Optimization and Uncertainty Quantification for Next-Generation Power Markets and Operations

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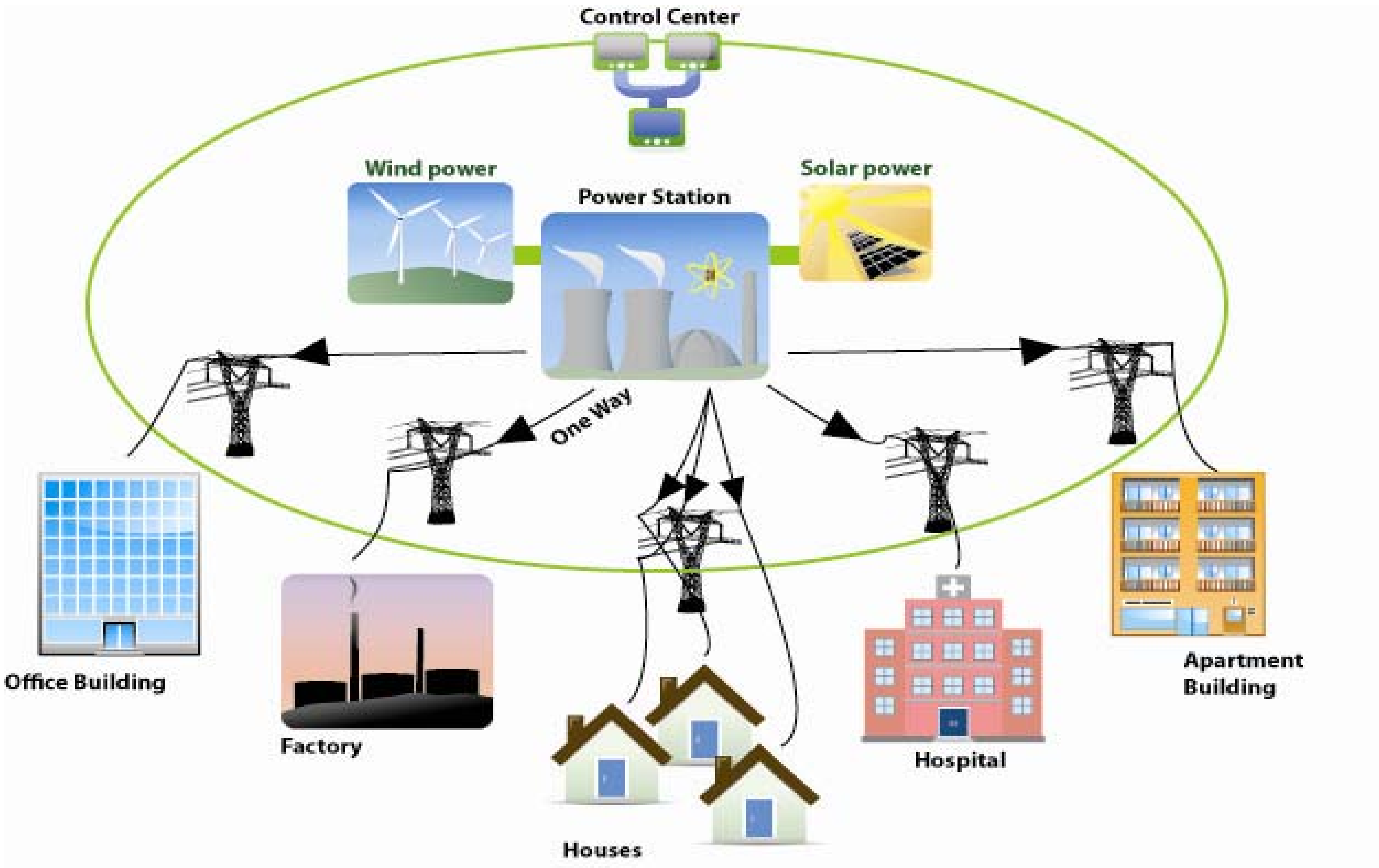
IBM T. J. Watson Center
April 13th, 2010

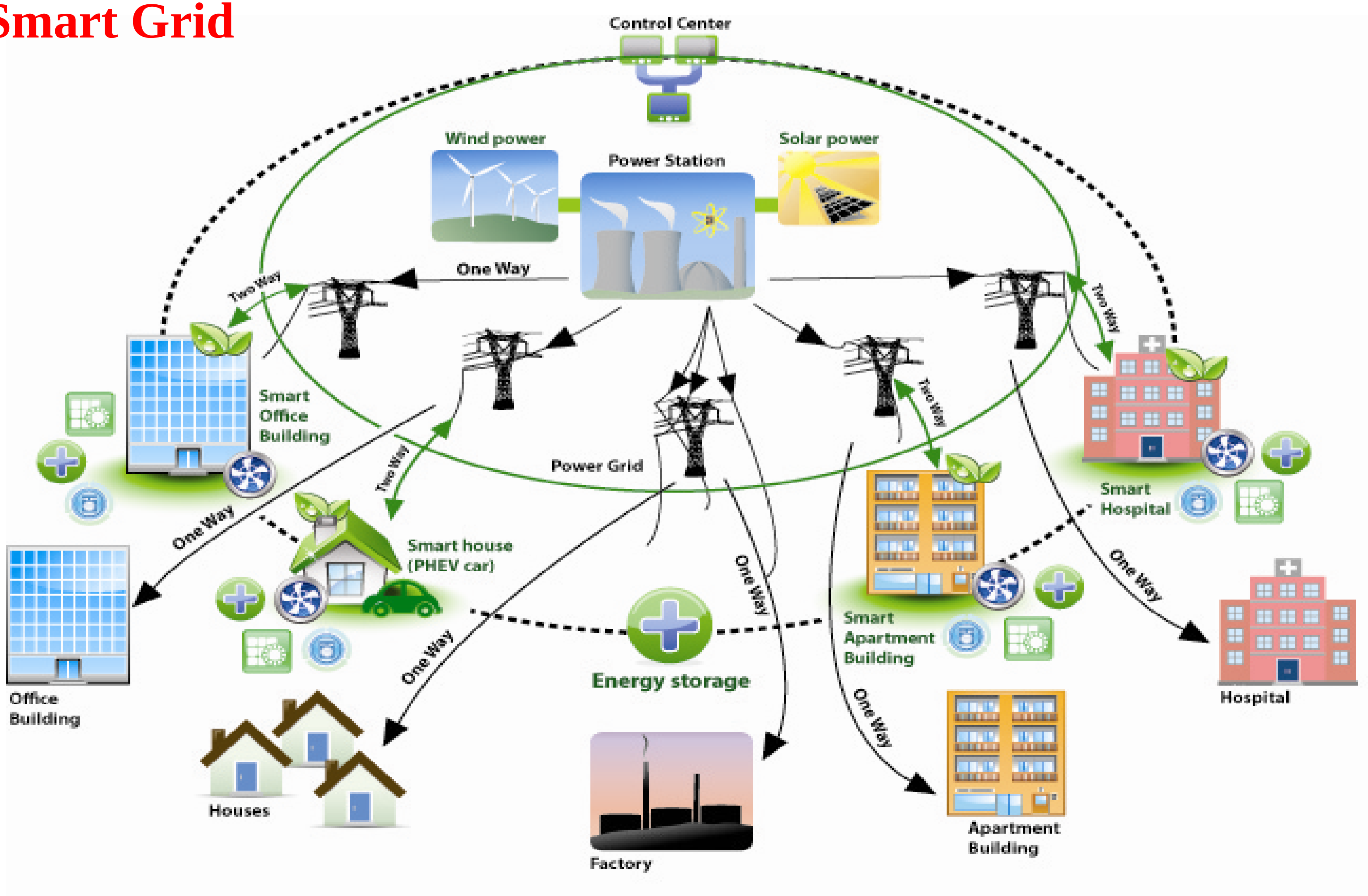
Motivation

Current Grid



Motivation

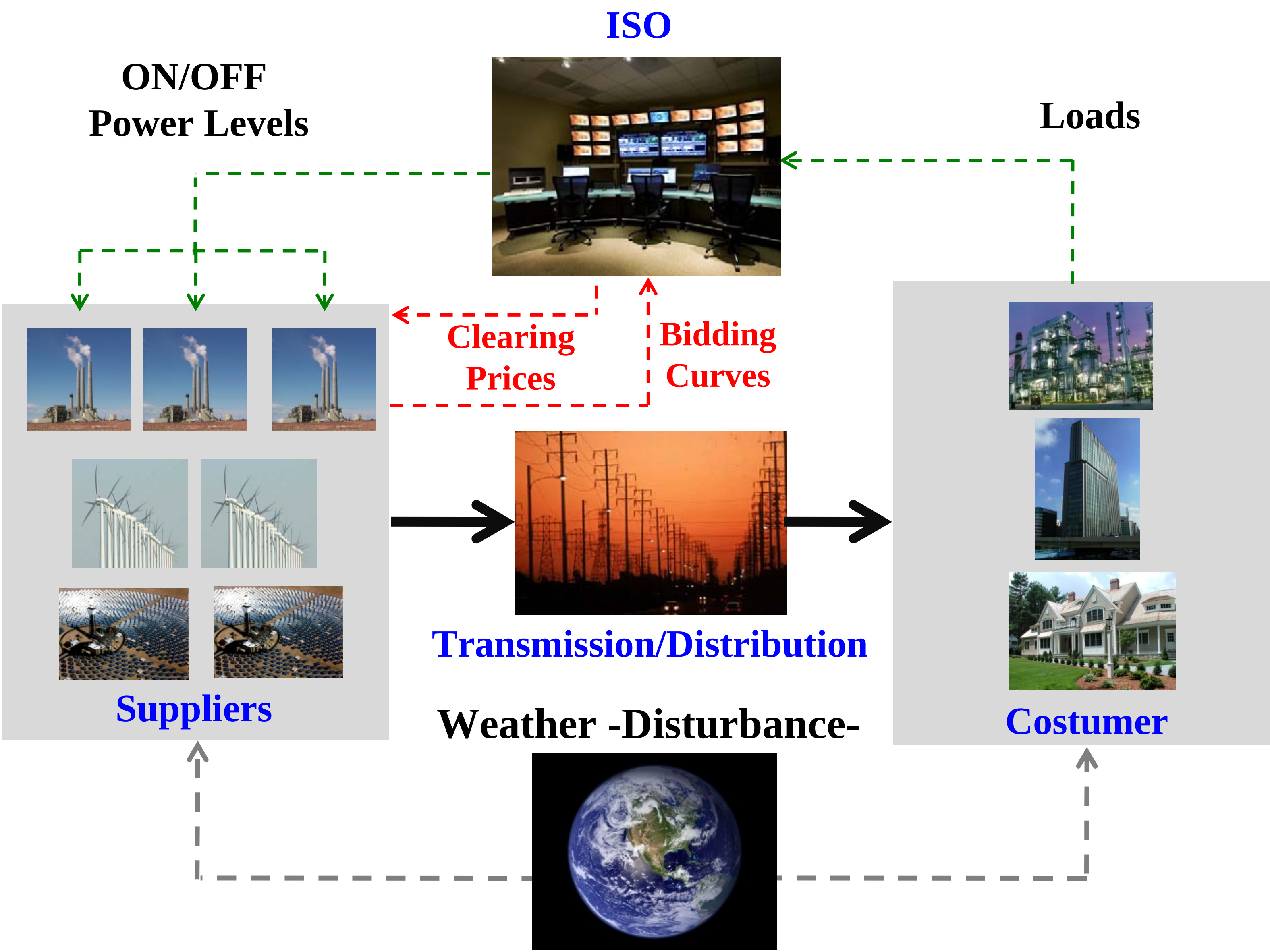
Smart Grid



Major Adoption of Renewable Resources (20-30%)

