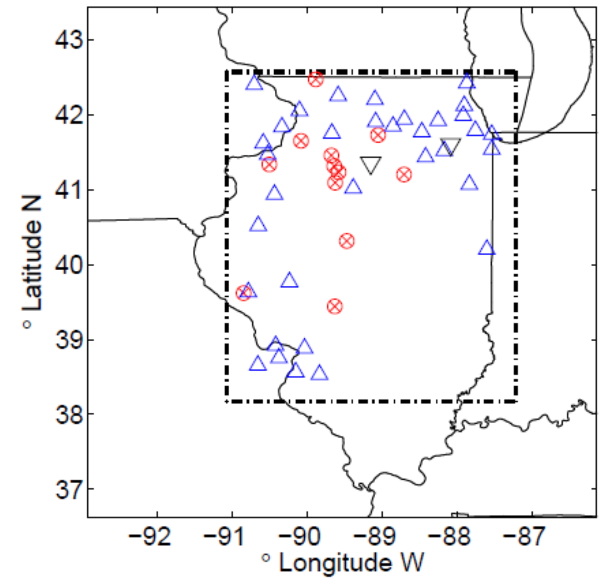
Wind Speed [m/s]

2. Stochastic Optimization – Unit Commitment

Stochastic Unit Commitment

Wind Adoption in Illinois





$$\min_{p_{s,j,k},\overline{p}_{s,j,k},\nu_{j,k}} \varphi(p^{wind}_{s,j,k}) := \frac{1}{N_S}\sum_{s\in\mathcal{S}}\left(\sum_{j\in\mathcal{N}}\sum_{k\in\mathcal{T}} c^p_{s,j,k} + c^u_{j,k} + c^d_{j,k}\right)$$

$$\text{s.t.} \sum_{j\in\mathcal{N}} p_{s,j,k} + \sum_{j\in\mathcal{N}_{wind}} p^{wind}_{s,j,k} = D_k,\; s\in\mathcal{S}, k\in\mathcal{T}$$

$$\sum_{j\in\mathcal{N}} \overline{p}_{s,j,k} + \sum_{j\in\mathcal{N}_{wind}} p^{wind}_{s,j,k} \geq D_k + R_k,\; s\in\mathcal{S}, k\in\mathcal{T}$$

- Dealing with Large Number of Scenarios and Thermal Units

- Impact of WRF Accuracy and Uncertainty Estimates on Reliability

Parallel Stochastic Unit Commitment

Structure of Optimization Problem Permeates Down to Linear Algebra

-Preserve Convergence of Simplex and Interior-Point Solvers (Avoid Lagrangian Relaxation)

-Dynamic Load Balancing, MPI, C++ Implementation

$$\min_{x, y_1, y_2, \ldots, y_N} f(x) + \frac{1}{N}\sum_{i=1}^{N} g_i(y_i)$$

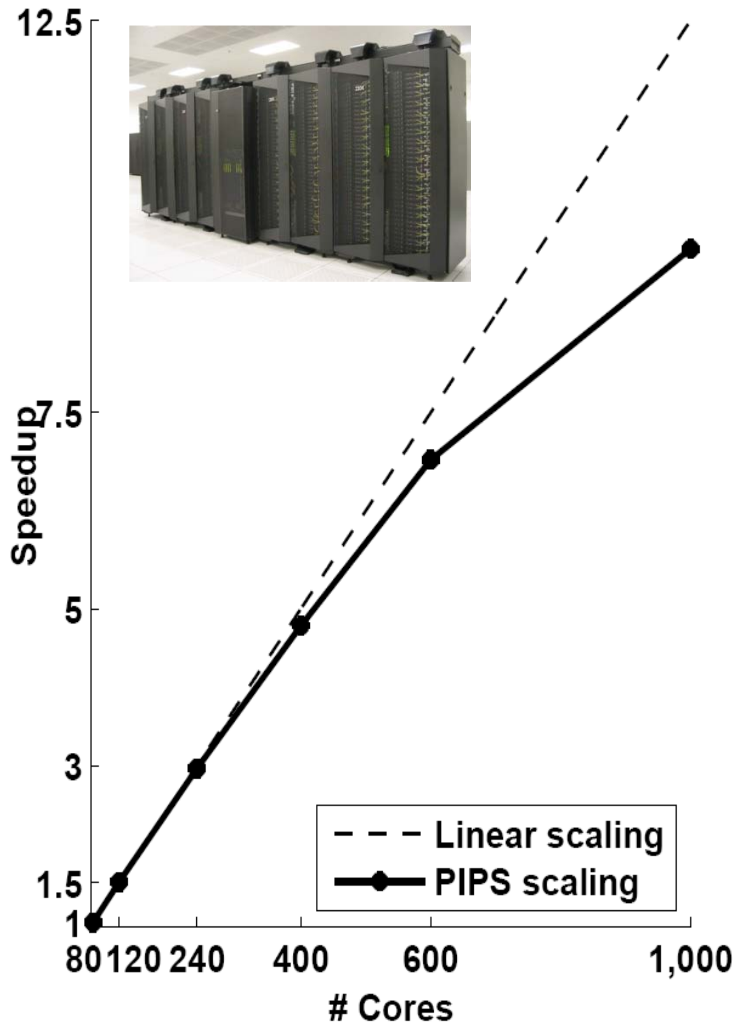
$$\begin{array}{lllllll}
A_0 x & & & & & = & b_0 \\
A_1 x + & B_1 y_1 & & & & = & b_1 \\
A_2 x + & & B_2 y_2 & & & = & b_2 \\
\vdots & & & \ddots & & & \vdots \\
A_N x + & & & & B_N y_n & = & b_N \\
x \geq 0, & y_1 \geq 0, & y_2 \geq 0, & \ldots & y_N \geq 0 & &
\end{array}$$

