Evaluating High Penetrations of Off-Shore Wind using SMART-ISO

FERC Technical Conference on Software
Washington, D.C.

June 23-25, 2014

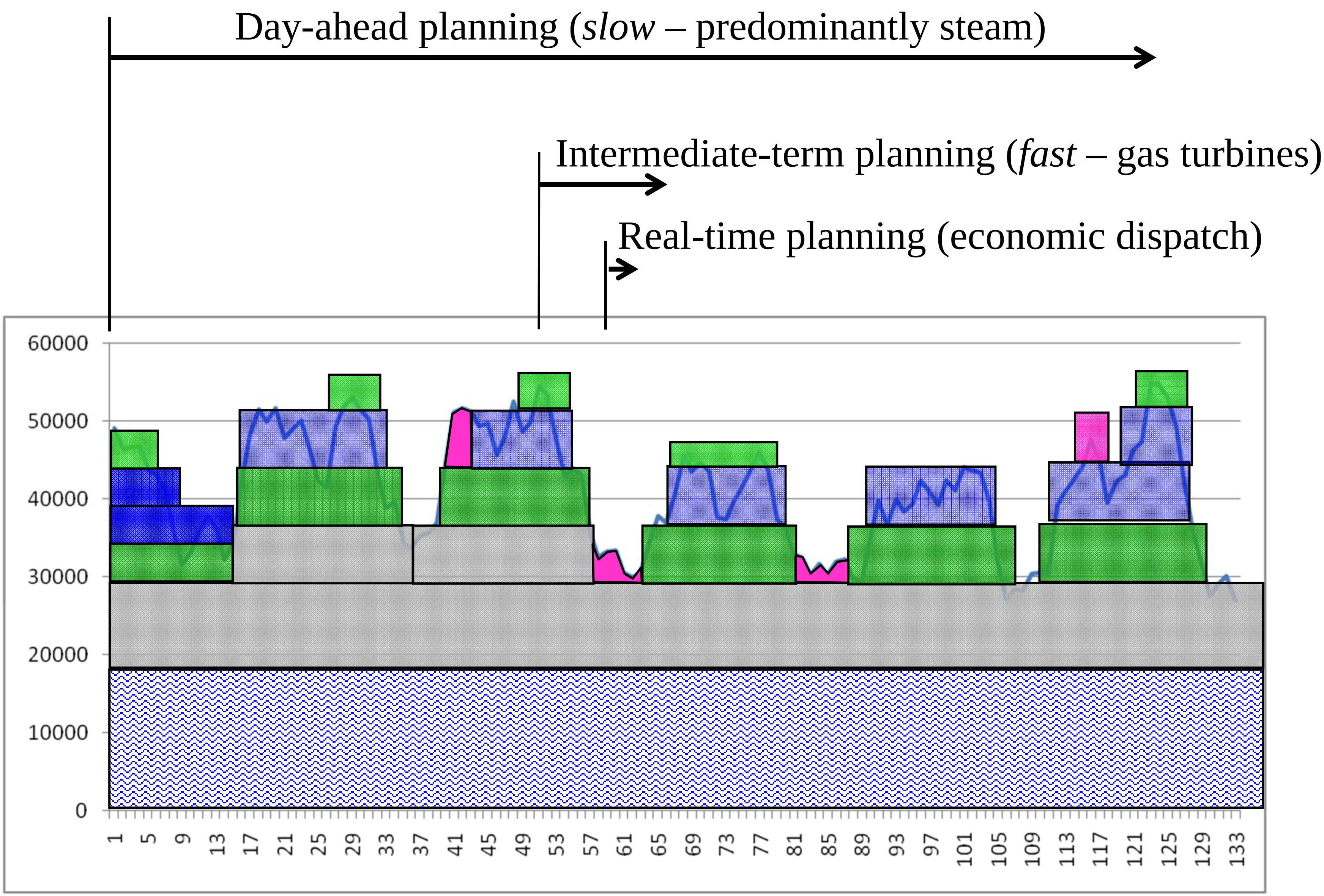
Warren B. Powell
Hugo P. Simao
Princeton University

Willett Kempton
Cristina Archer
University of Delaware

Lecture outline

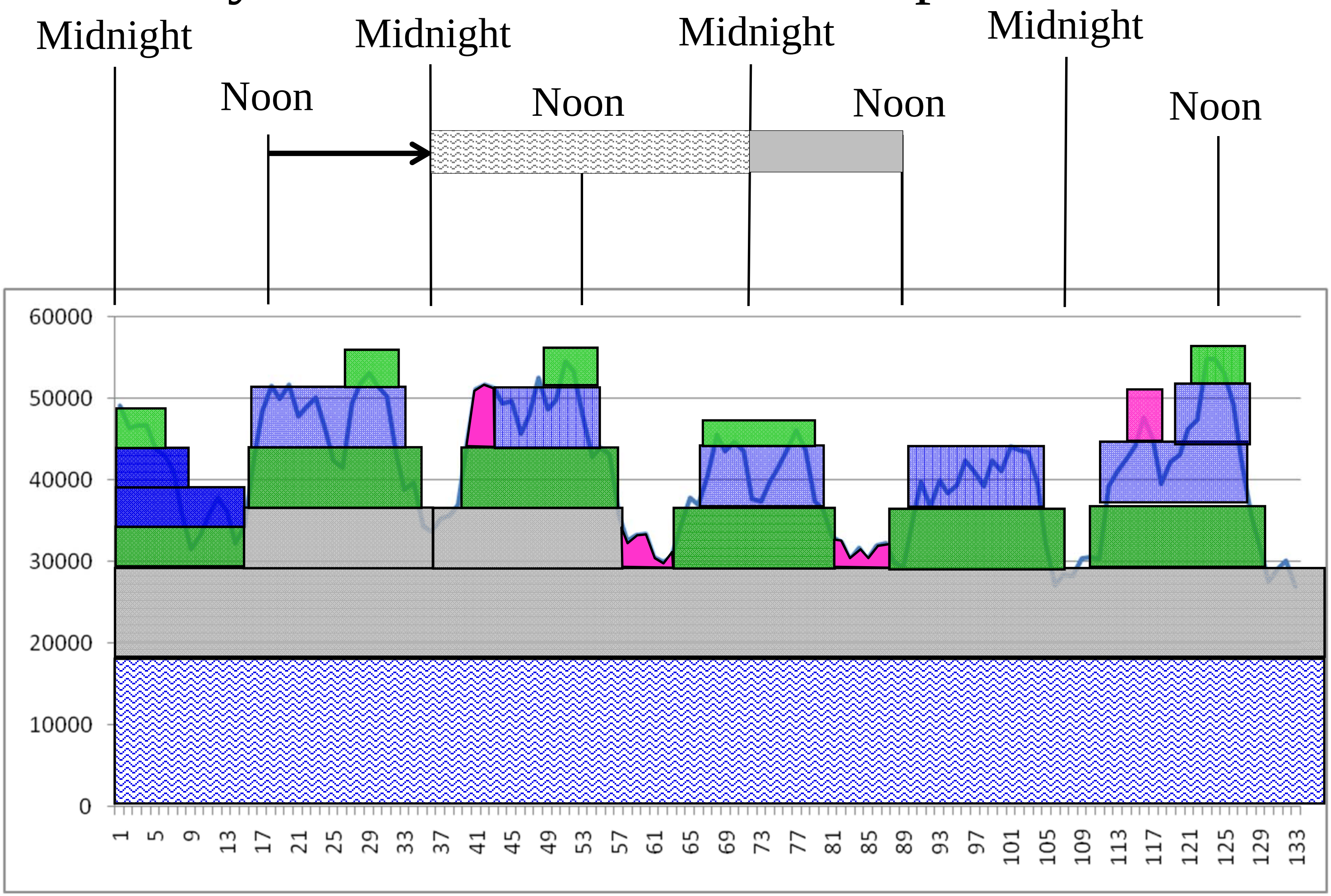
- The PJM grid and planning process
- SMART-ISO – Model validation
- Modeling wind
  - Onshore error model
  - Offshore sample paths
- Designing a robust policy
- Experiments