Highly <u>Distributed</u> Generation and Demands

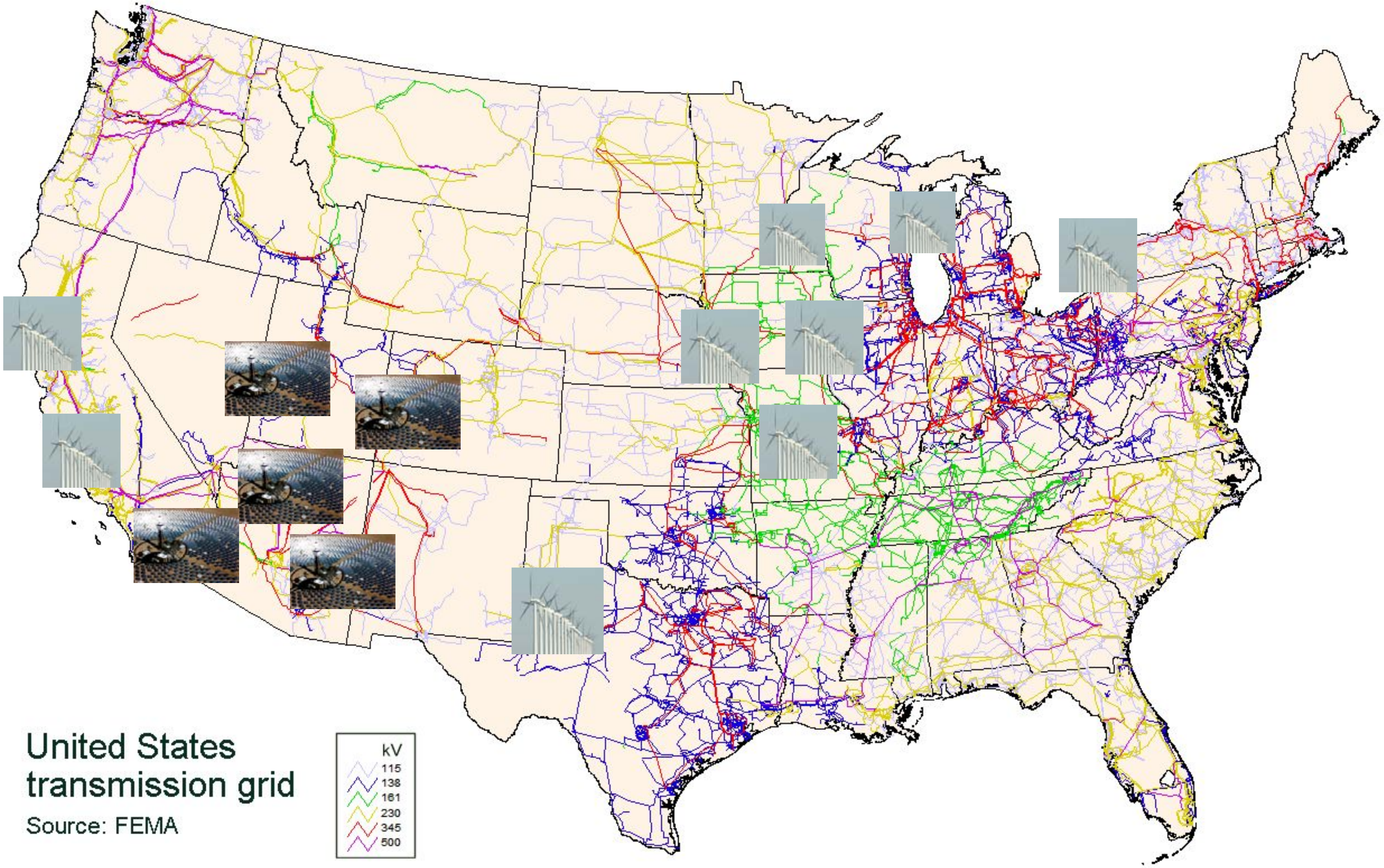
Power Grid as a Feedback System



Weather Drives Markets and Operations – Forecasting is Critical

Motivation

Smart Grid



Loads and Generation Exhibit <u>Complex Spatio-Temporal</u> Correlations at Multiple Scales

Some Research Questions

- **Demand is function of Weather (Physical) and Human Behaviors (Non-Physical)**
    - **How to target weather forecasts to ISO, GENCOs, and TRNSCOs needs?**
    - **How to quantify and deal with uncertainty?**

      - Stochastic Programming vs. Reserves
- **Price is function of feedback interactions between GENCOs, TRANSCOs and ISO**
    - **How to forecast prices?**

      - Game-Theoretical vs. Agents vs. Statistical Models
    - **How to develop effective bidding strategies?**
- **In Smart Grid, costumers will become active market participants (demands also result from market feedbacks)**
    - **How to model "smart" costumers?**

Future is On the Integration - <u>Real-Time</u> Grid Simulation

Massive Numerical Problems - <u>Where and How</u> to Solve them?

Outline of the Talk

1. **Argonne's Research on Optimization**

2. **Recent Work**
   - **Market Equilibrium Models**
   - **Uncertainty Quantification and Weather Forecasting**
   - **Stochastic Unit Commitment**
   - **Real-Time Energy Management of Co-Generation and Building Systems**

3. **Conclusions and On-Going Projects**

1. Argonne’s Research on Optimization

Argonne's Research on Optimization

Nonlinear Programming and Complementarity

- Sven Leyffer, Todd Munson and Mihai Anitescu

Mixed-Integer Nonlinear Programming (MINLP)

- Sven Leyffer

Stochastic Programming and Uncertainty

- Mihai Anitescu, Emil Constantinescu, VZ

Automatic Differentiation and Graph Partitioning

- Paul Hovland, Jean Utke, and Ilya Safro

Markets and Grid Modeling

- Todd Munson and VZ

Real-Time Optimization and Automatic Control

- VZ

2. Recent Work

Market Equilibrium Models

Market Equilibrium Models (Leyffer and Munson)

Nash Game: non-cooperative equilibrium of several producers

$$z_i^* \in \begin{cases} \underset{z_i}{\operatorname{argmin}} & b_i(\hat{z}) \\ \text{subject to} & c_i(z_i) \geq 0 \end{cases} \qquad \text{producer } i$$

- $\hat{z} = (z_1^*, \ldots, z_{i-1}^*, z_i, z_{i+1}^*, \ldots, z_l^*)$
- All producers/players are equal

- Find equilibrium by –simultaneously- solving KKT conditions of all players

Nonlinear Complementarity Problem – PATH Solver *Ferris & Munson*

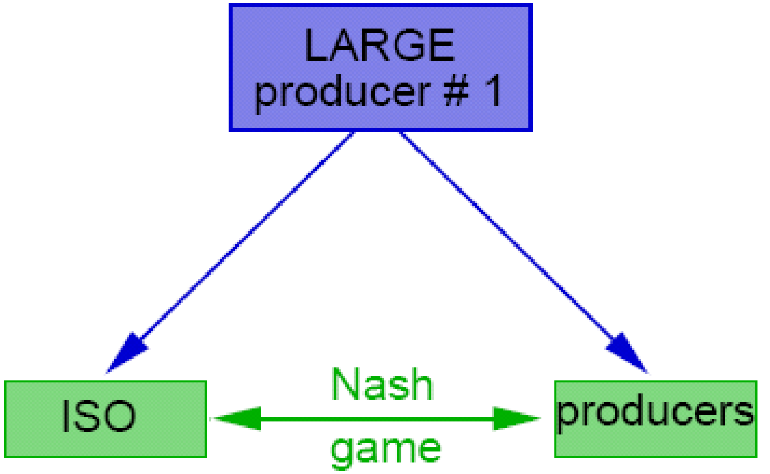
$$\begin{aligned} \nabla b(z) - \nabla c(z)\lambda &= 0 \\ s - c(z) &= 0 \\ 0 \leq \lambda \perp s &\geq 0 \end{aligned}$$

Market Equilibrium Models

Stackelberg Games

Single dominant producer & Nash followers

$$\left\{ \begin{array}{ll} \underset{x\geq 0, y}{\text{minimize}} & f(x,y) \\ \text{subject to} & h(x,y) = 0 \\ & 0 \leq y_1 \perp y_2 \geq 0 \end{array} \right.$$



Nash game ($h(x,y) = 0$) parameterized in leader's variables x

Mathematical Program with Equilibrium Constraints (MPEC)

Market Equilibrium Models

Approaches:

1. Apply nonlinear solver directly ... relax complementarity
2. Penalize equilibrium minimize $f(x) + \pi x_1^T x_2$
   - Well behaved smooth problem: constraints satisfy MFCQ
   - Anitescu: $\pi^* < \infty$ and $X_1 x_2 \leq 0 \Rightarrow$ strongly-stationary
   - How to adjust π? ... L., Lopez-Calva & Nocedal
3. Relax equilibrium $X_1 x_2 \leq \tau e$ & $x_1, x_2 \geq -\delta e$
   - Well behaved smooth problem
   - Adjust $\tau \searrow 0$ or $\delta \searrow 0$ ... not both

Aim: NLP solver with small modification that works for MPECs

Key Observations after Numerical Testing *Leyffer*

- **NLP Solvers (IPOPT, Knitro, FilterSQP) Faster than Specialized MPEC Solvers**
- **Fast Local Convergence ~ Newton's Method, Linear Algebra**

2. Recent Work

Uncertainty Quantification and Weather Forecasting

Uncertainty Quantification (Constantinescu, Zavala and Anitescu)

Major Advances in Meteorological Models (WRF)