- 150 Thermal Units and 6000 Scenarios
  LP with O(10^7) Variables
  600 Times Faster Than Serial

- Scaling Bottlenecks Avoided with Matrix-Free Schur Strategy

- Computing is NOT The Only Bottleneck …

Fusion Cluster at Argonne National Laboratory



Stochastic Unit Commitment

Integration Uncertainty Quantification & Stochastic Programming

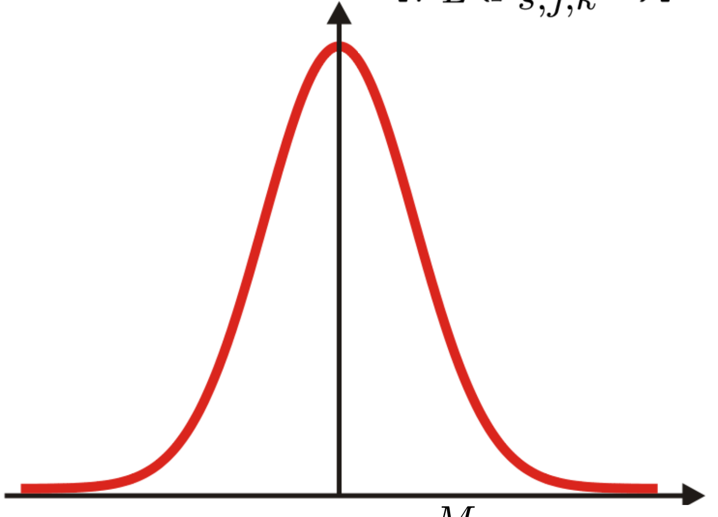
- **Forecast Probability Distribution is <u>NOT Explicitly Available</u>**
- **Weather Scenarios Are Expensive (~ 50) → Optimal Cost Never Known Exactly!**

How to Generate More Realizations? Inference Analysis with <u>Resampling</u>

1) **Sample Weights on Hyperplane** $\sum_{s\in\mathcal{S}} w_{s,\ell} = 1$ **and Compute** $p_{s,j,k}^{wind,\ell} = \sum_{s\in\mathcal{S}} w_{s,\ell} \cdot p_{s,j,k}^{wind}$
2) **Solve Stochastic Problem with** M **Batches of Realizations**