The timing of decisions



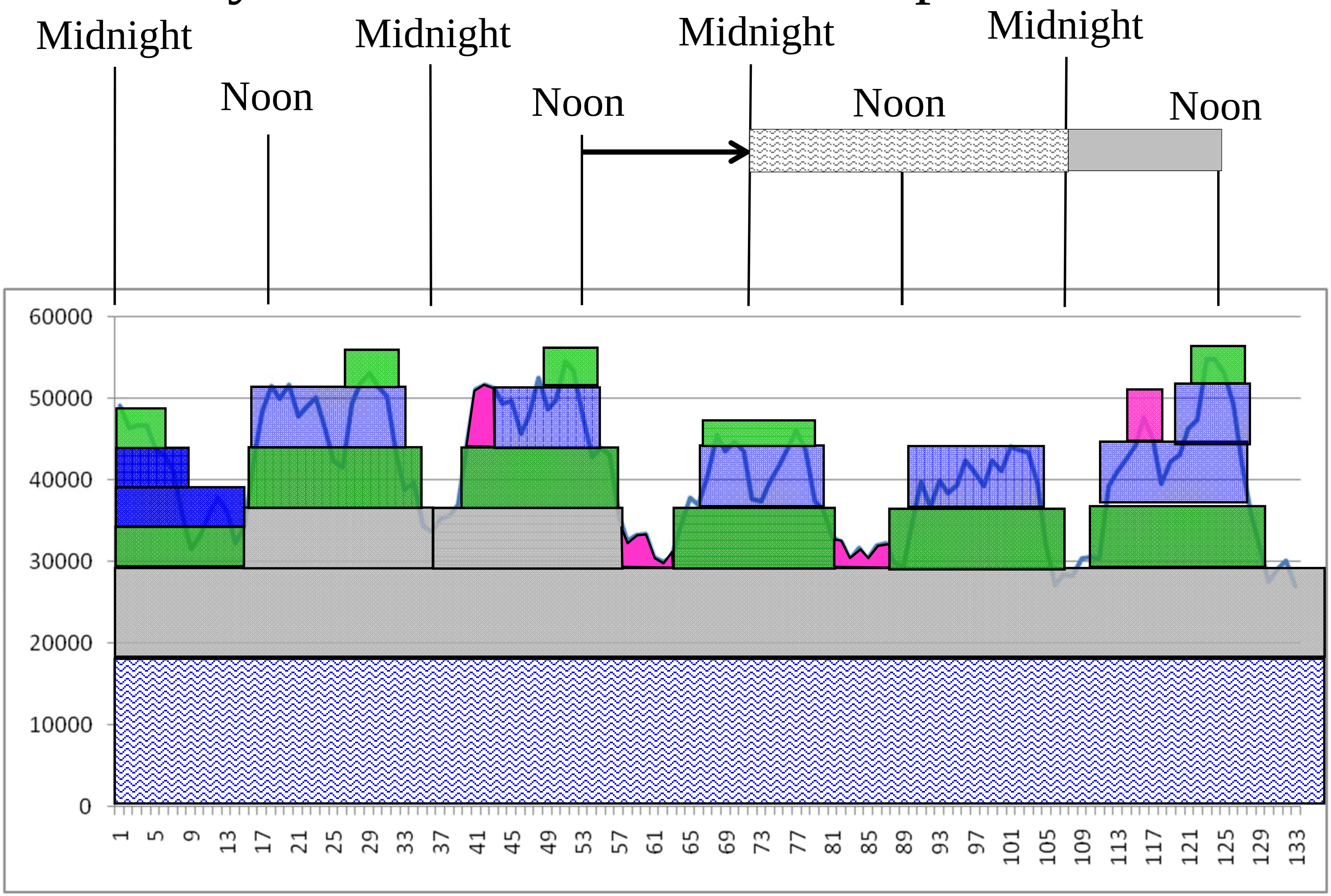
The timing of decisions

- ❑ The day-ahead unit commitment problem



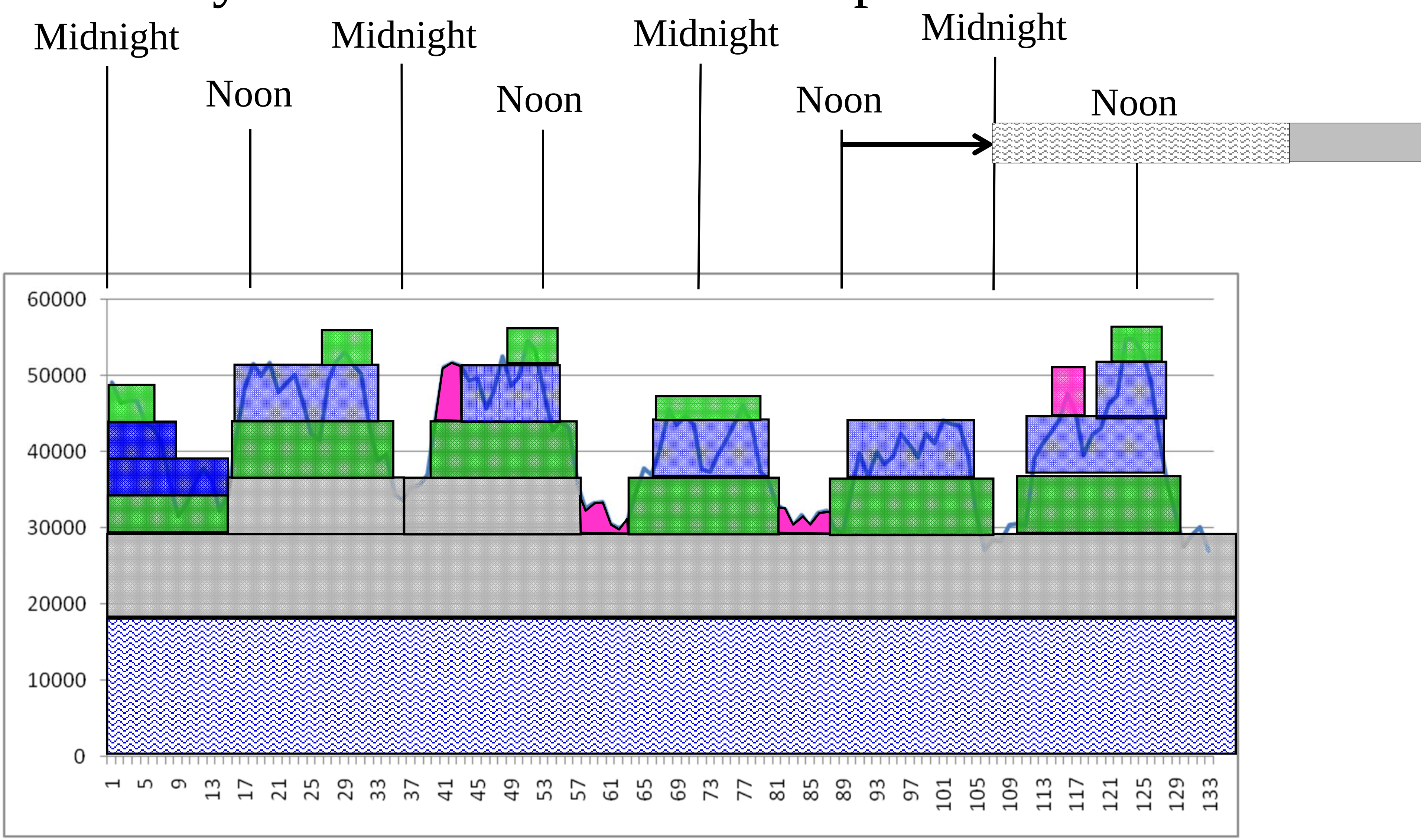
The timing of decisions

- The day-ahead unit commitment problem



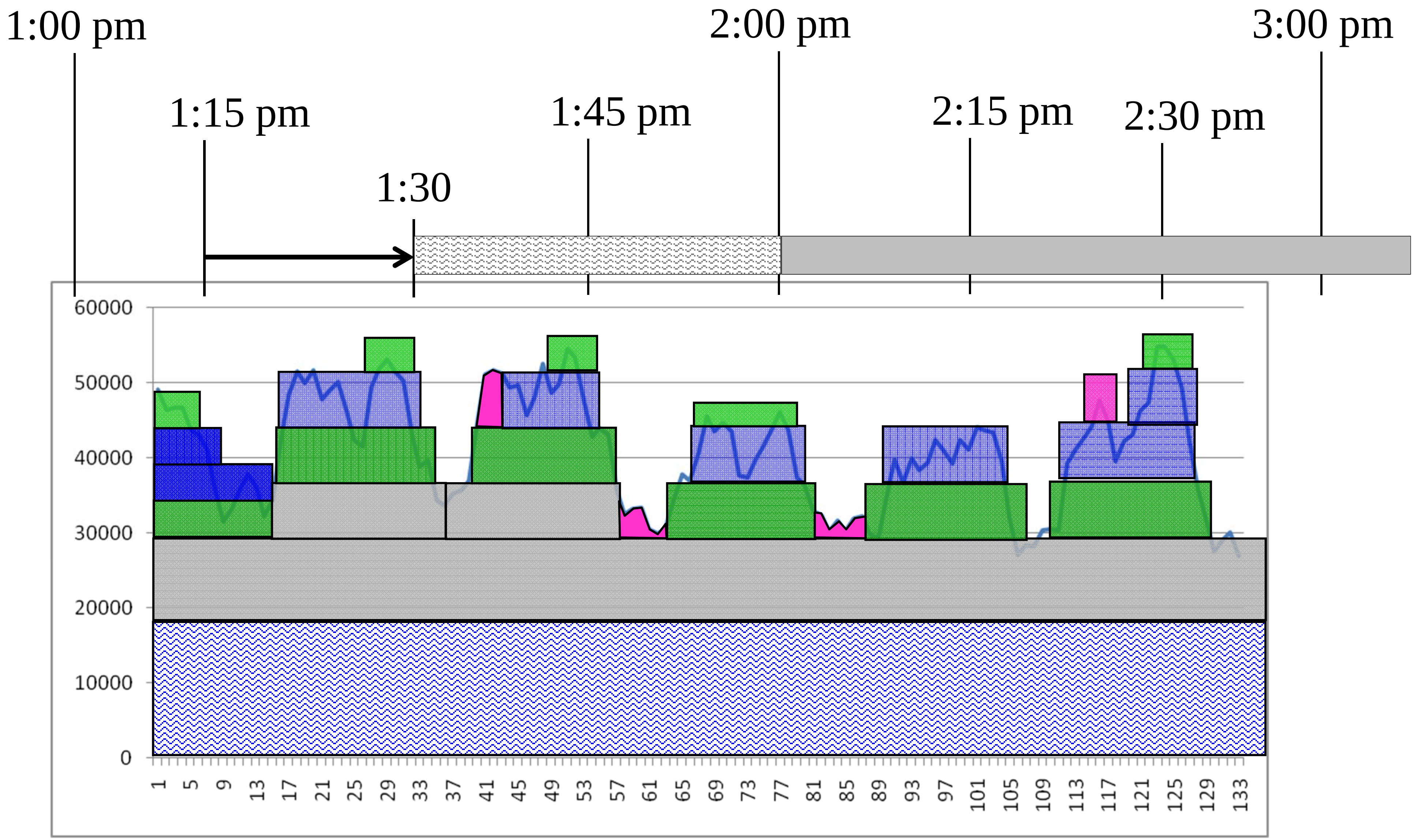
The timing of decisions

- The day-ahead unit commitment problem



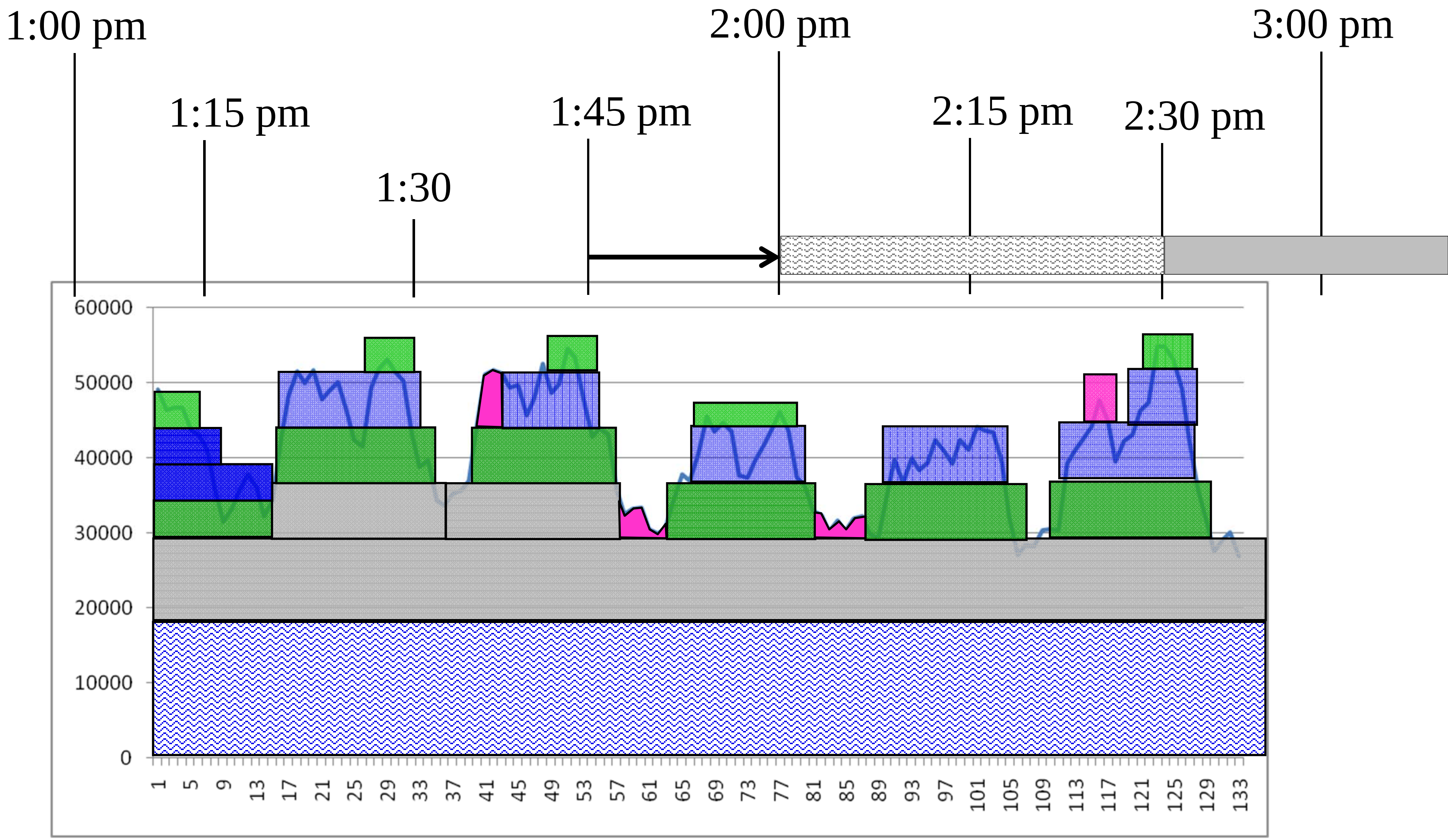
The timing of decisions

- Intermediate-term unit commitment problem



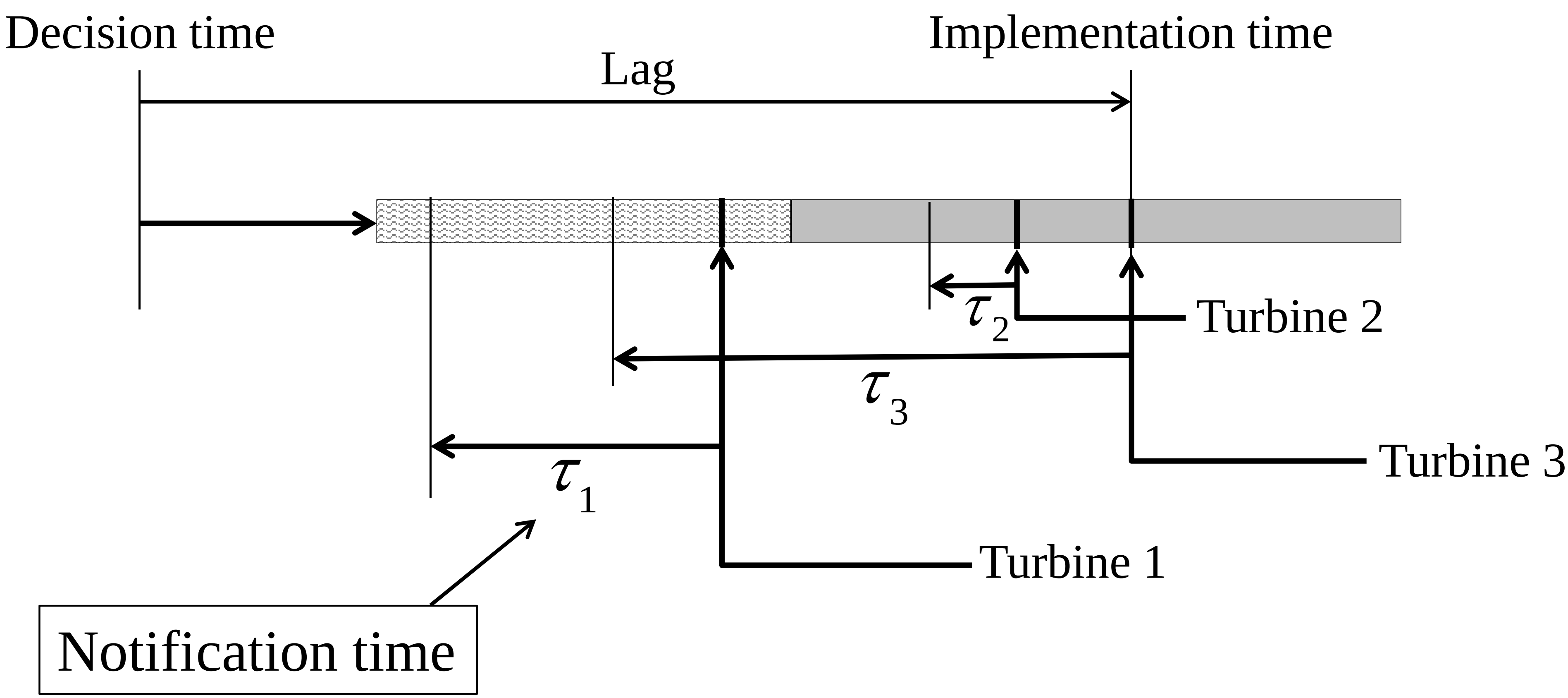
The timing of decisions

- Intermediate-term unit commitment problem