Highly Detailed Phenomena

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

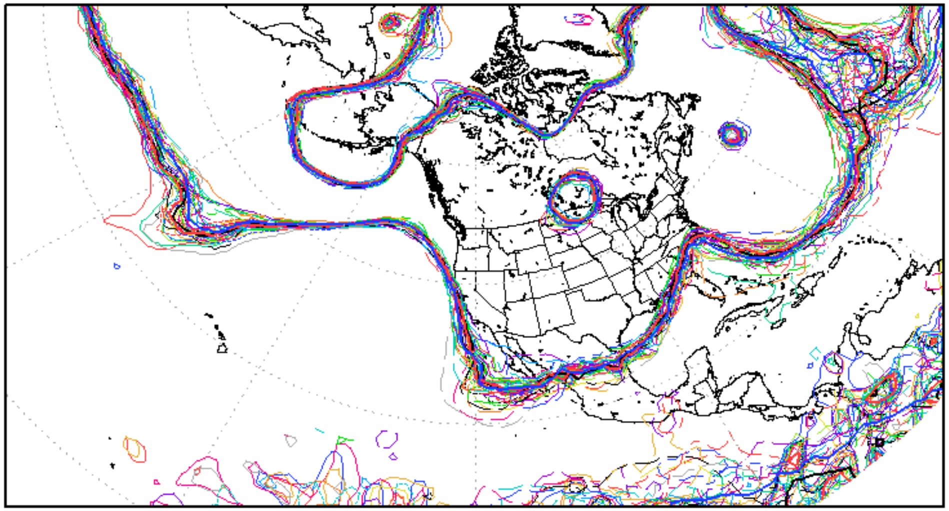
Model Reconciled to Measurements From Meteo Stations

Data Assimilation Techniques:

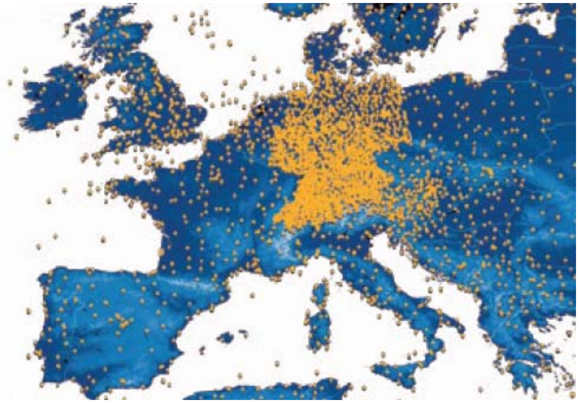
3-D Var *Courtier, et.al. 1998*

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

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



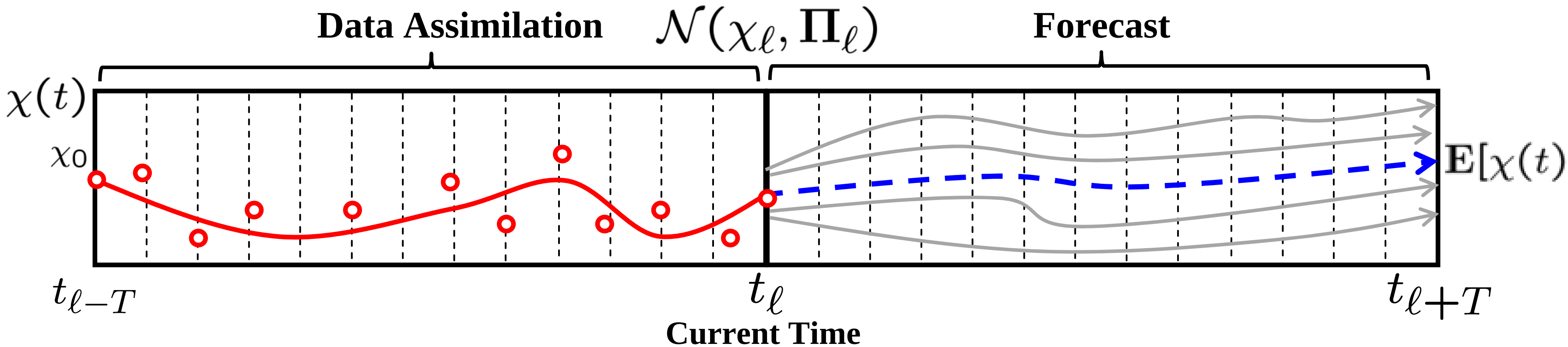
http://www.emc.ncep.noaa.gov/gmb/ens/



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>:

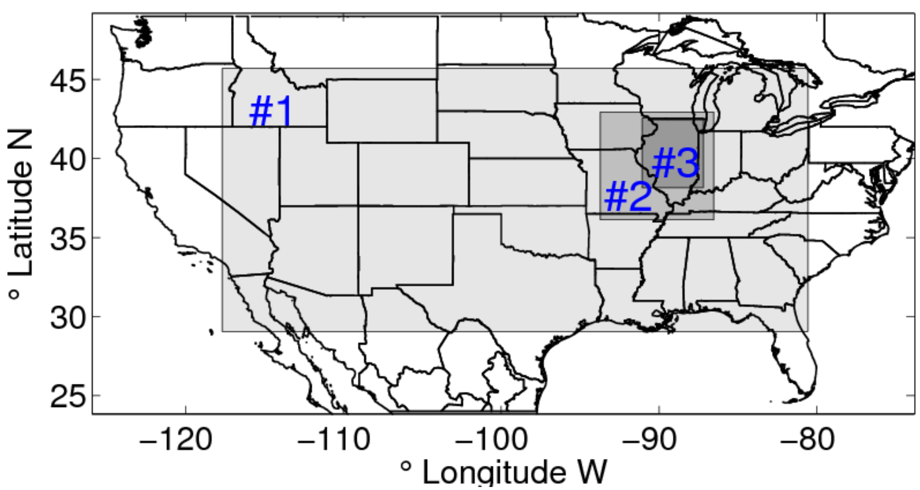
1) **Create Empirical Distribution of Current Atmospheric State**

2) **Propagate Samples through WRF Model**

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

Making WRF Feasible:

<u>Grid-Targeted</u> Resolutions and Computational Resources



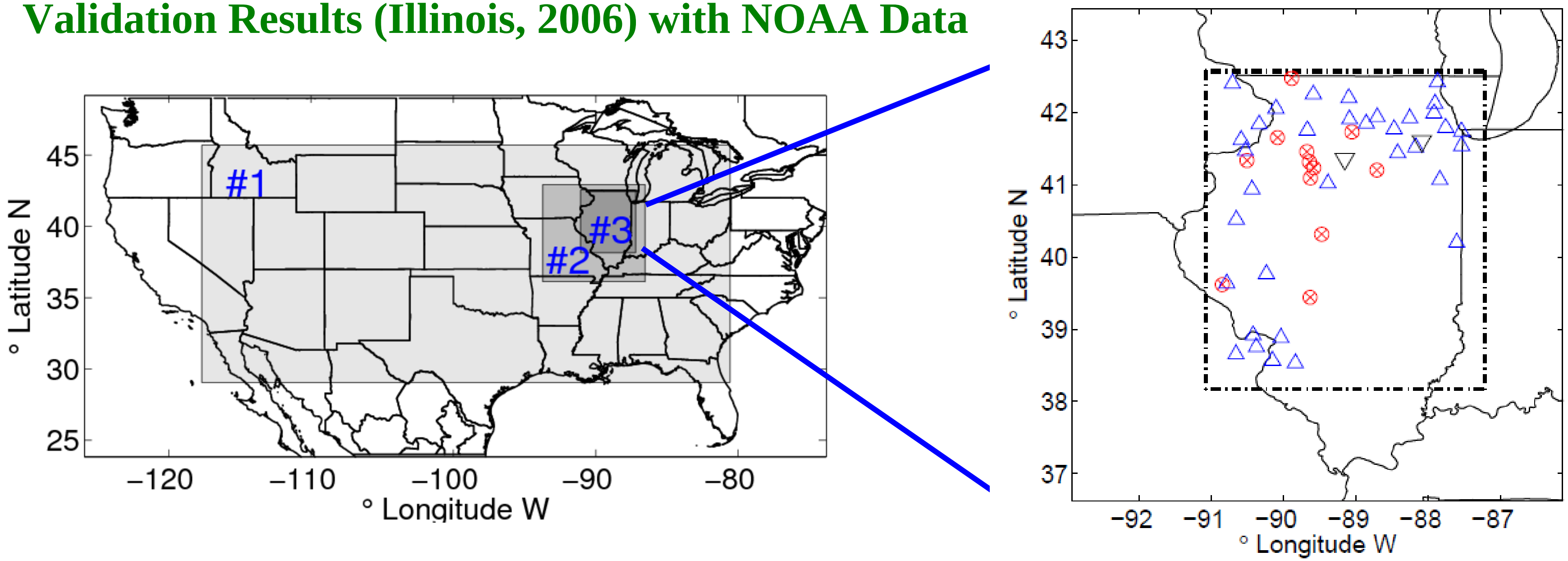
CPUs	Wall-time [hr]
4	50
8	28
16	17
32	10

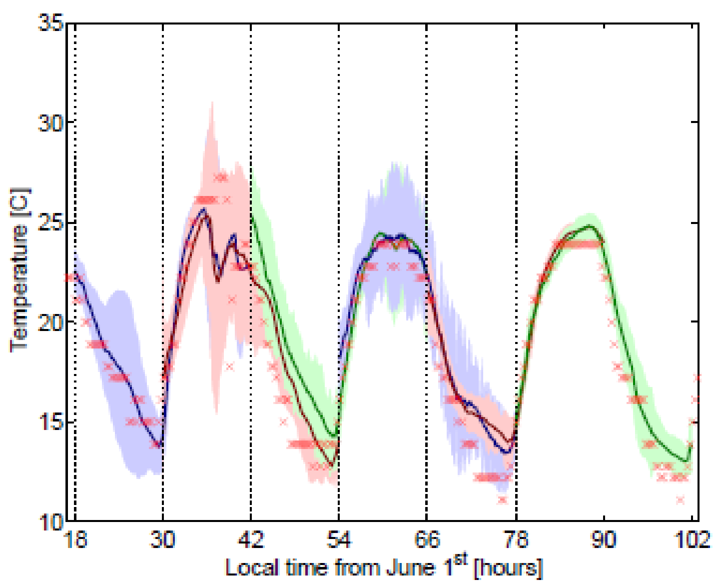
Jazz Cluster at Argonne National Lab

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

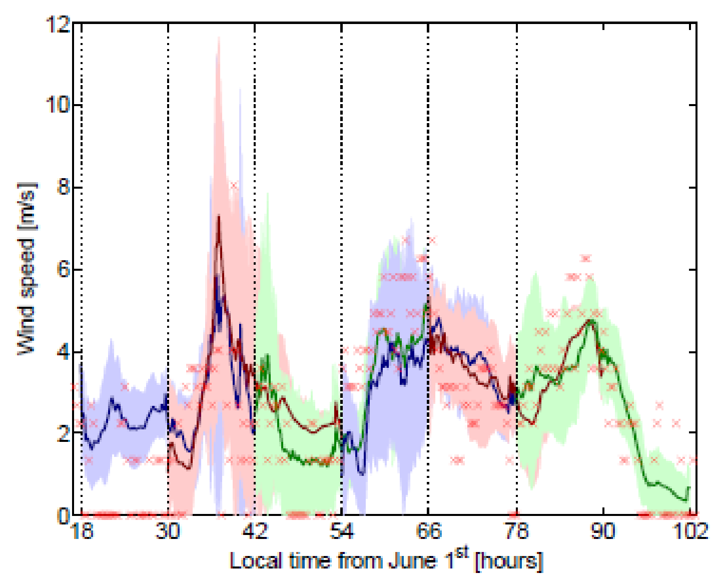
Uncertainty Quantification

Validation Results (Illinois, 2006) with NOAA Data





Temperature [^{o}C]