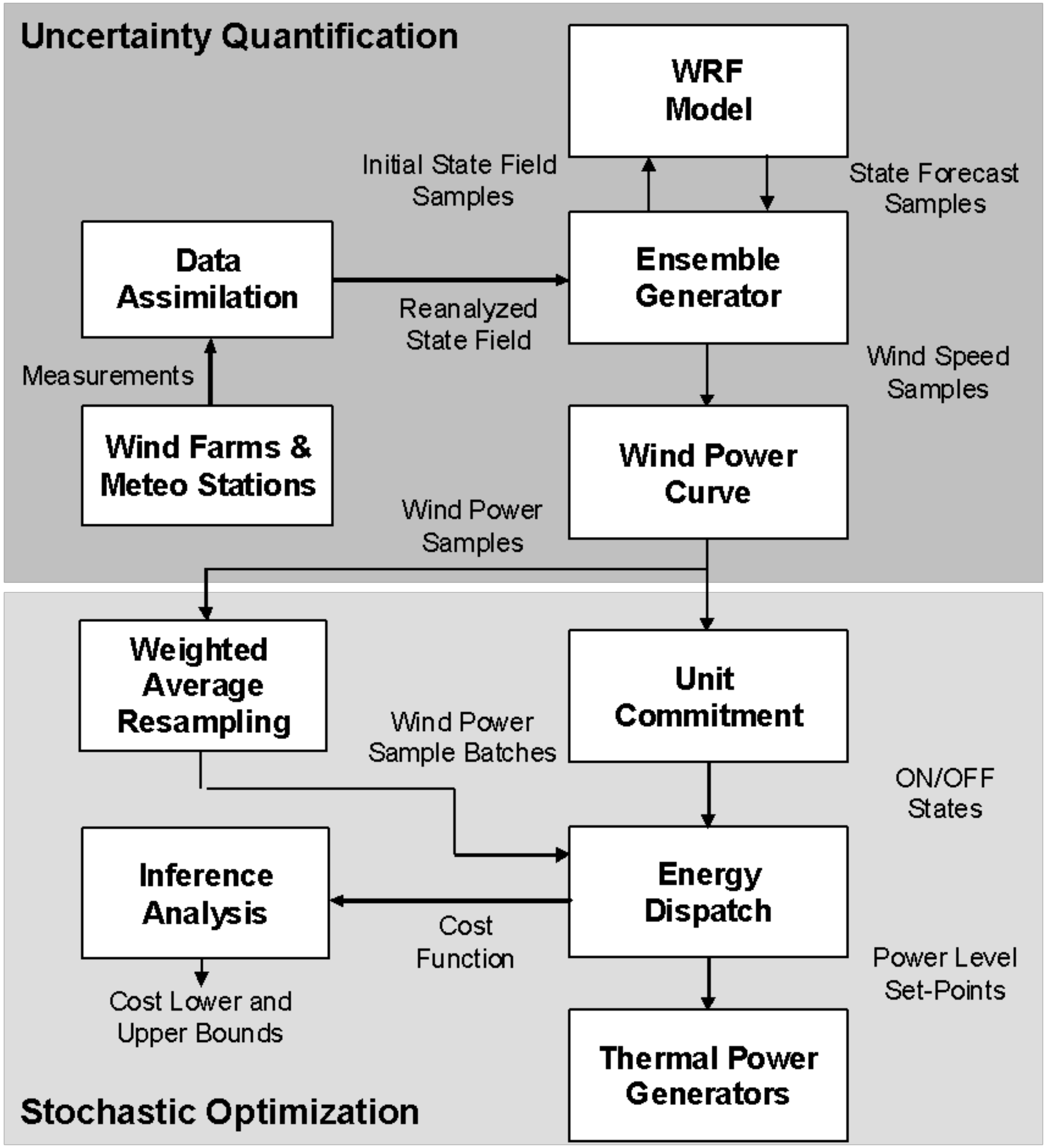
Cost Confidence Intervals

$$\mathbf{E}[\varphi_L(p_{s,j,k}^{wind,\ell})] \approx L_M := \frac{1}{M}\sum_{j=1}^{M} \varphi(p_{s,j,k}^{wind,\ell})$$



$$\mathrm{Var}[\varphi_L(p_{s,j,k}^{wind,\ell})] \approx \frac{1}{M-1}\sum_{j=1}^{M} (\varphi(p_{s,j,k}^{wind,\ell}) - L_M)^2$$