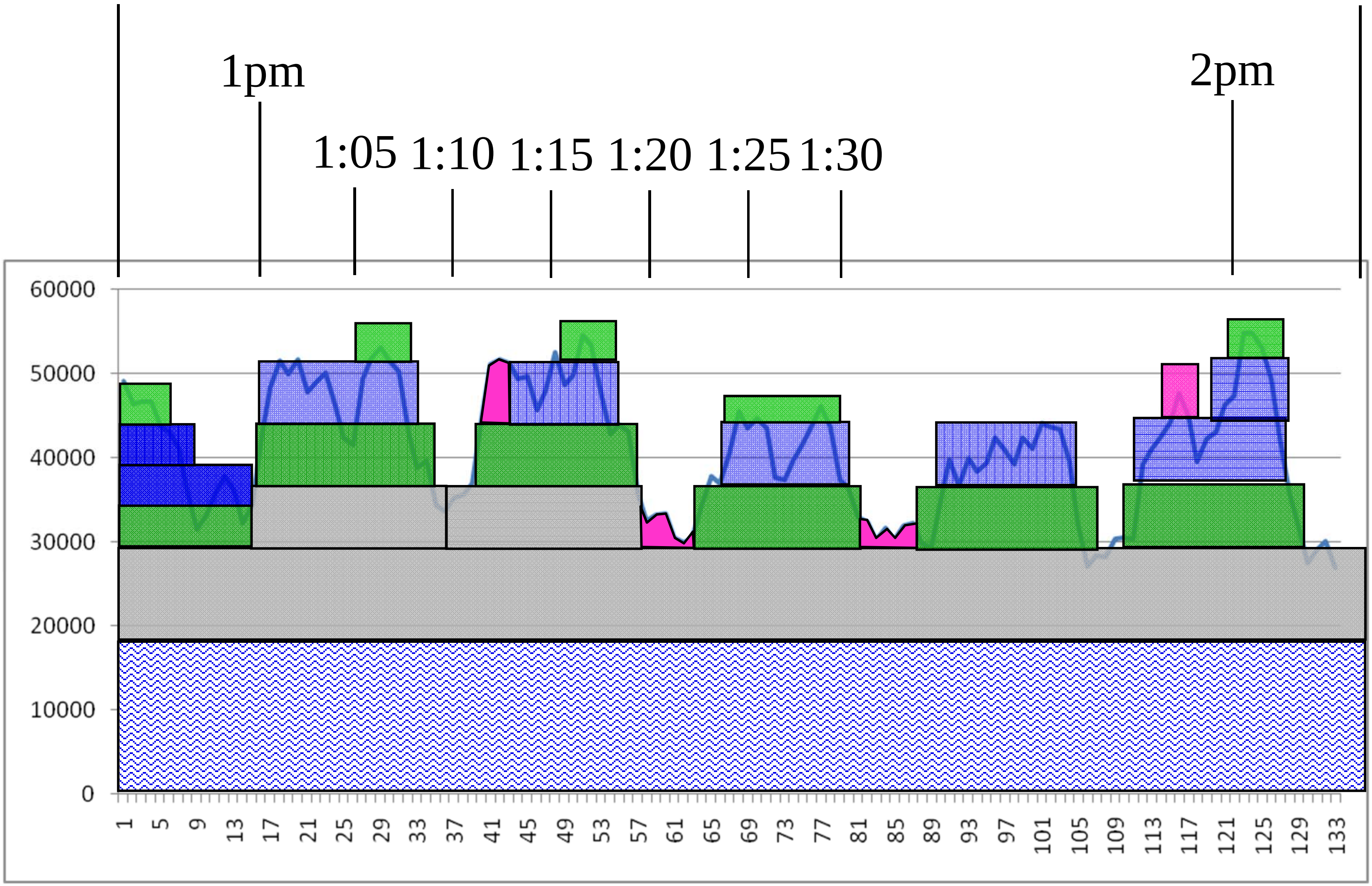
The timing of decisions

- Intermediate-term unit commitment problem



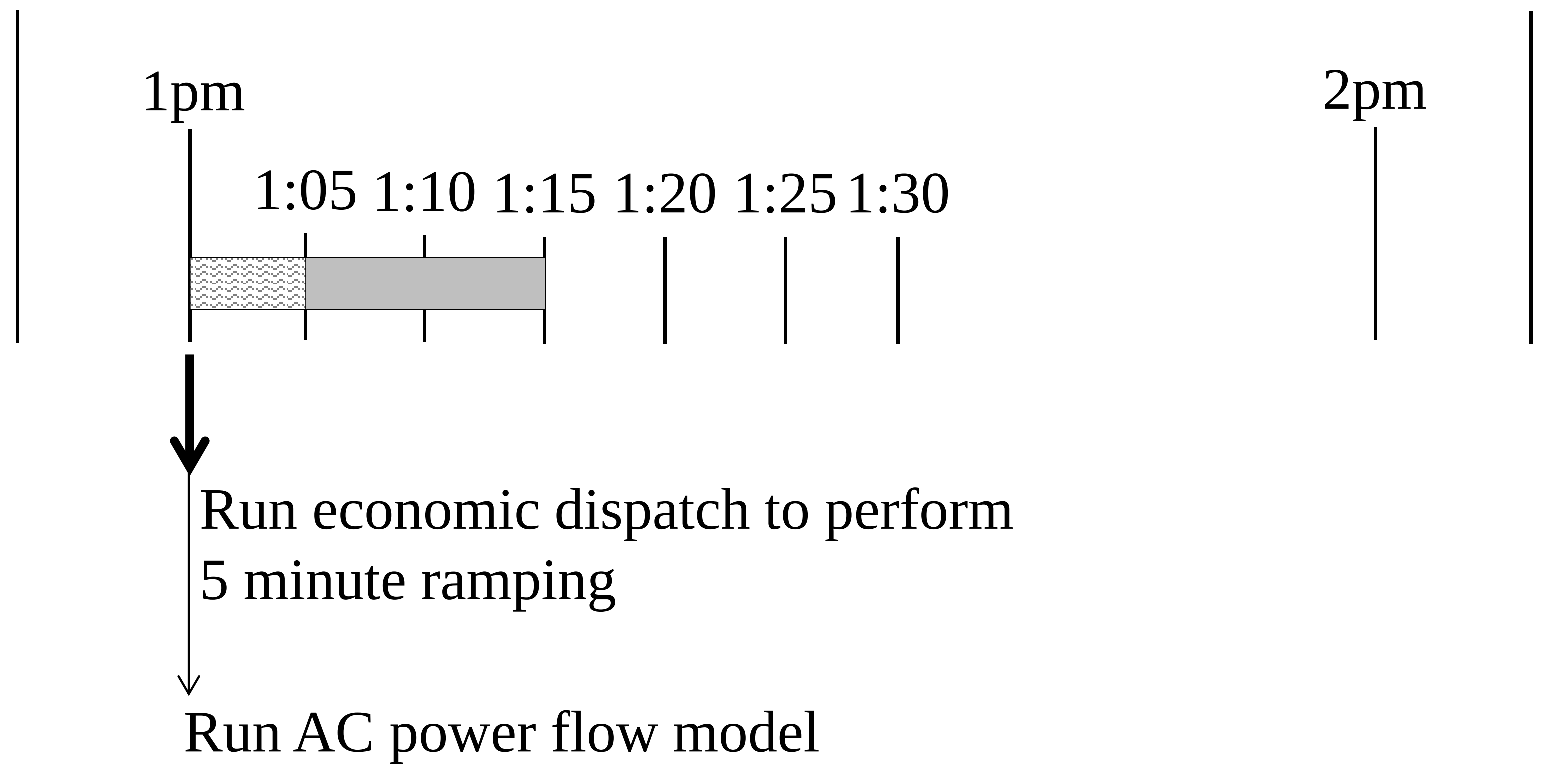
The timing of decisions

- ❑ Real-time economic dispatch problem



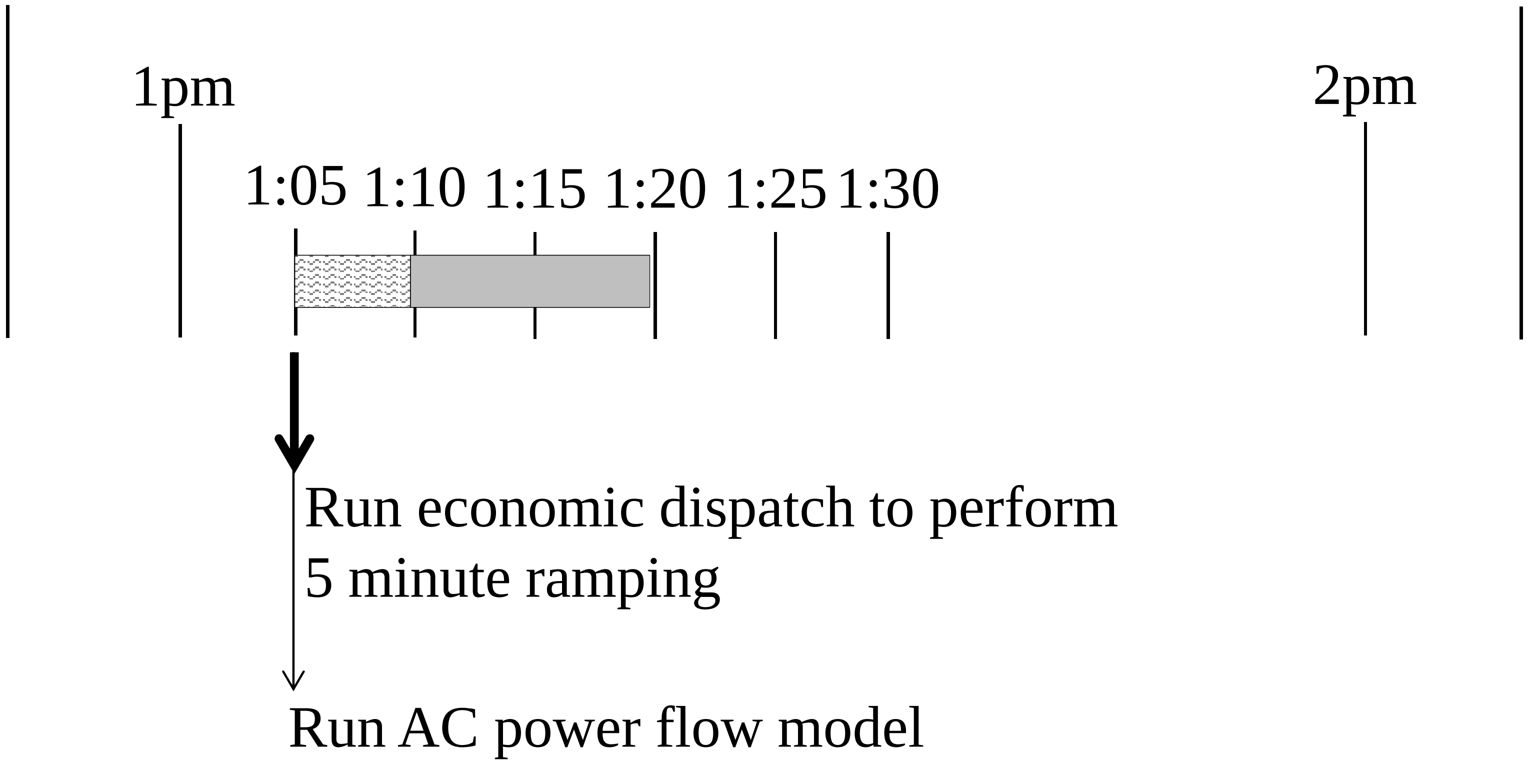
The timing of decisions

- Real-time economic dispatch problem



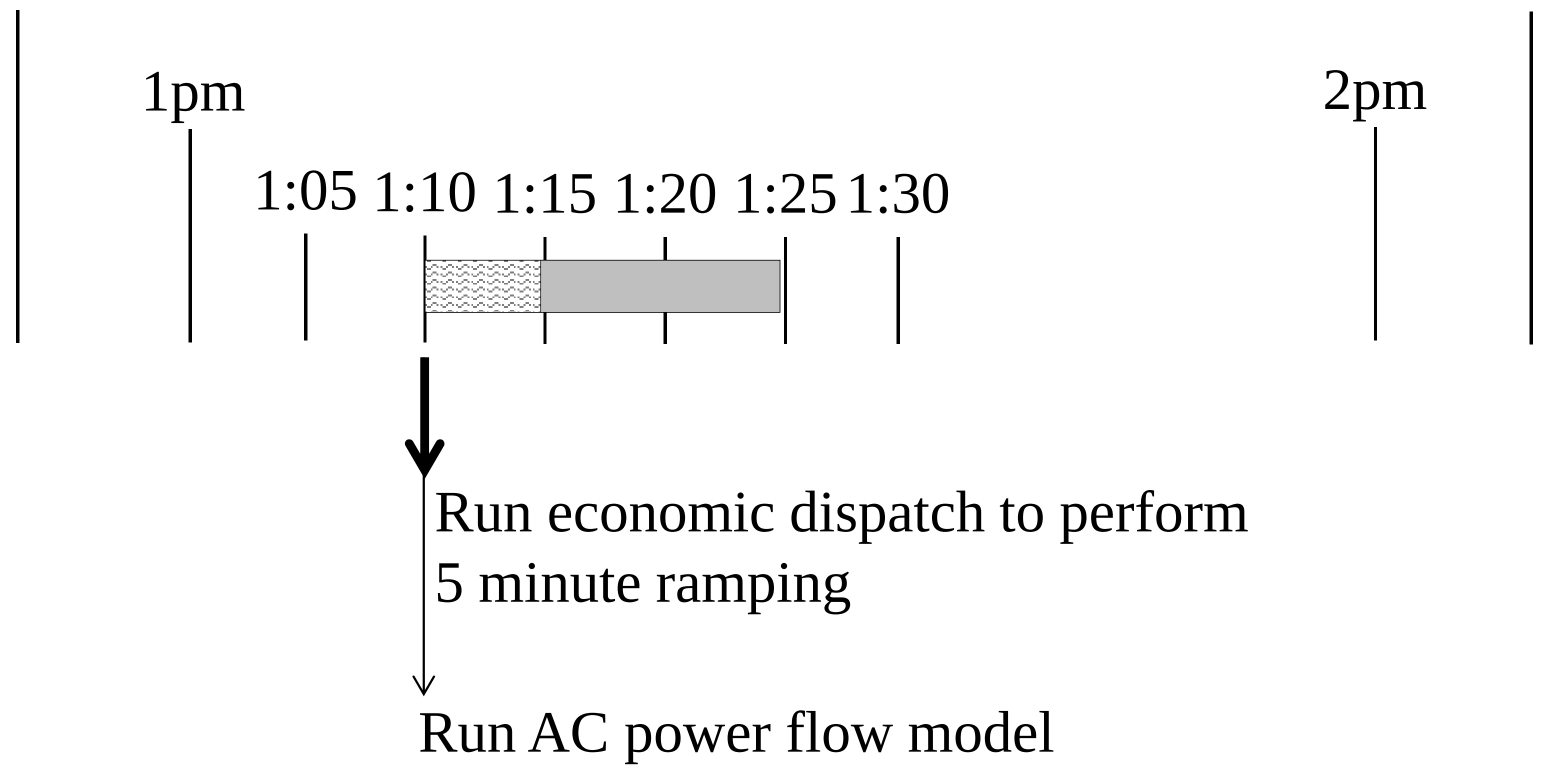
The timing of decisions

- Real-time economic dispatch problem



The timing of decisions

- Real-time economic dispatch problem



Lecture outline

- The PJM grid and planning process
- SMART-ISO – Model validation