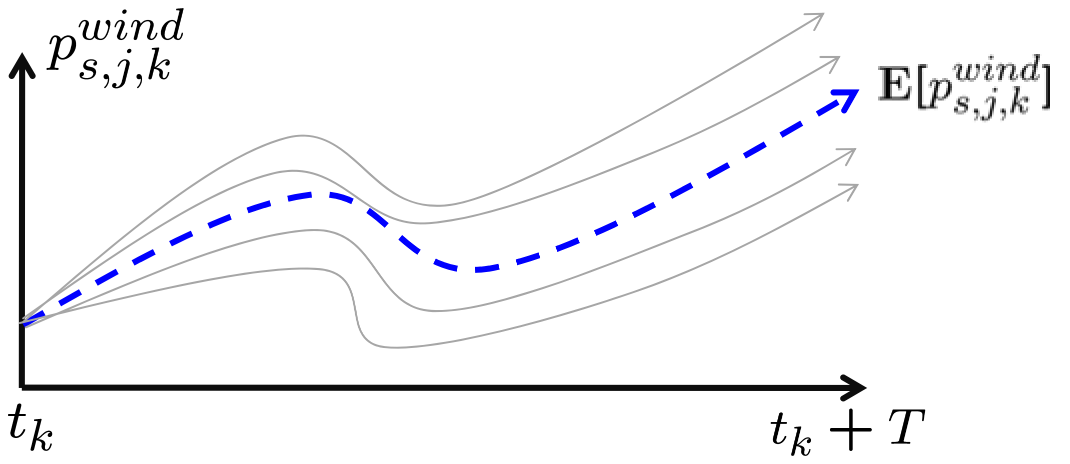


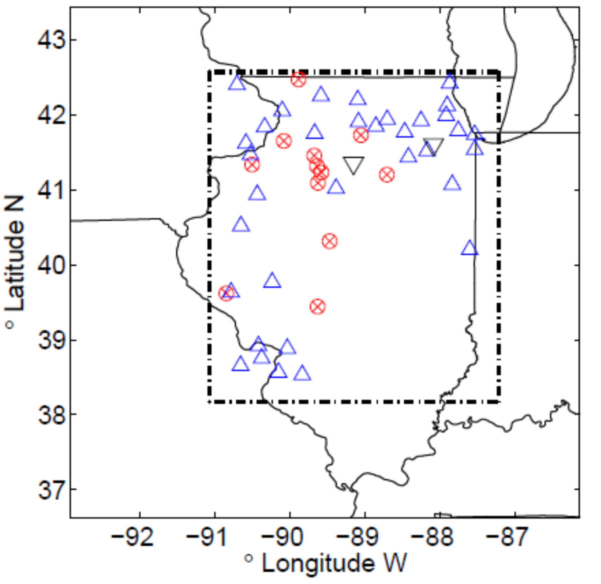
Wind Speed [m/s]

2. Recent Work

Stochastic Unit Commitment

Stochastic Unit Commitment (Zavala, Constantinescu and Anitescu)





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

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

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

- Dealing with Large Number of Scenarios and Units
- Impact of WRF Accuracy and Uncertainty on Reliability
- Capturing More Detailed Physics (Ramps, Power Flow)

Parallel Stochastic Programming (Petra and Anitescu)

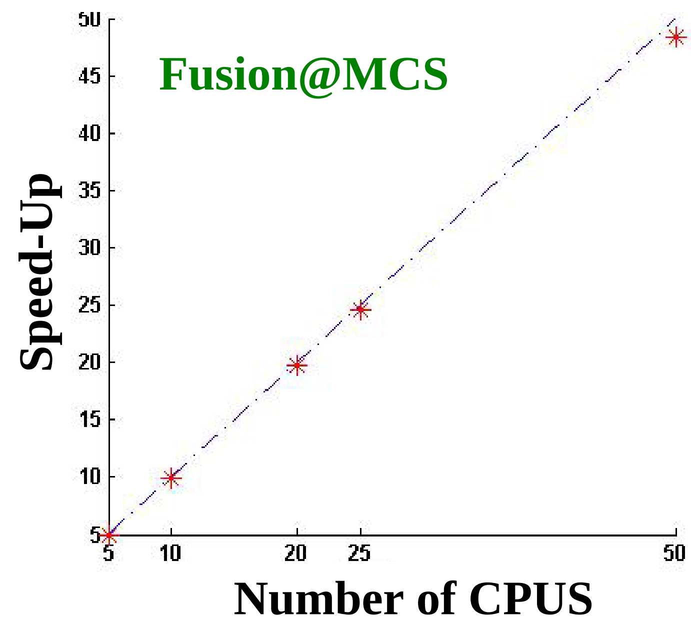
Structure of Optimization Problem Permeates Down to Linear Algebra

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

-**Dynamic Load Balancing, MPI, C++ Implementation**

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

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



-**Nearly perfect scalability with scenarios (building and unit commitment)**

-**Up to 10^6-10^7 variables and constraints feasible**

-**Bottlenecks due to coupling can be avoided with Matrix-Free Schur strategy**

Stochastic Unit Commitment

Issue: Integration Uncertainty Quantification & Stochastic Programming

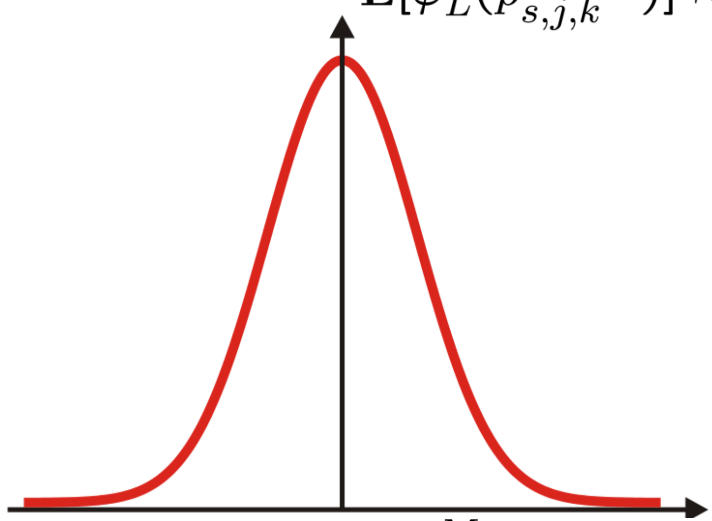
- **Forecast Probability Distribution is NOT Explicitly Available**
- **Few Weather Realizations (~ 50) → Optimal Cost Never Known Exactly!**