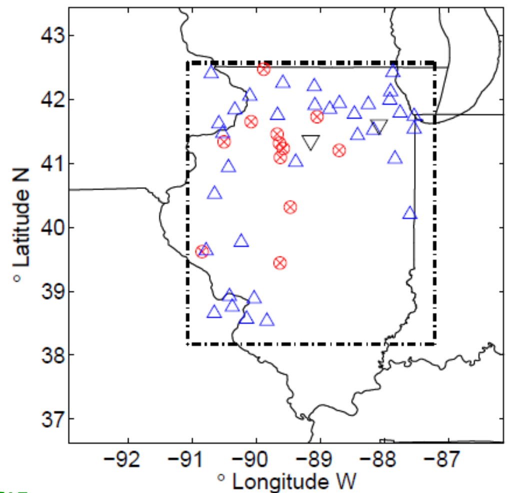
Stochastic Unit Commitment

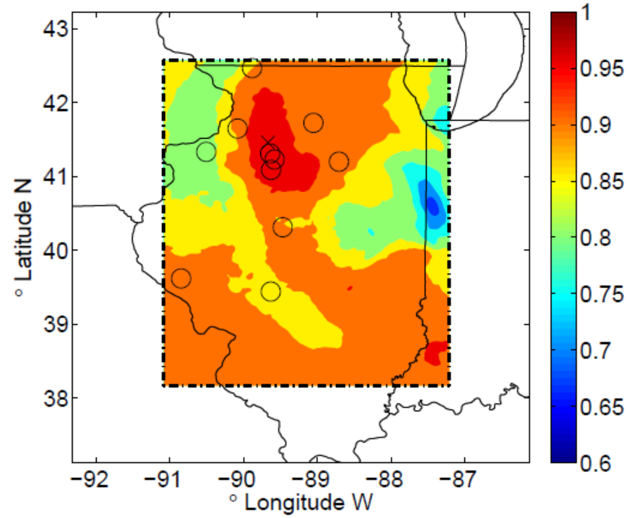


WRF Resolution and Number of Scenarios <u>Must</u> be Adapted in Real-Time

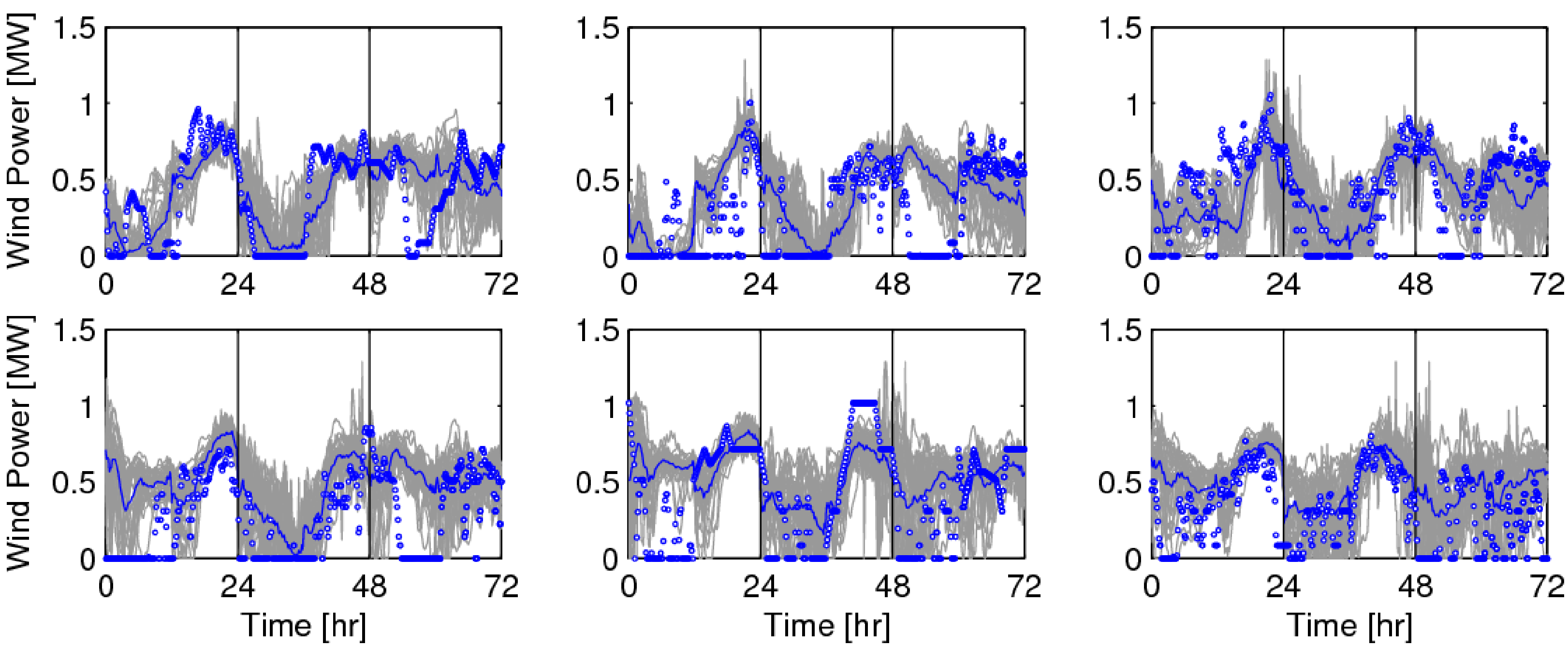
Stochastic Unit Commitment

3 Days of Operation (Wind Adoption Level 20%)



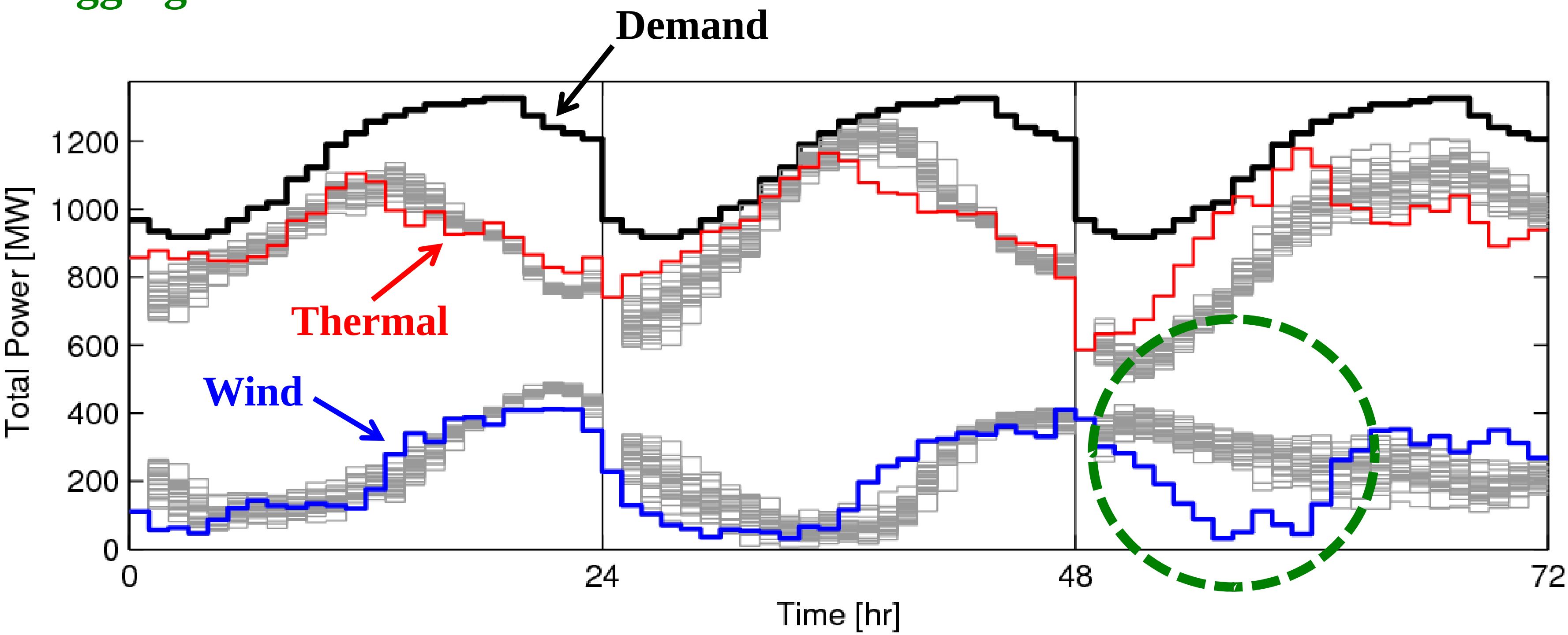


Wind Power Profiles



Stochastic Unit Commitment

Aggregated Power Profiles



- **Daily WRF Forecasts are -In General- Accurate with Tight Uncertainty Bounds**

- **Inference Analysis Reveals that <u>30 WRF Samples</u> are Sufficient to Estimate Cost!**
  Cost ~ \$474,000, Upper Bound σ^2 (1,082 $\$^2$), Lower Bound σ^2 (1,656 $\$^2$)

- **However, <u>Excursions</u> Do Occur: Probability Distribution on 3rd Day is Inaccurate!**
  Need High-Frequency <u>Data Assimilation</u> (1 hour)? Missing Physics?

Key: Stochastic Optimization NOT Useful if Uncertainty Estimates are Wrong

3. Conclusions and Research Challenges

Conclusions and Research Challenges

Smart Grid

- **Weather, Loads, and Generation Forecasts with <u>Accurate</u> Uncertainty Estimates**

Many Advances in Optimization But Not On Uncertainty Quantification

- **How to Generate <u>Low Cost</u> Forecasts for ISOs, GENCOs, TRNSCOs?**

  <u>Grid-Tailored</u> Resolution Constrained by <u>Computational</u> Resources

- **Need for High-Performance Computing**

  Expanding Network Domains, High-Frequency Data Assimilation

Argonne's Vision

- **Grid Simulator for Detailed Market , Planning, and Operations Studies**

  Grid-Tailored Uncertainty Quantification Capabilities

  Unit Commitment with AC-Transmission (MINLP)

  Transmission Planning Over Interconnects

  Market Models and Data Assimilation for Price Forecasting

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