- Modeling wind
  - Onshore error model
  - Offshore sample paths
- Designing a robust policy
- Experiments

SMART-ISO: Calibration

- Any dynamic model consists of two fundamental equations:
  - » The decisions (determined by a policy)

$$x_t = X^{\pi}(S_t)$$

  - » The dynamics (determined by the physics of the problem)

$$S_{t+1} = S^M\left(S_t, x_t, W_{t+1}\right)$$

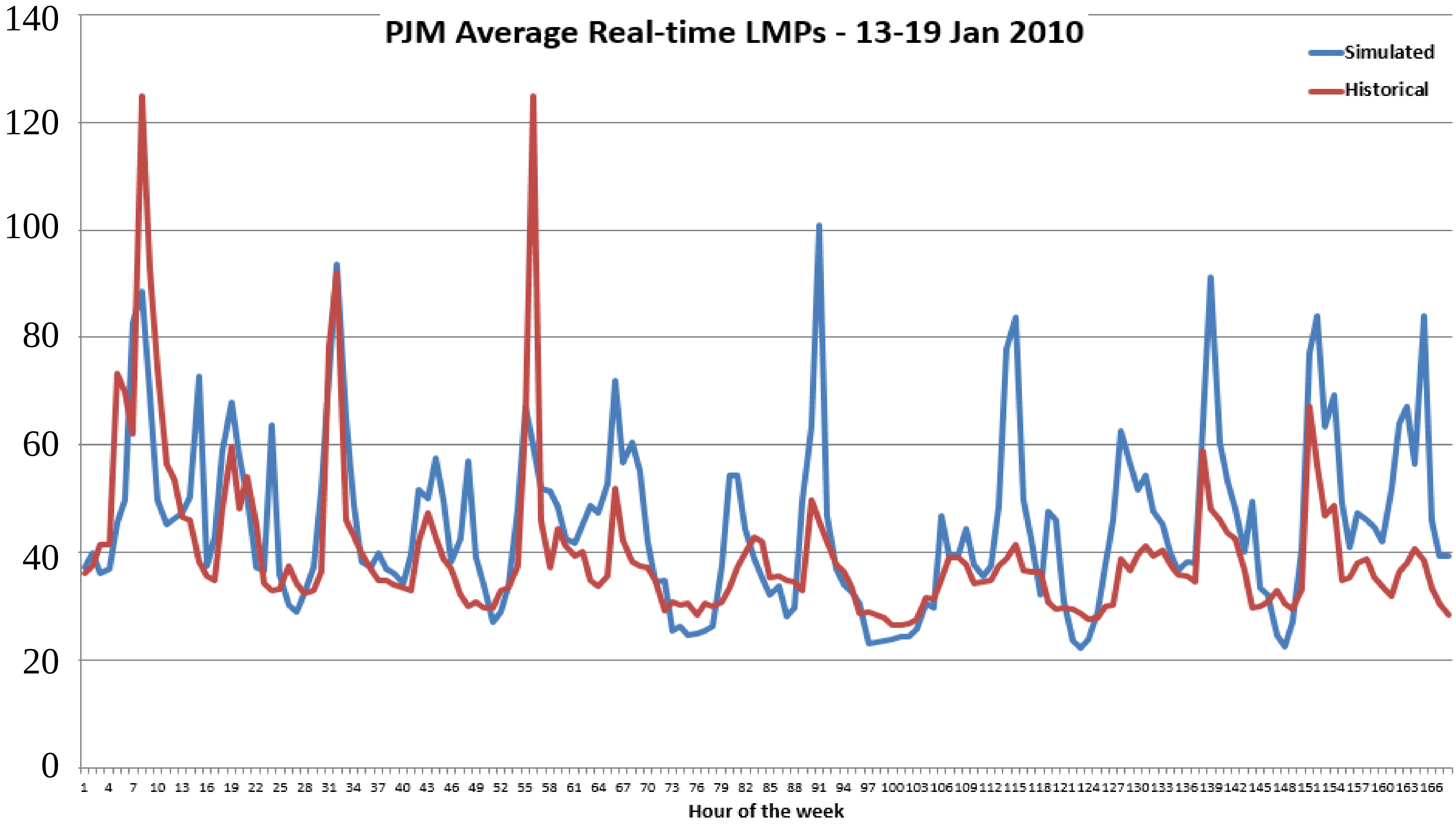
  - » We have initially focused on replicating the PJM policy

$$x_t = X^{PJM}(S_t)$$

Once we calibrate our model, *then* we can start looking for a better policy.