Generating More Realizations? Inference Analysis with Resampling

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**

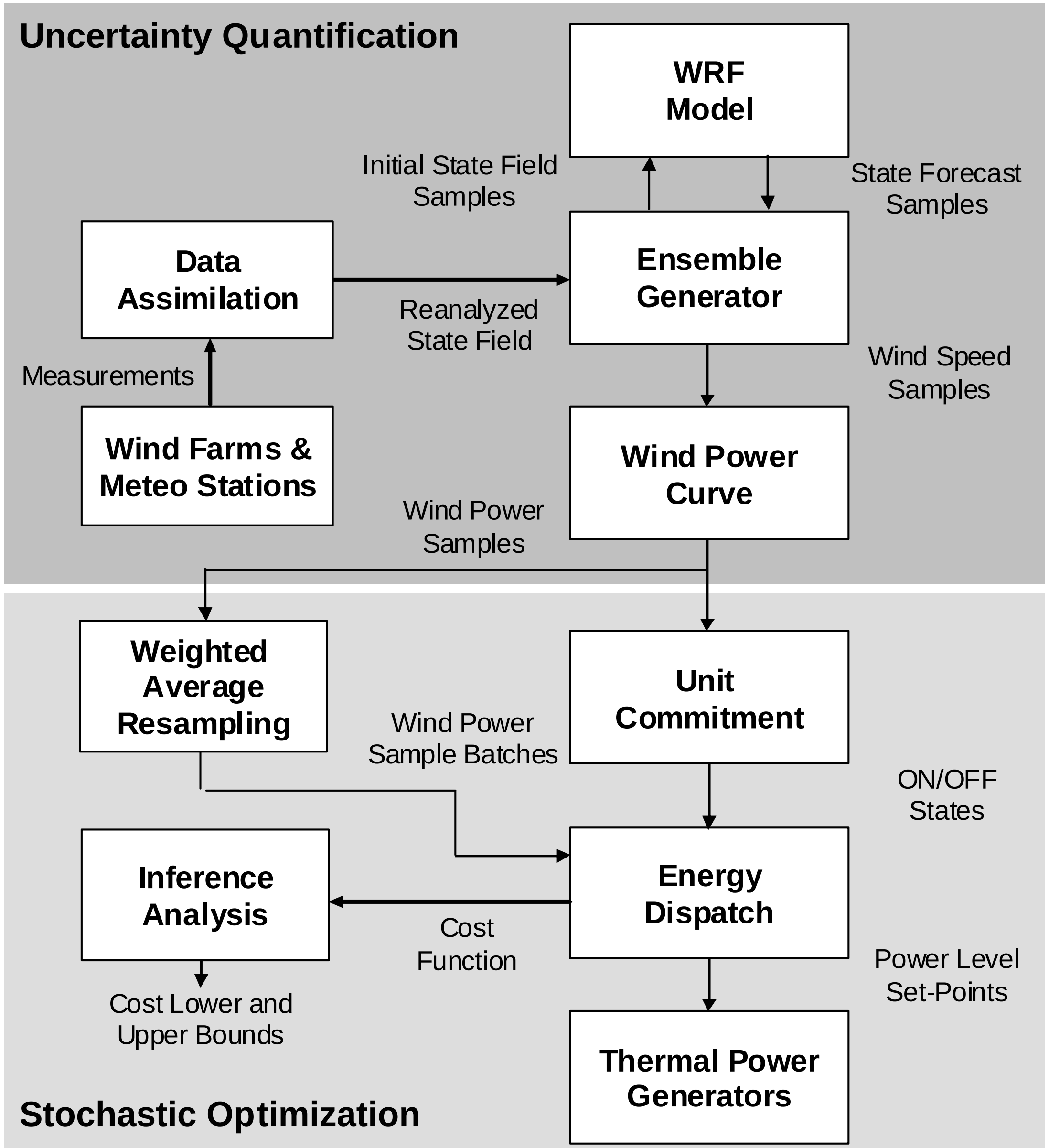
Lower Bound Distribution

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



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

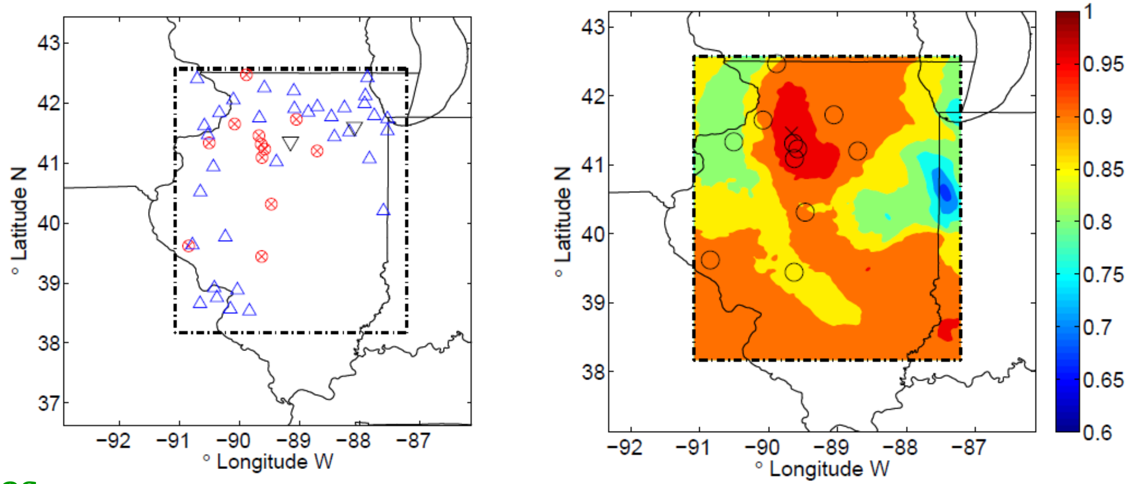
Stochastic Unit Commitment



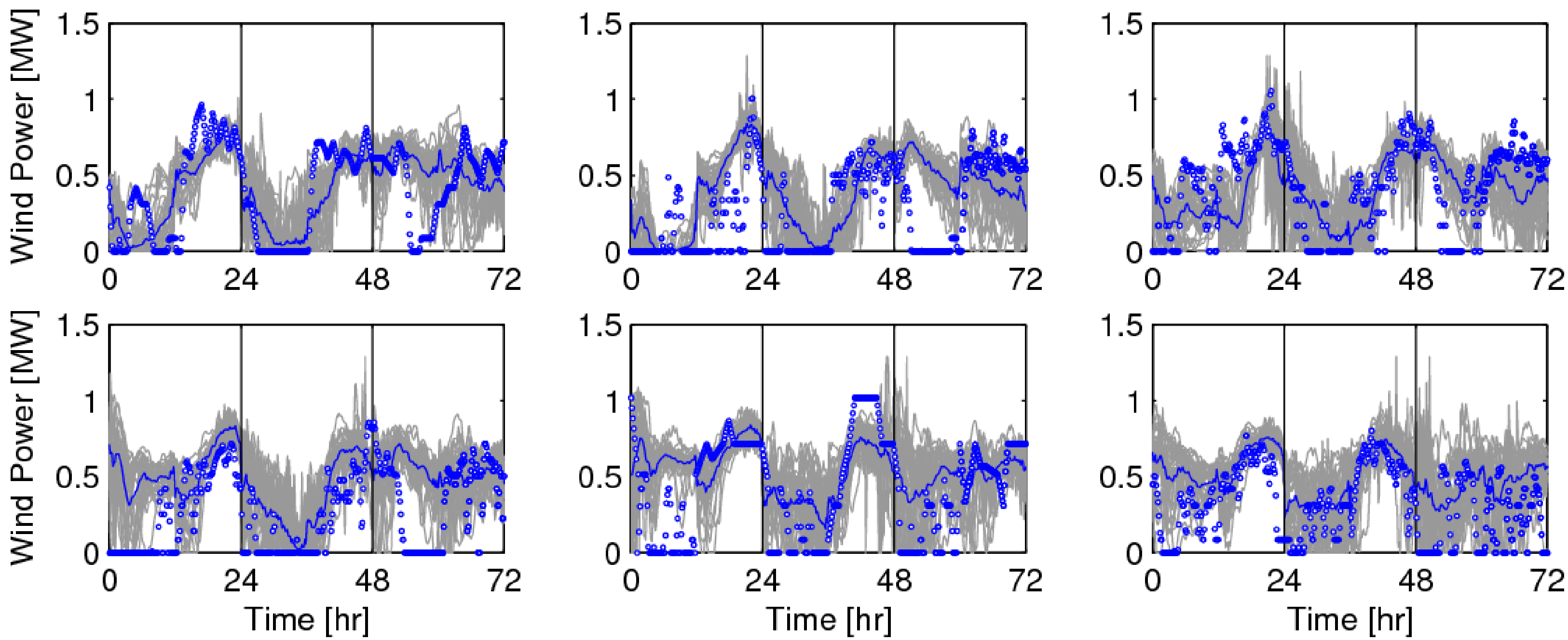
WRF Resolution and Realizations Must be Adapted in Real-Time (Transients)

Stochastic Unit Commitment

3 Days of Operation (Wind Adoption Level 20%)

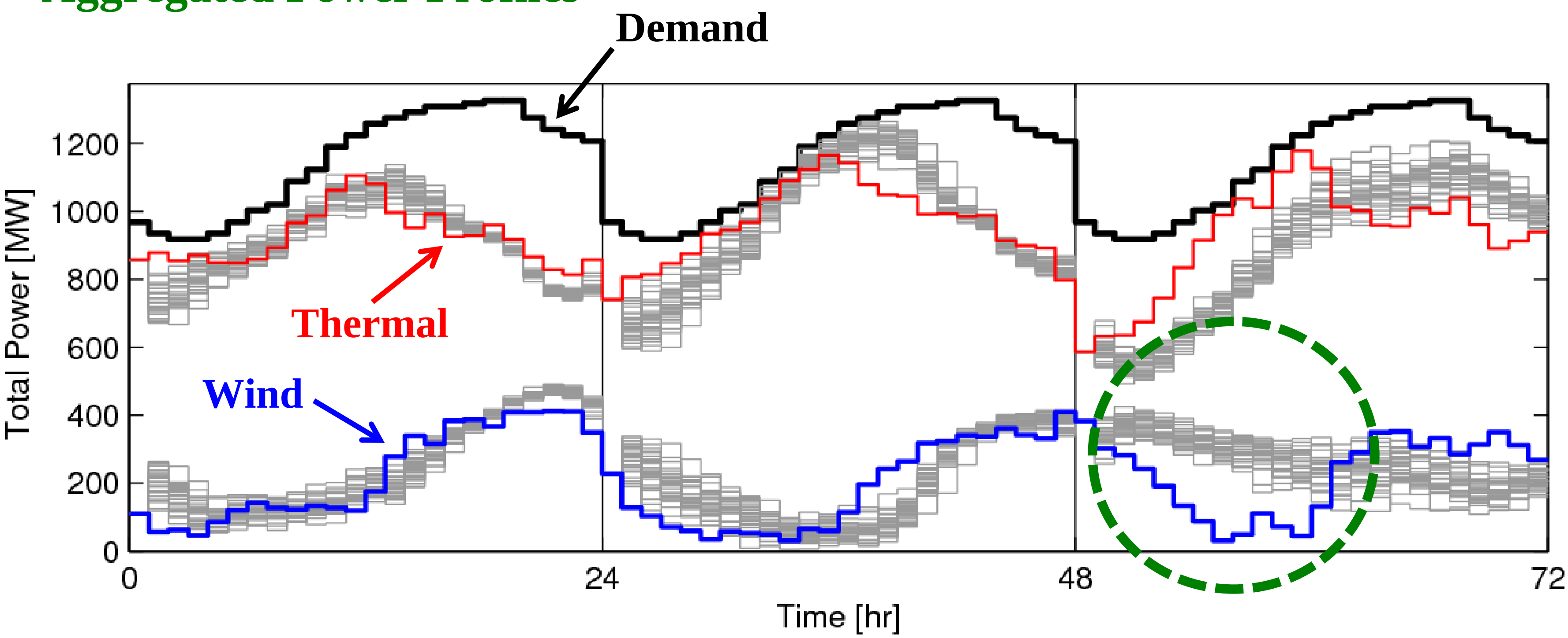


Wind Power Profiles



Stochastic Unit Commitment

Aggregated Power Profiles



- **WRF is -In General- Accurate with Tight Uncertainty Bounds**

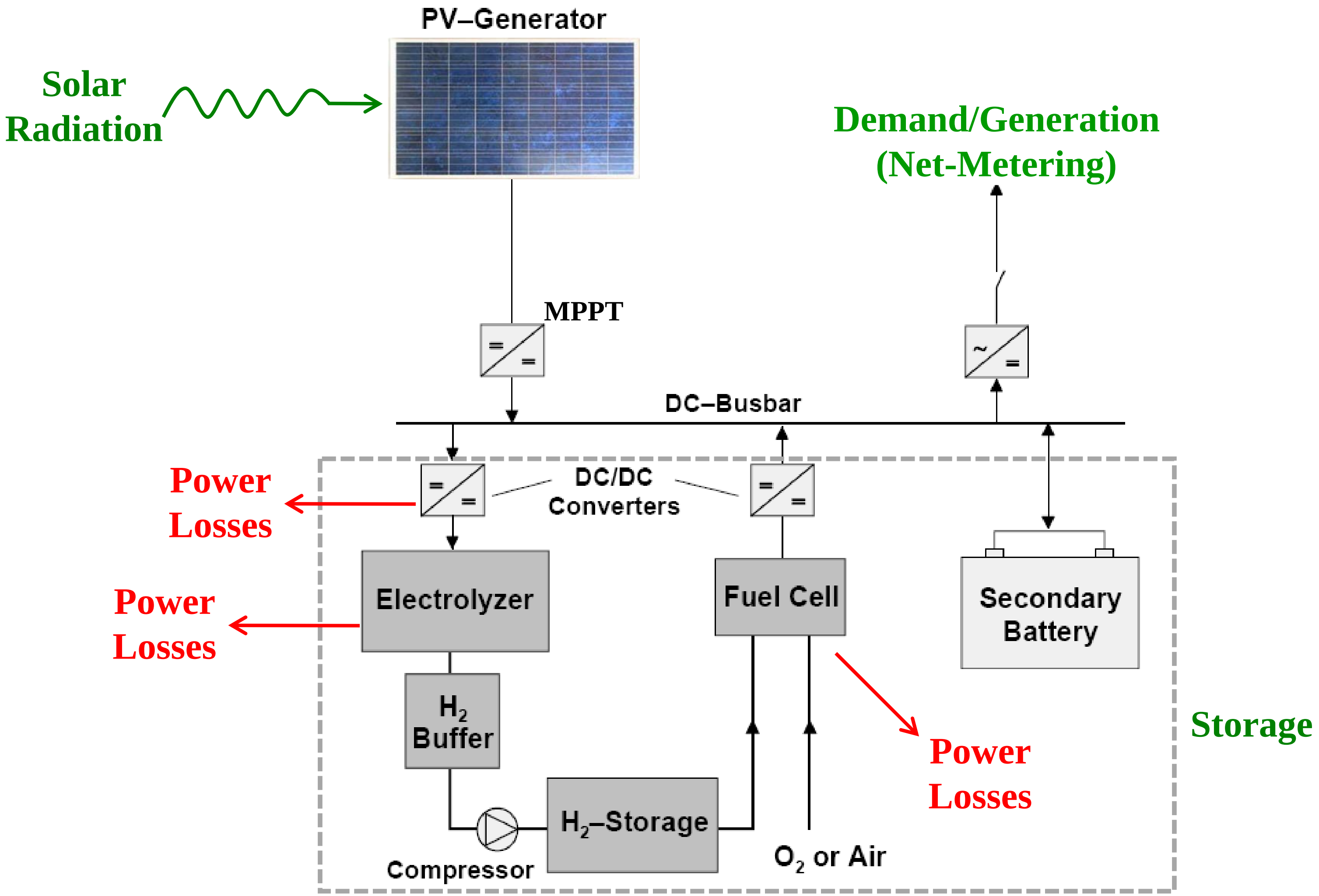
- **Inference Analysis Reveals that <u>30 WRF Samples</u> are Sufficient to Estimate Cost!**
  Cost ~ \$474,000, Upper Bound σ^2 (1,082 $\$^2$), Lower Bound σ^2 (1,656 $\$^2$)

- **However, <u>Excursions</u> Do Occur: Probability Distribution of 3rd Day is Inaccurate!**
  Need to <u>Tailor</u> Resolution of <u>Data Assimilation</u> Step, Missing Physics?

2. Recent Work

Real-Time Energy Management of Co-Generation and Building Systems

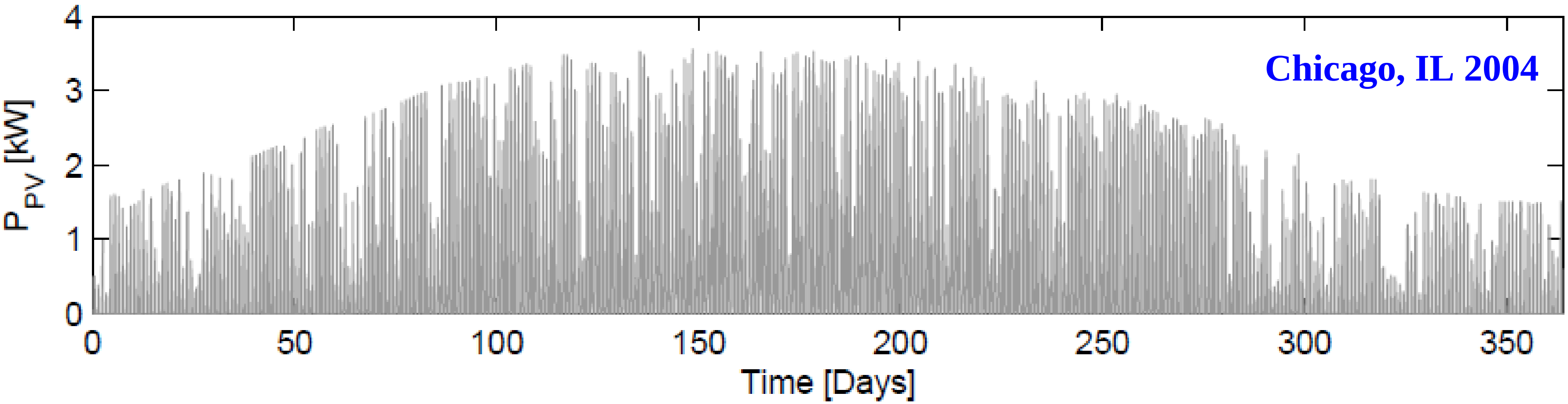
Energy Management (Zavala and Anitescu)



- **Fuel Cells for Distributed Generation -Building is Market Participant-**
- **Operation Driven by <u>Dynamic Patterns</u> of Solar Radiation** *Ulleberg, 2004*

Energy Management

Proactive Energy Management



Radiation Forecast

$$\min_{u(t)} \int_{t_\ell}^{t_{\ell+N}} \varphi(z(t), y(t), u(t), \chi(t))dt$$ **Minimize Power Losses**

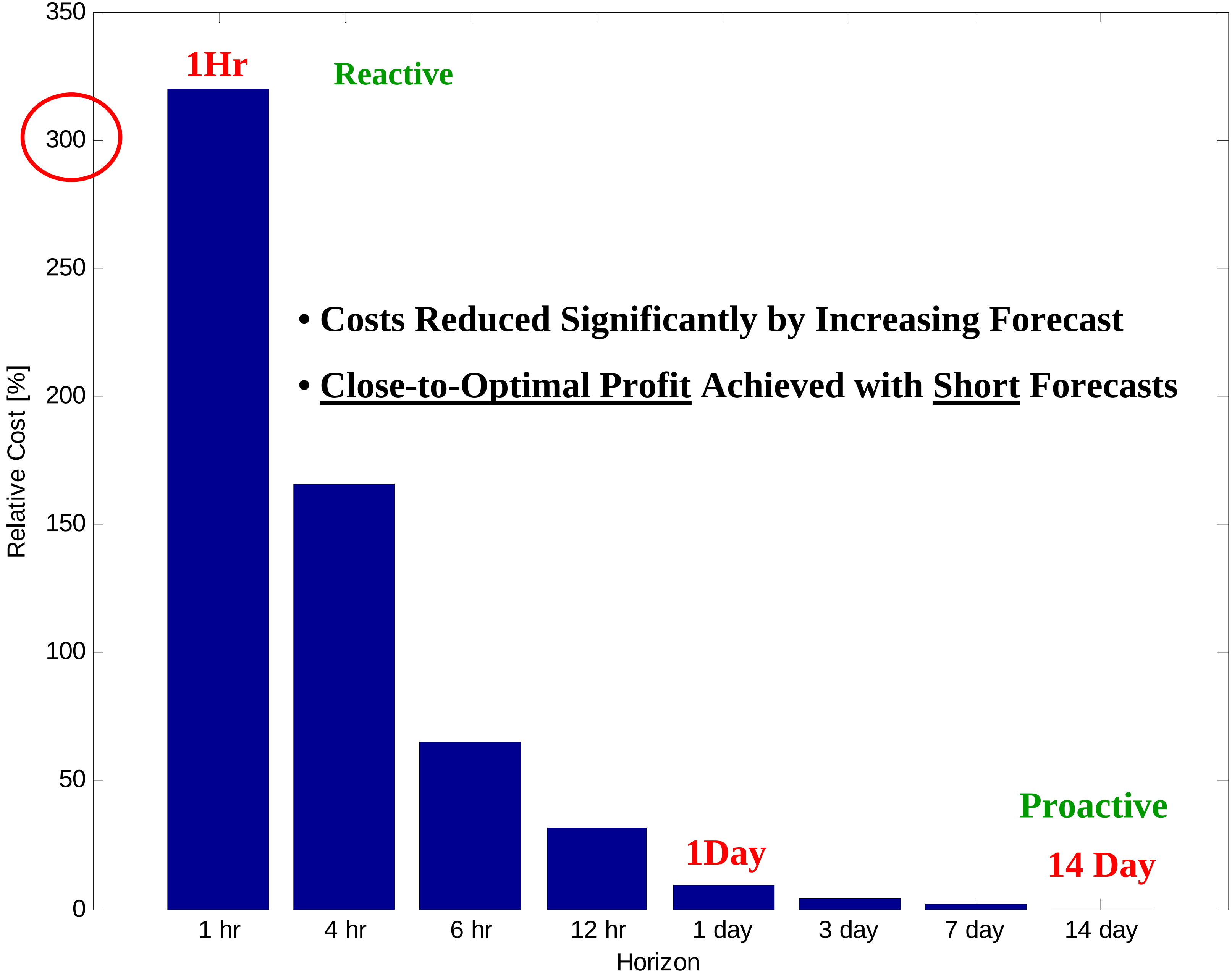
$$\begin{aligned} \frac{dz}{dt} &= \mathrm{f}(z(t), y(t), u(t), \chi(t)) \\ 0 &= \mathrm{g}(z(t), y(t), u(t), \chi(t)) \\ 0 &\geq \mathrm{h}(z(t), y(t), u(t), \chi(t)) \\ z(0) &= x_\ell \end{aligned}$$

Dynamic Model of Hybrid System (DAE)