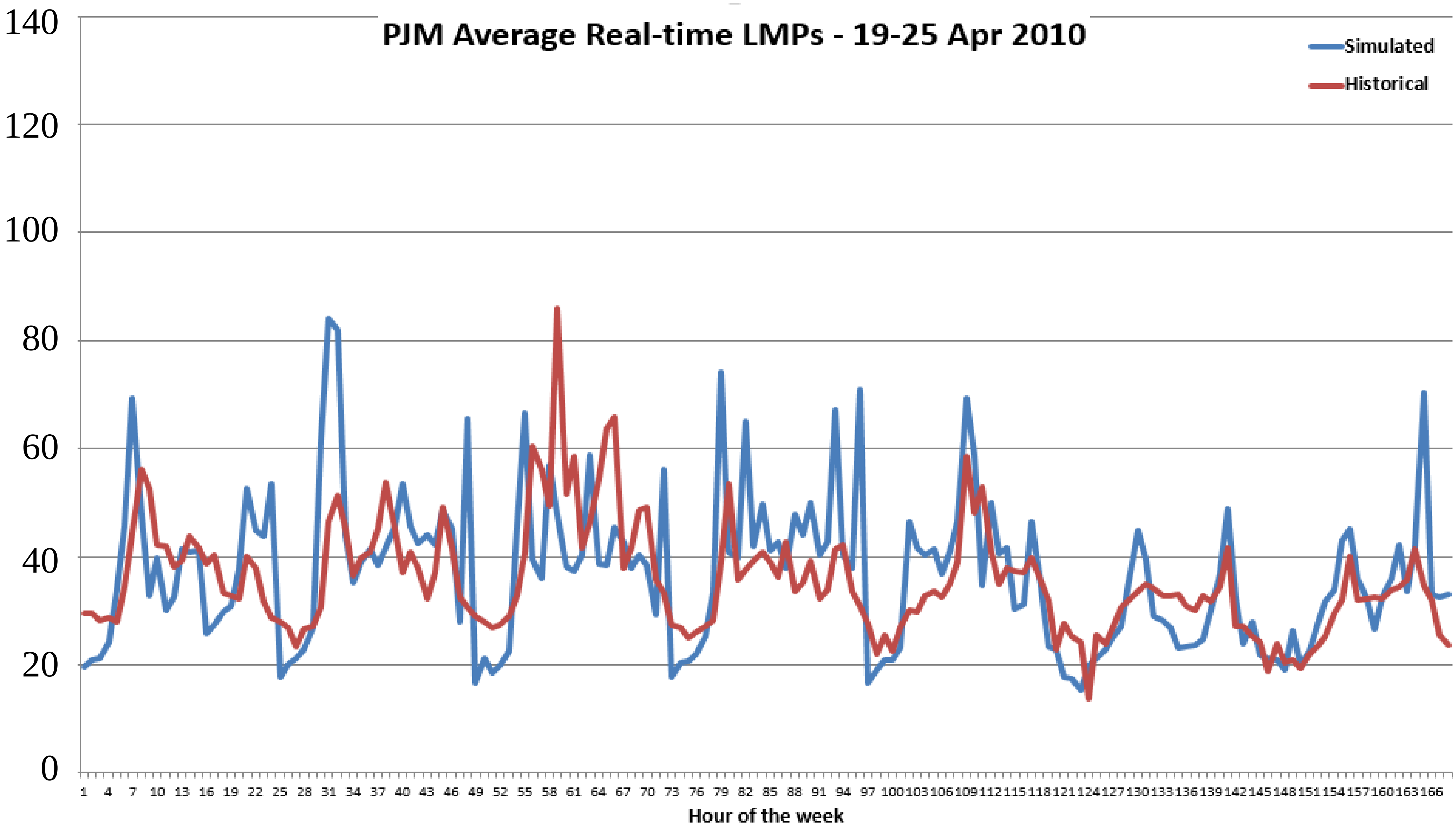
Calibration

- ❑ 1300MW reserve



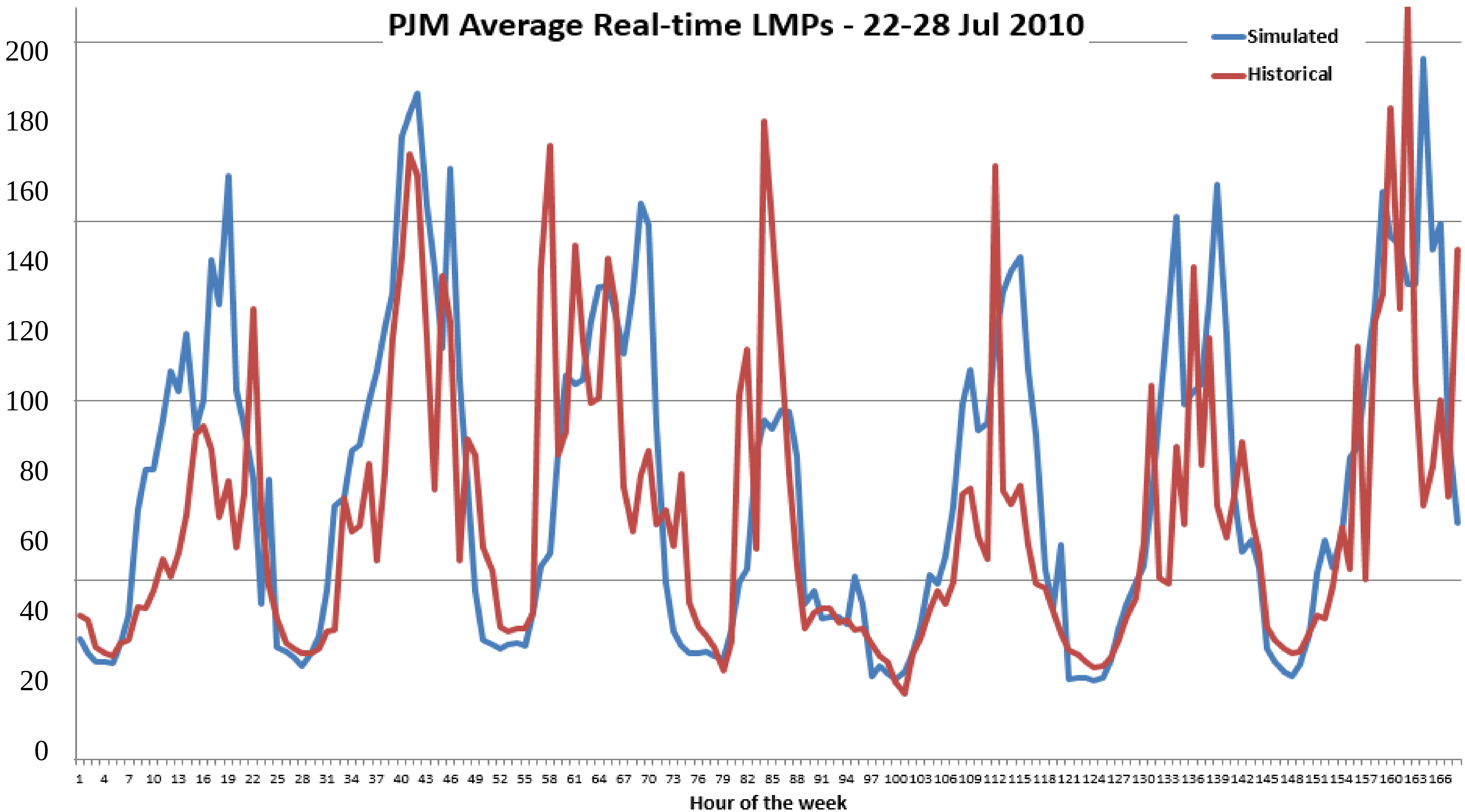
Calibration

- 1300MW reserve



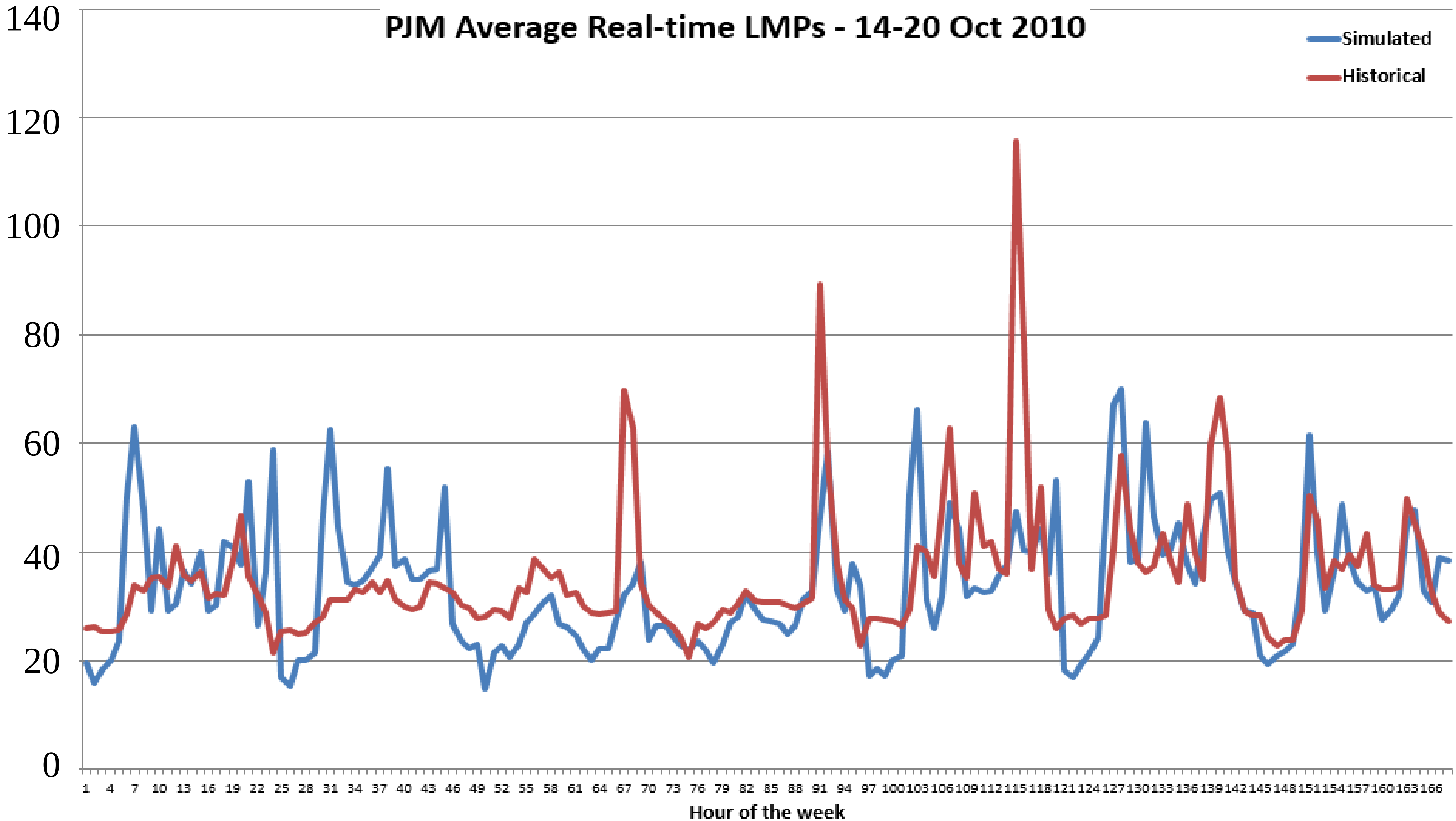
Calibration

- 1300MW reserve



Calibration

- 1300MW reserve

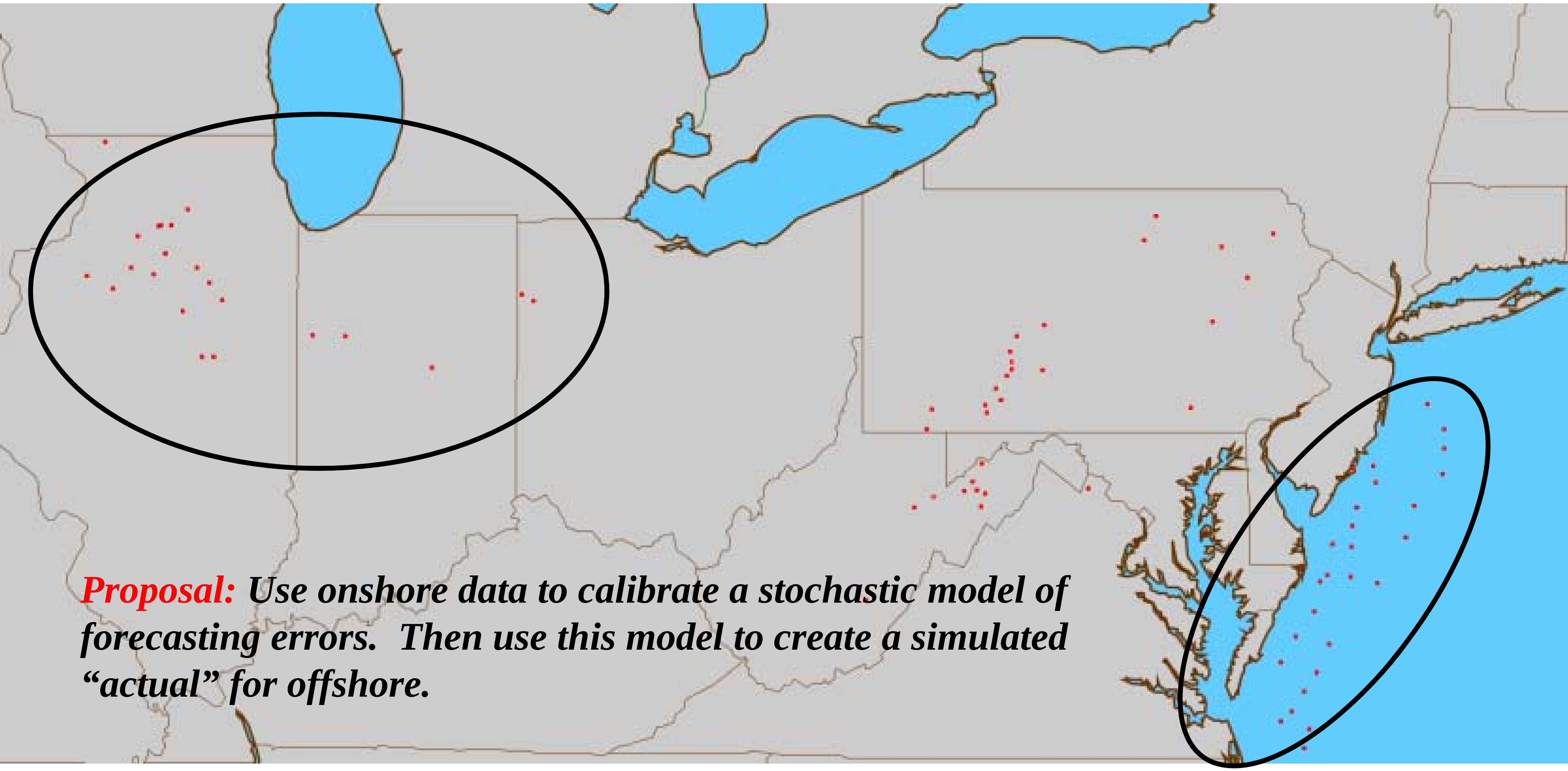


Lecture outline

- The PJM grid and planning process
- SMART-ISO – Model validation
- Modeling wind
  - Onshore error model
  - Offshore sample paths
- Designing a robust policy
- Experiments

Onshore & offshore wind farms

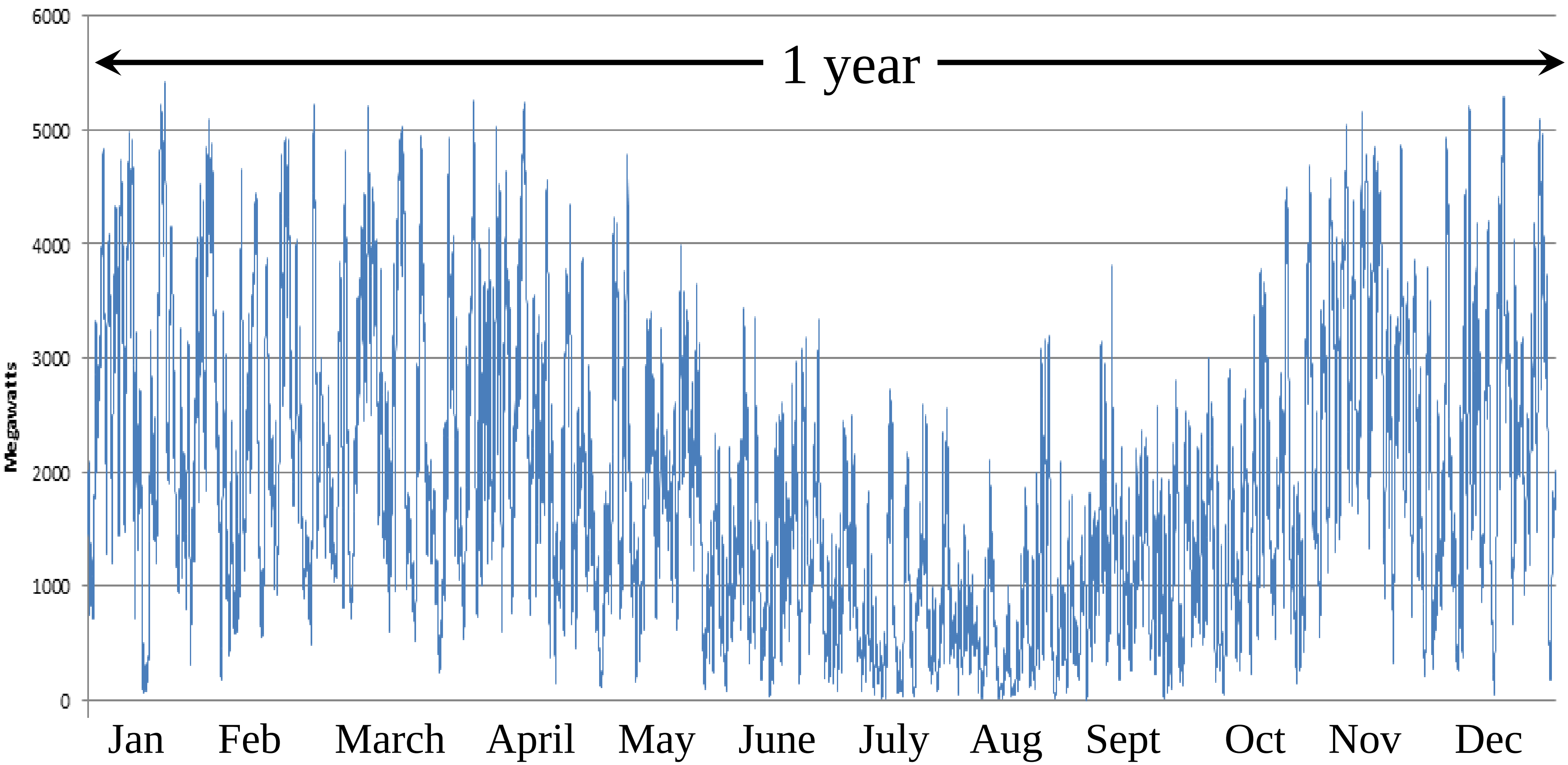
- We were given access to data on the wind power generated by onshore wind farms within PJM



Proposal: ***Use onshore data to calibrate a stochastic model of forecasting errors. Then use this model to create a simulated "actual" for offshore.***