State-of-Charge, Fuel Cell and Electrolyzer Limits

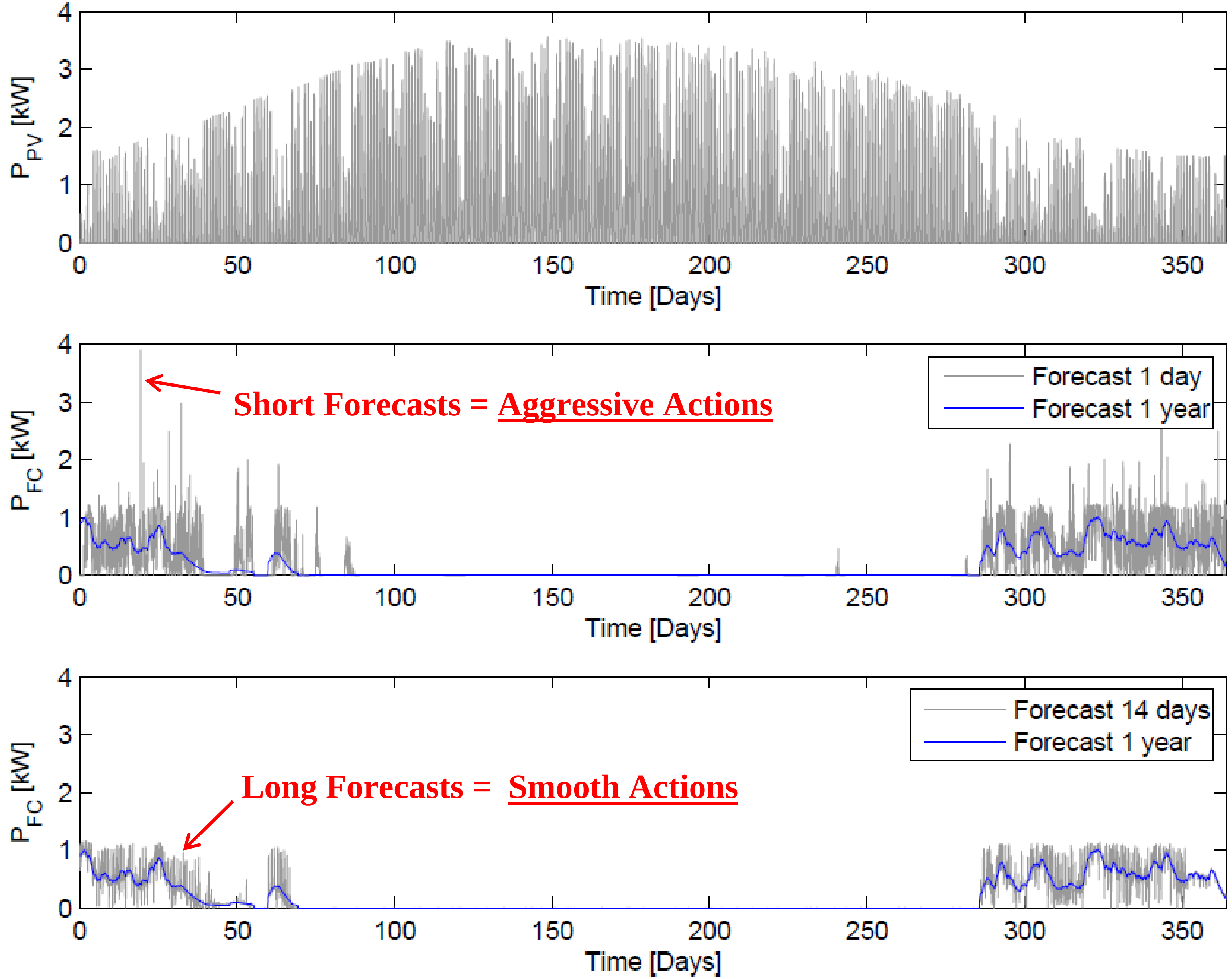
- **Real-Time Energy Management Technology is <u>Reactive</u> (Johnson Controls, Siemens)**
- **Proactive Management with Forecast Horizon of <u>1hr, 1 Day, …,14 Days</u>**
- **Large-Scale Optimal Control - IPOPT + Sparse Linear Algebra (Nested Dissection)**

Energy Management



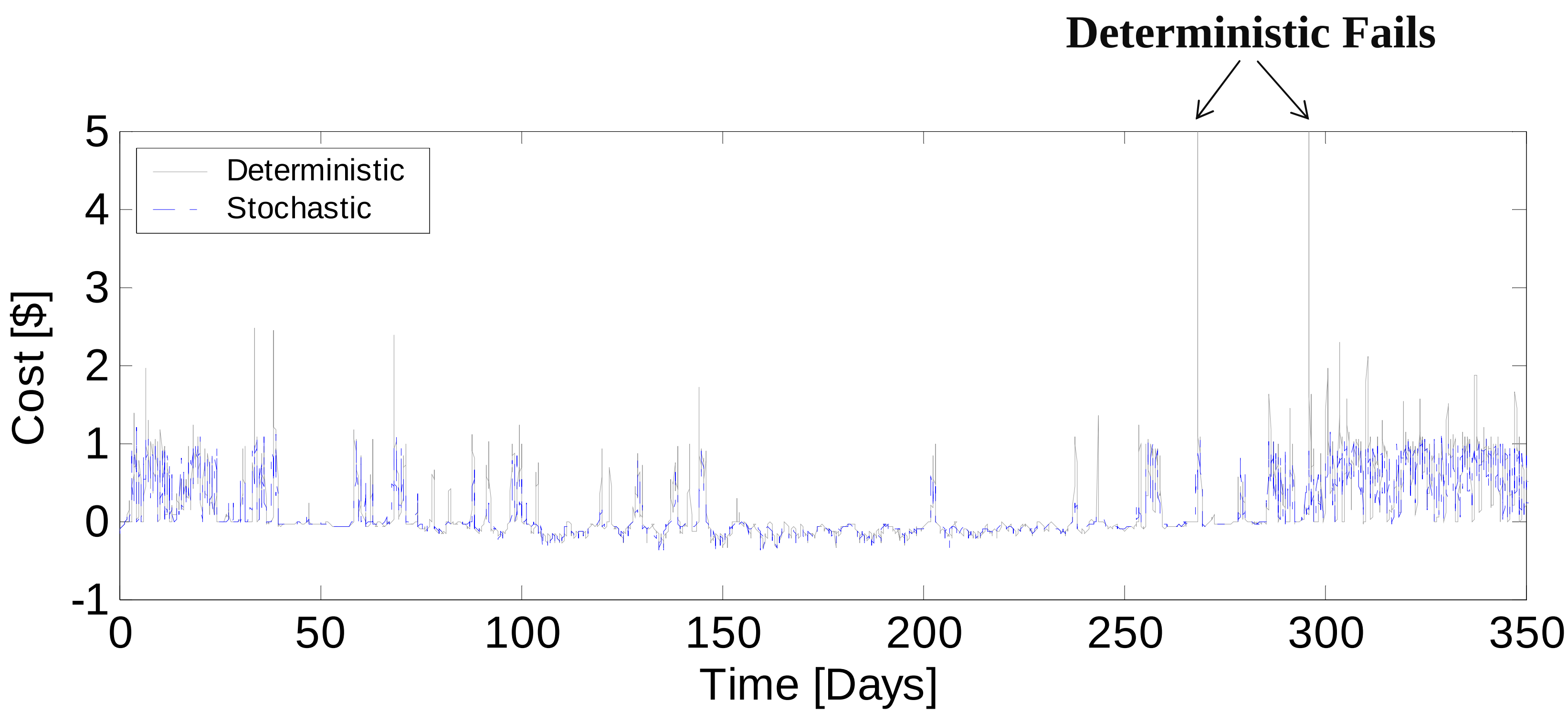
Energy Management

Profiles of Fuel Cell Power



Energy Management

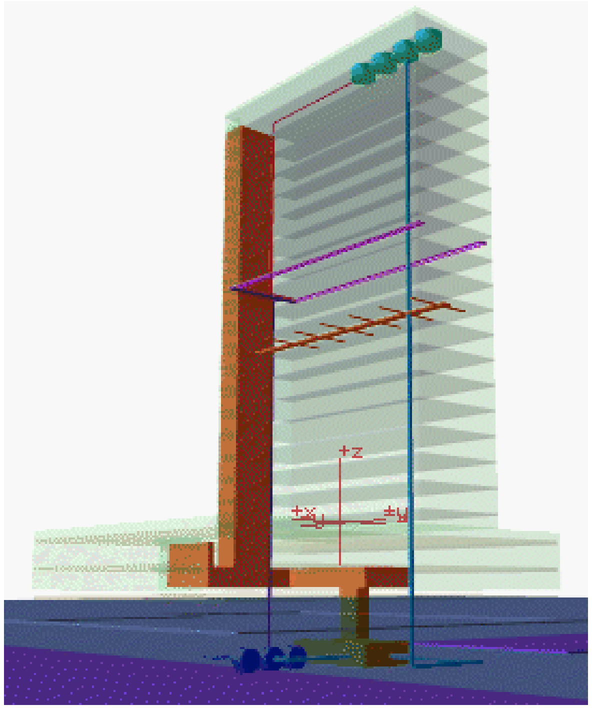
Reliability Deterministic vs. Stochastic



Proactive Manager Implicitly Forecasts Electricity Demand Profile

- Ability to Capture Market Interactions

Energy Management



www.columbia.edu/cu/gsapp/BT/LEVER/

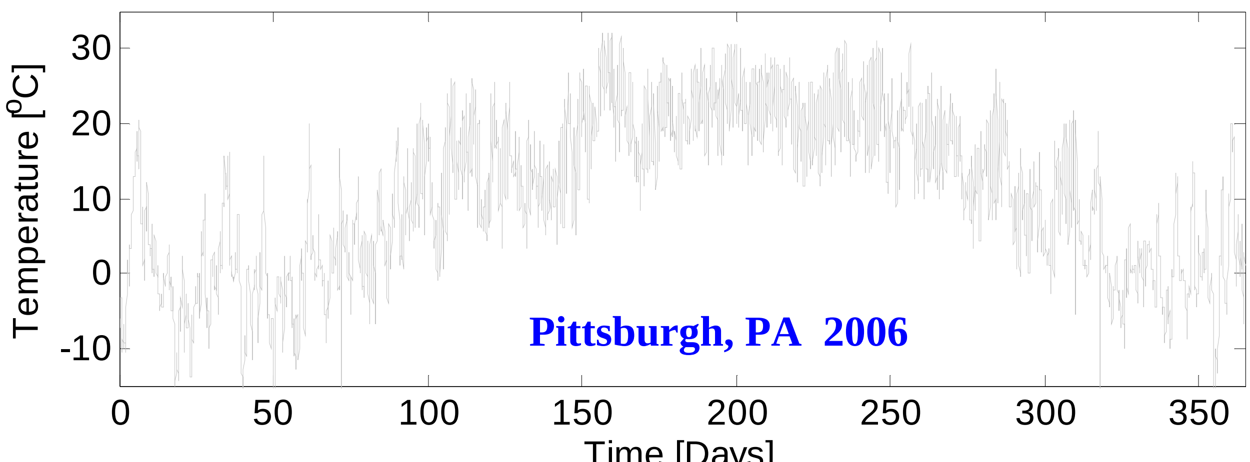
Minimize Daily Energy Costs

$$\min_{u(t)} \quad \int_{t_\ell}^{t_{\ell+N}} \left[C_c(t)\varphi_c(t) + C_h(t)\varphi_h(t)\right] dt$$

$$\begin{aligned}
C_I \cdot \frac{\partial T_I}{\partial \tau} &= \varphi_h(\tau) - \varphi_c(\tau) - S \cdot \alpha' \cdot (T_I(\tau) - T_W(\tau, 0)) \\
\frac{\partial T_W}{\partial \tau} &= \beta \cdot \frac{\partial^2 T_W}{\partial x^2} \\
\alpha' \left(T_I(\tau) - T_W(\tau, 0)\right) &= -\mathbf{k} \cdot \left.\frac{\partial T_W}{\partial x}\right|_{(\tau,0)} \\
\alpha'' \left(T_W(\tau, L) - T_A(\tau)\right) &= -\mathbf{k} \cdot \left.\frac{\partial T_W}{\partial x}\right|_{(\tau,L)} \\
T_I(0) &= T_I^\ell \\
T_W(0, x) &= T_W^\ell(x)
\end{aligned}$$