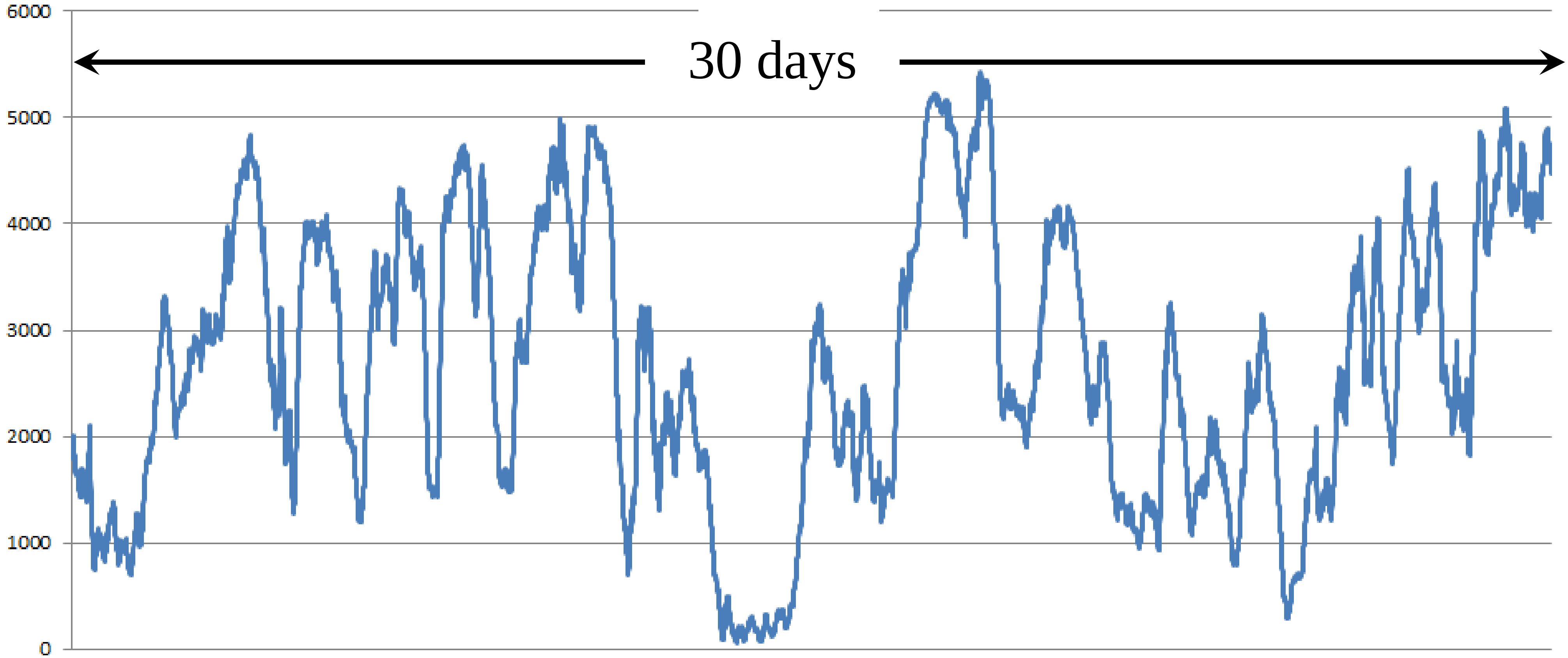
Modeling renewables

- Wind power from all PJM wind farms



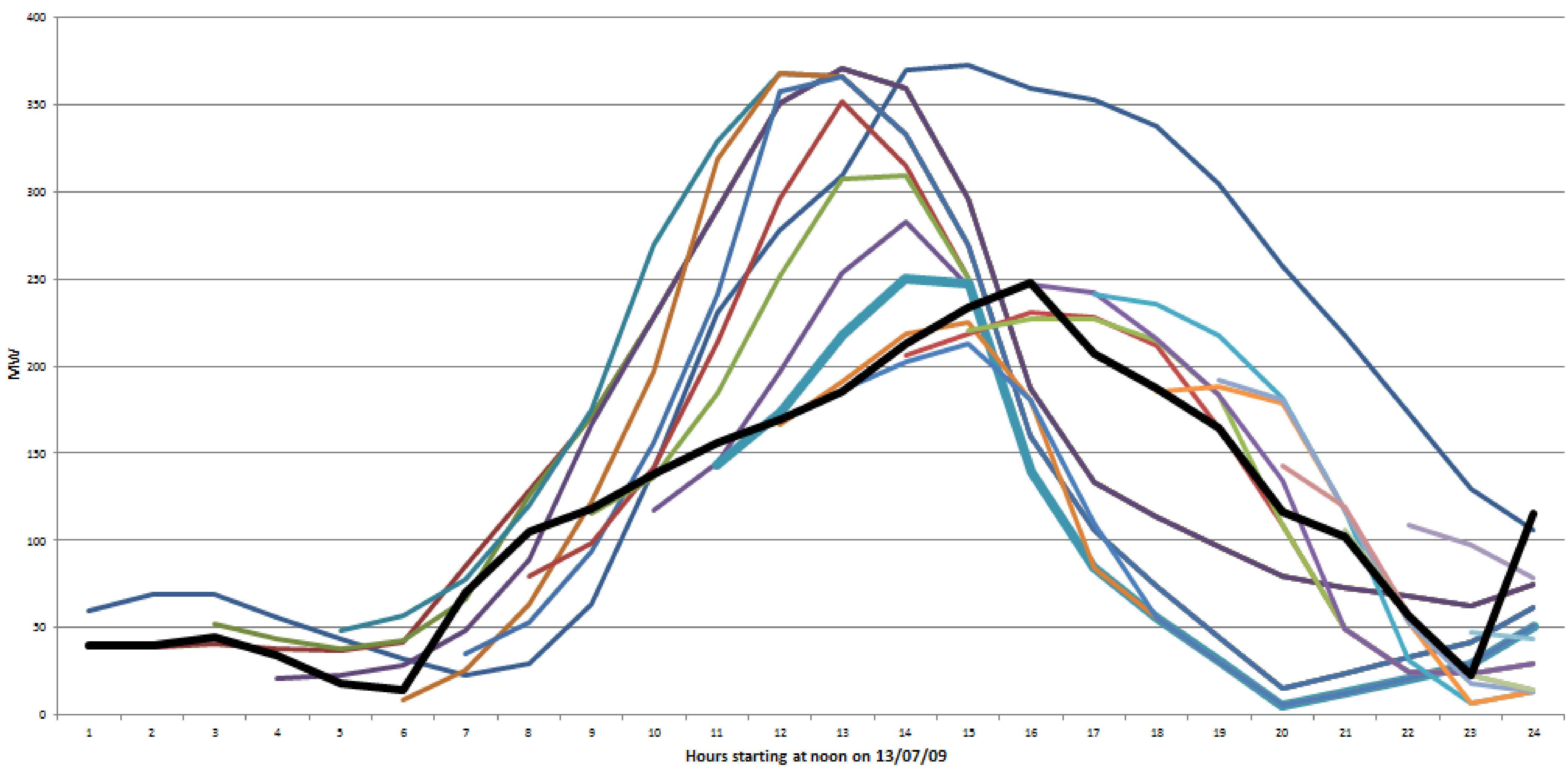
Energy from wind

- Wind power from all PJM wind farms



Forecasting wind

- Rolling 24-hour forecast of PJM wind farms

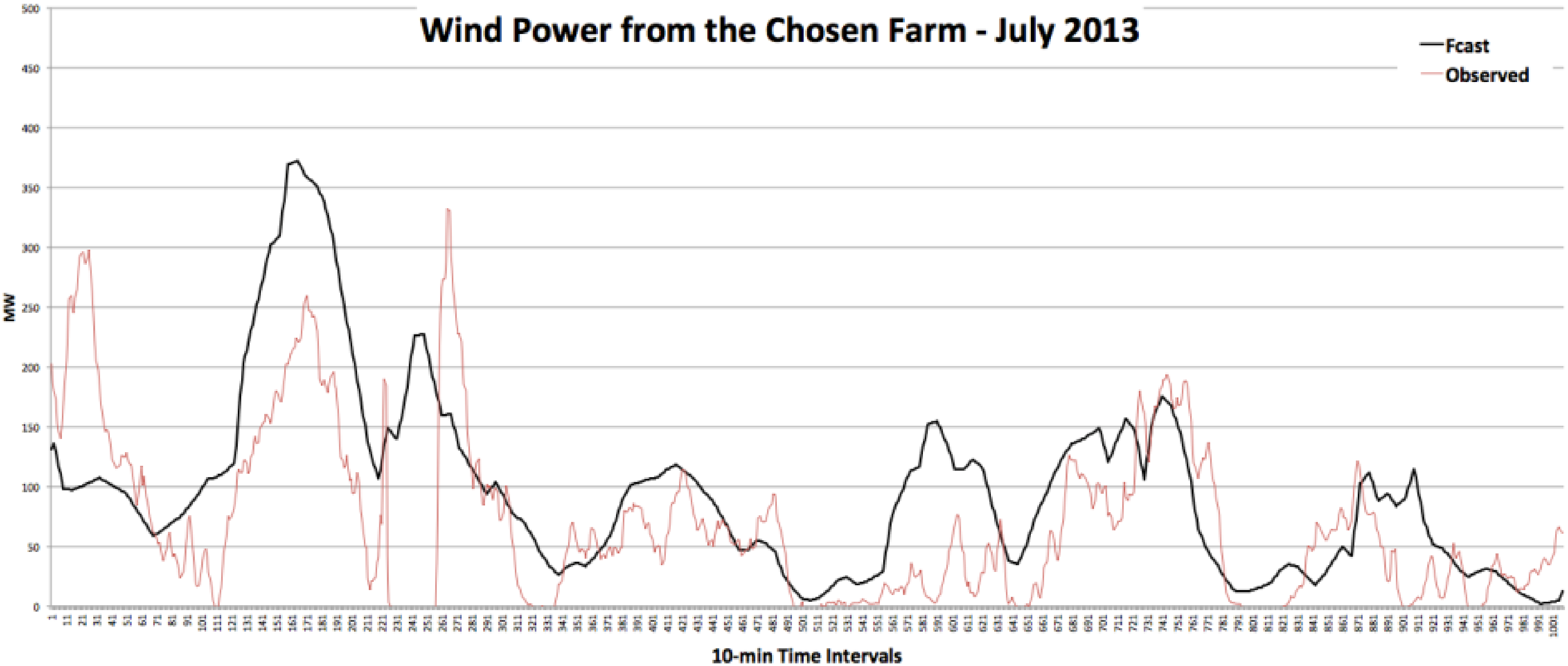


Generating wind sample paths

- Methodology for creating off-shore wind samples
  - » Use actual forecasts from on-shore wind to develop a stochastic error model
  - » Use meteorological forecasts for 12 different weeks using WRF
  - » Generate sample paths of wind by sampling errors from on-shore stochastic error model
  - » Repeat this for base case and five buildout levels
- Our sample paths are based on:
  - » Four months: January, April, July and October
  - » Forecasts from three weeks each month
  - » Seven sample paths generated around each forecast
  - » Total of 84 sample paths representing a cross section of seasons and weather patterns
- Is this enough?

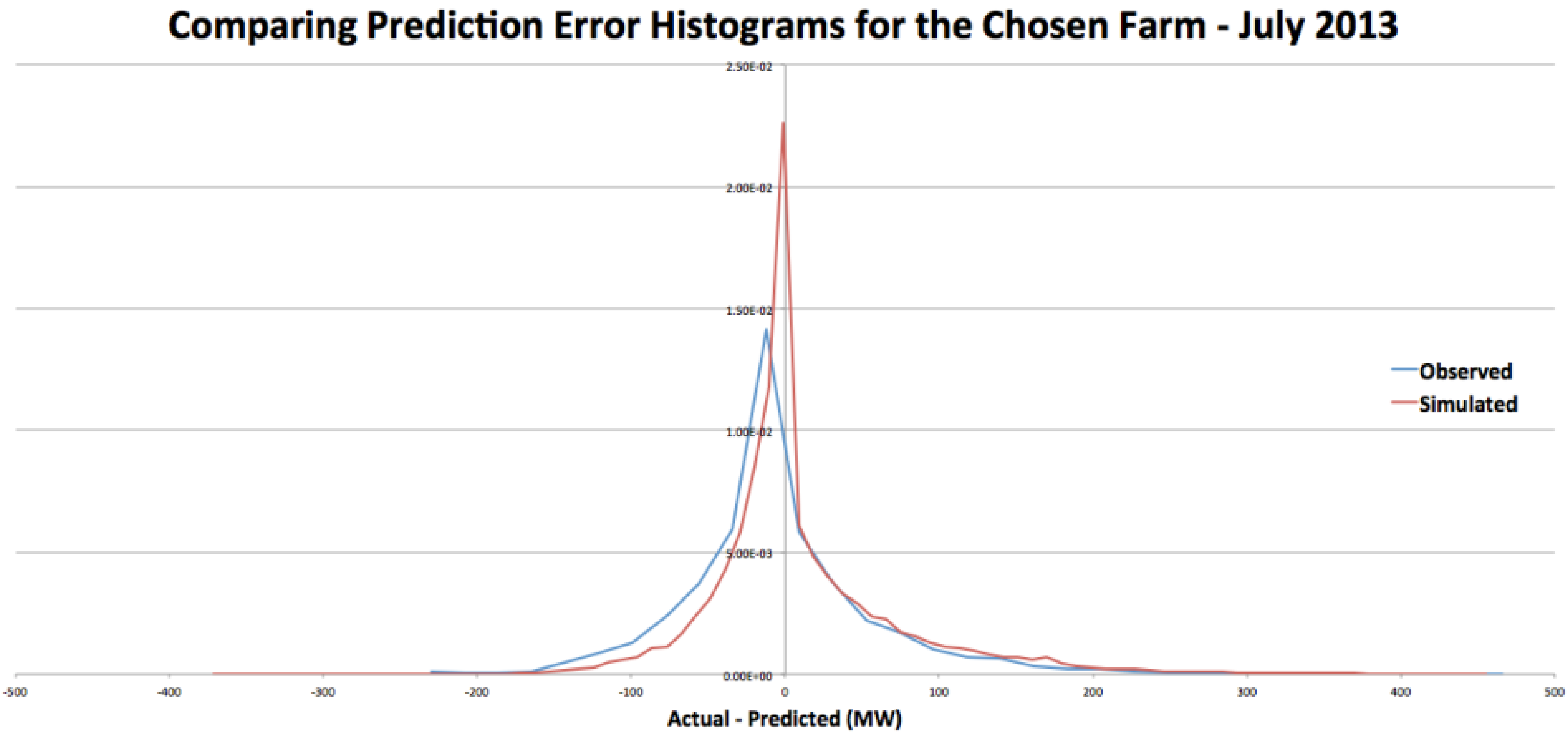
Simulating onshore wind

- Actual (observed) time series (chosen farm only):