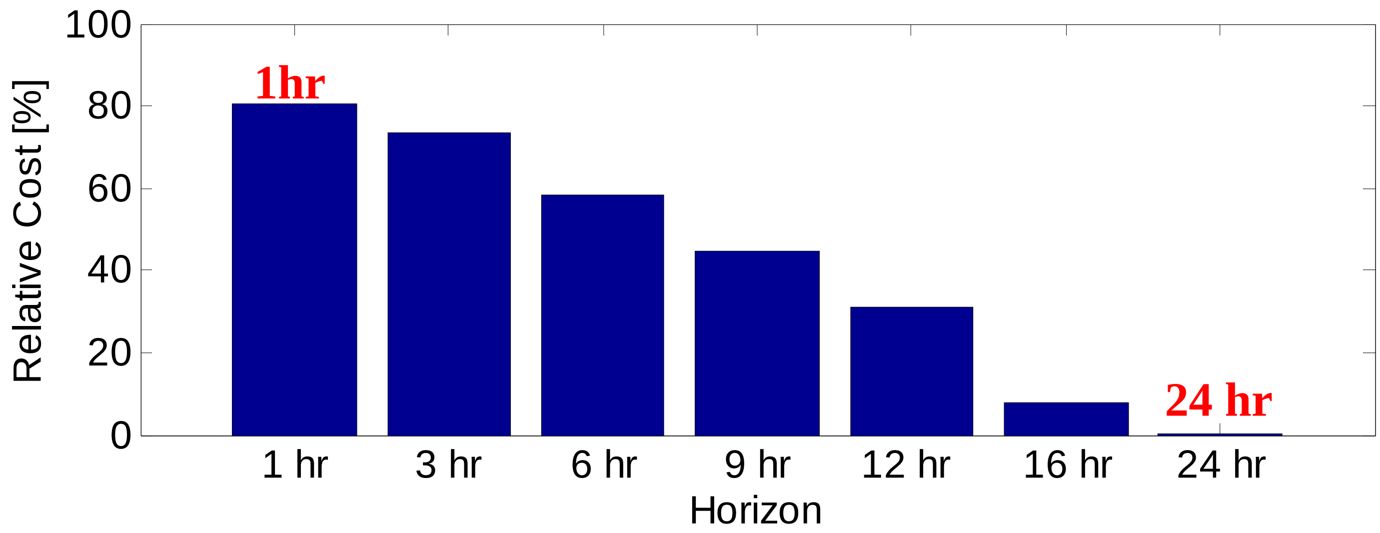
Dynamic Building Model (PDE)

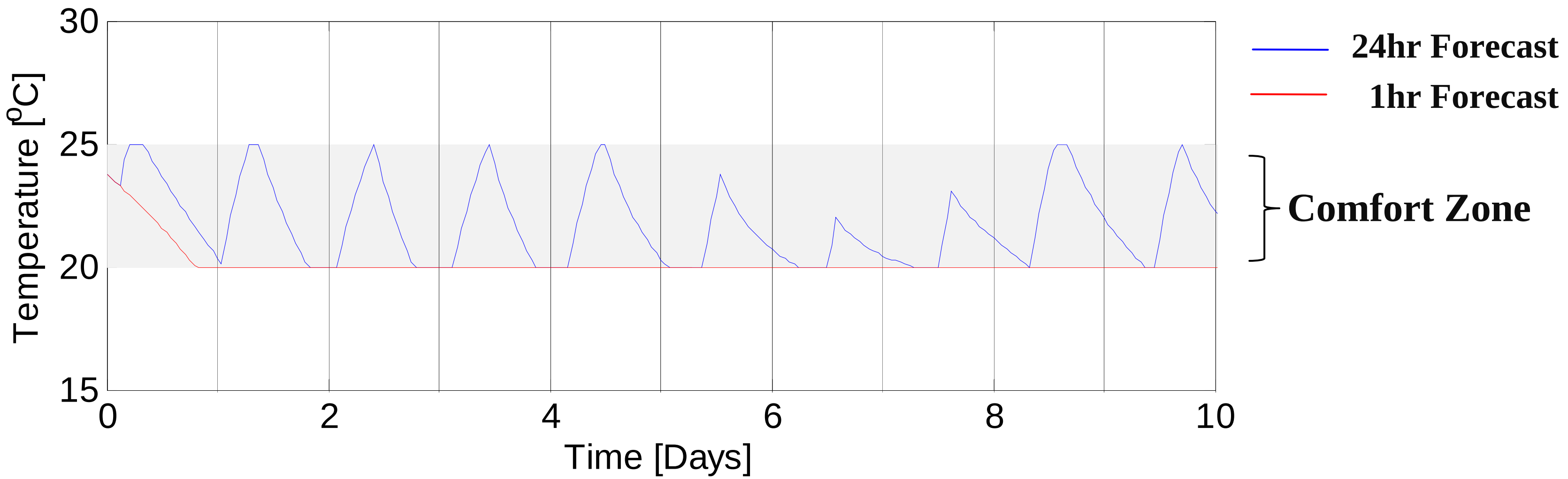
Time-Varying Electricity Prices (Peak & Off-Peak)



Energy Management

Effect of Forecast on Costs

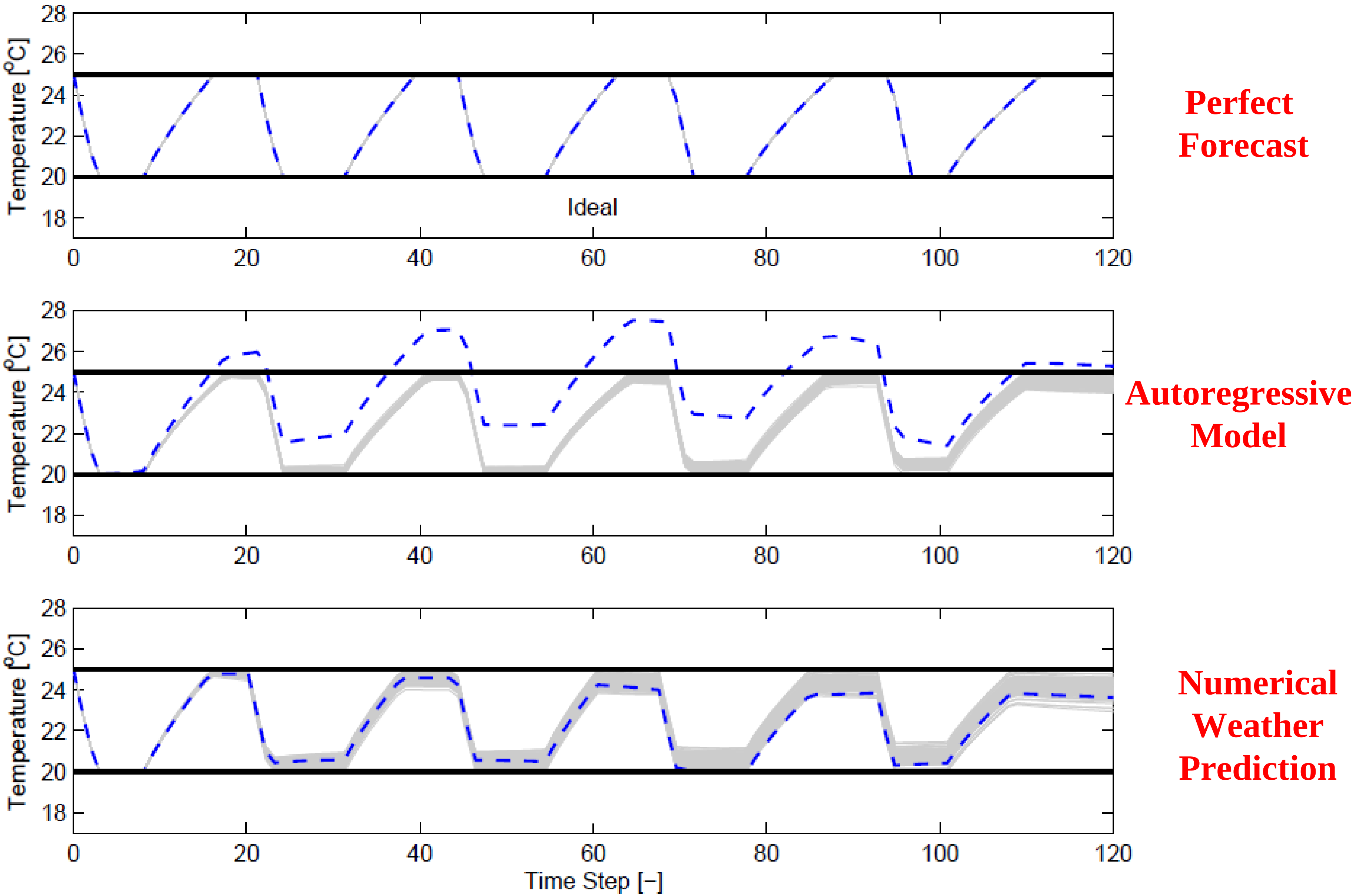




Proactive Manager Implicitly <u>Forecasts</u> Demand Profile

Energy Management

Proactive Manager with Different Weather Forecast Models



5. Conclusions and On-Going Projects

Conclusions and On-Going Projects

Smart Grid

- **Market and Demand Forecasts with Detailed Uncertainty Information**
- **Deregulation Forcing Game-Oriented Formulations and Algorithms**

Many Advances in Optimization Algorithms BUT LACK OF INTEGRATION

- **Economic Potential of Optimization Has Not Been Fully Exploited**

Vision

- **Grid Simulator to Assess Effects of Forecasting in Market and Operations**

  Market Models Used for Real-Time Price Forecasting

  Unit Commitment with Transmission (MINLP)

  New Modeling Paradigms (Continuous-Time)

  Real-Time Optimization (Synchronization, Warm-Starts, Exploit Periodicity)

- **How to Generate Low Cost Forecasts for ISOs, GENCOs, TRNSCOs?**

  Grid-Oriented Resolution Constrained by Computational Resources

- **Integrative Studies to Assess and Motivate New Optimization Technology**

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