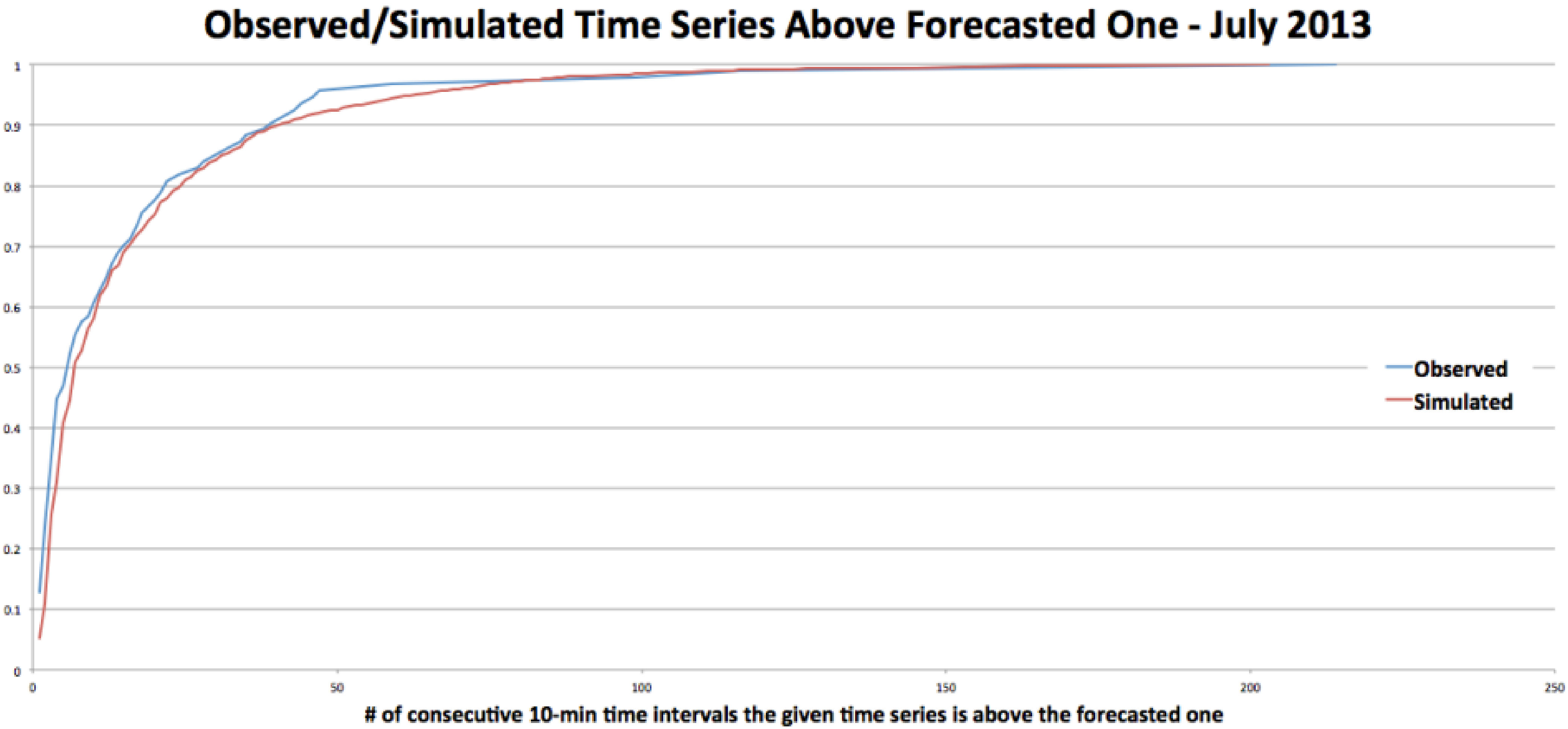
Simulating onshore wind

- ❑ Histogram of the prediction error (observed/simulated – forecast) for the chosen farm only:



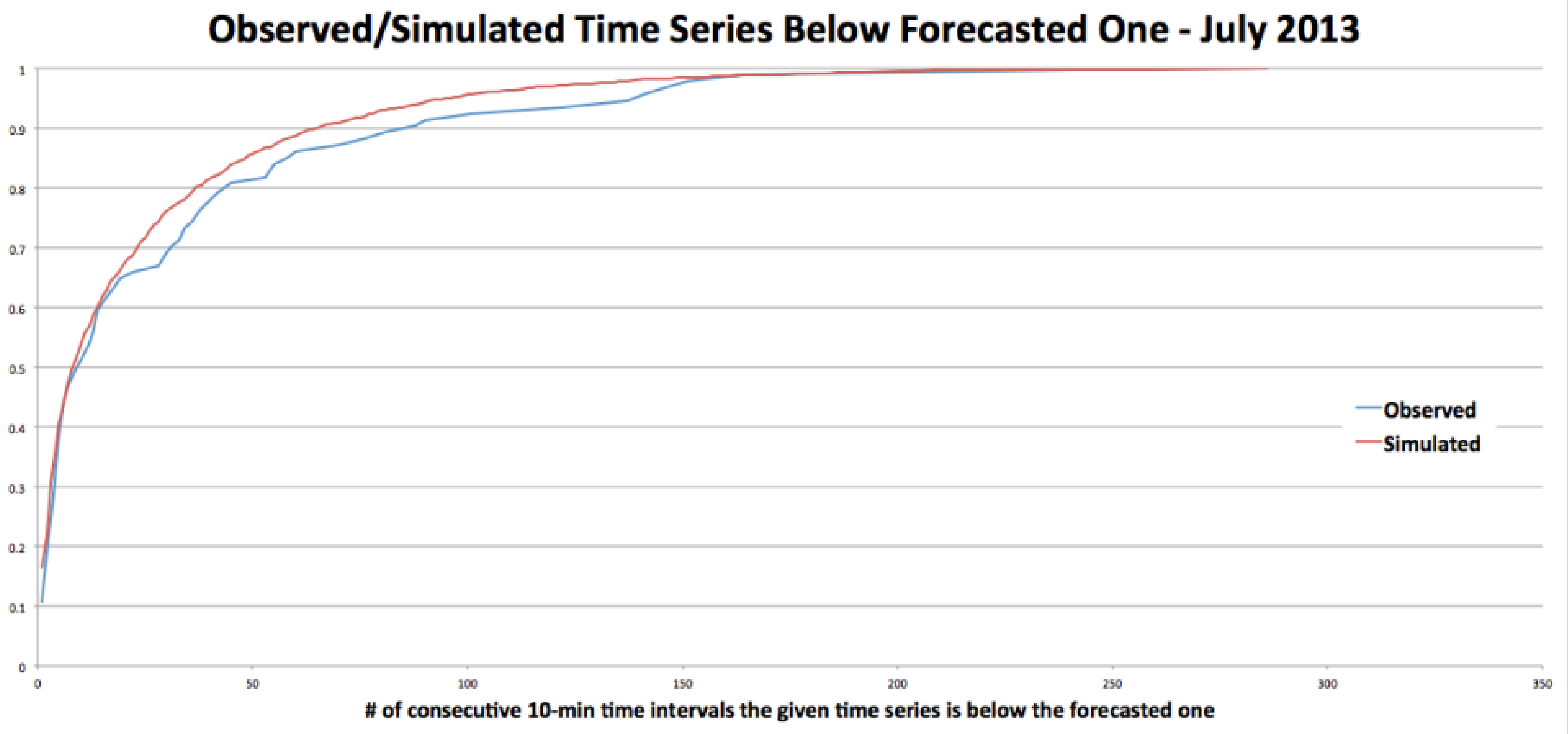
Simulating onshore wind

- Cumulative histogram of the # of consecutive time intervals the observed/simulated time series is above the forecasted one (chosen farm only):



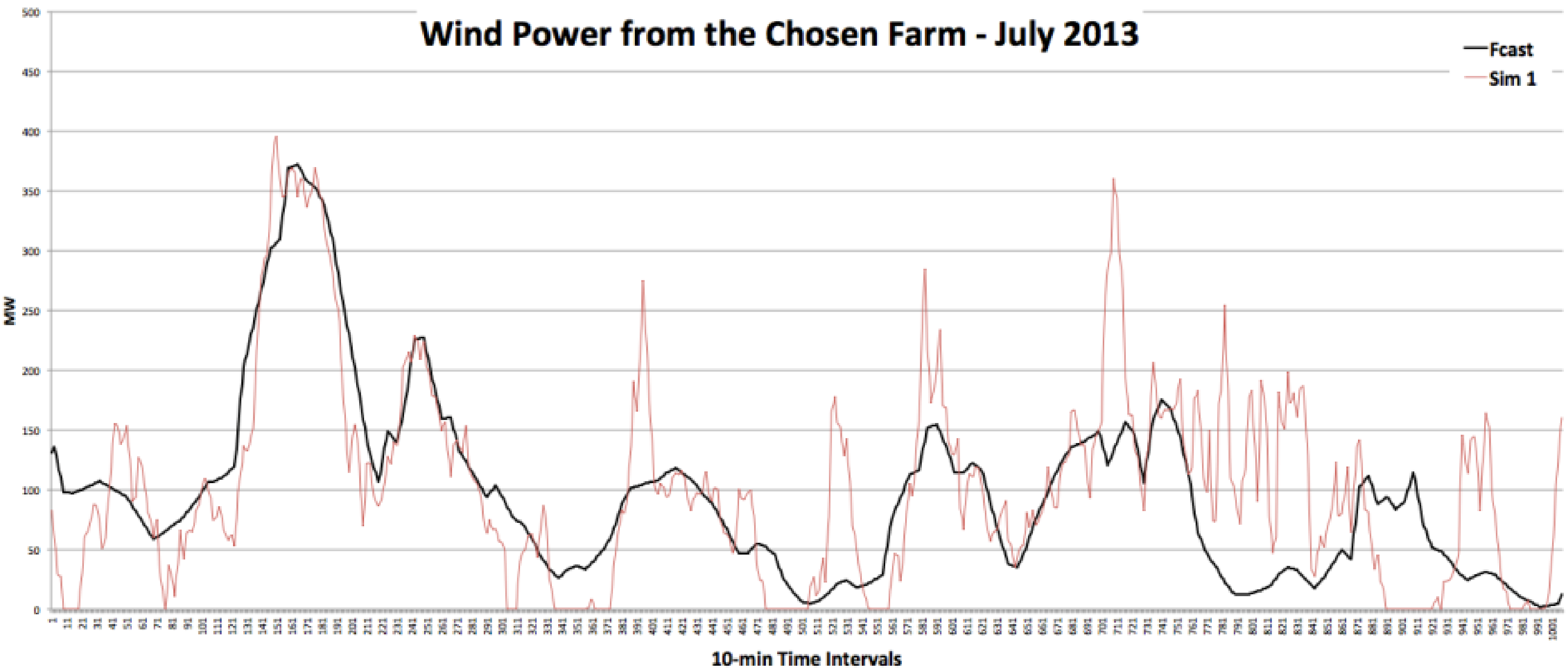
Simulating onshore wind

- Cumulative histogram of the # of consecutive time intervals the observed/simulated time series is below the forecasted one (chosen farm only):



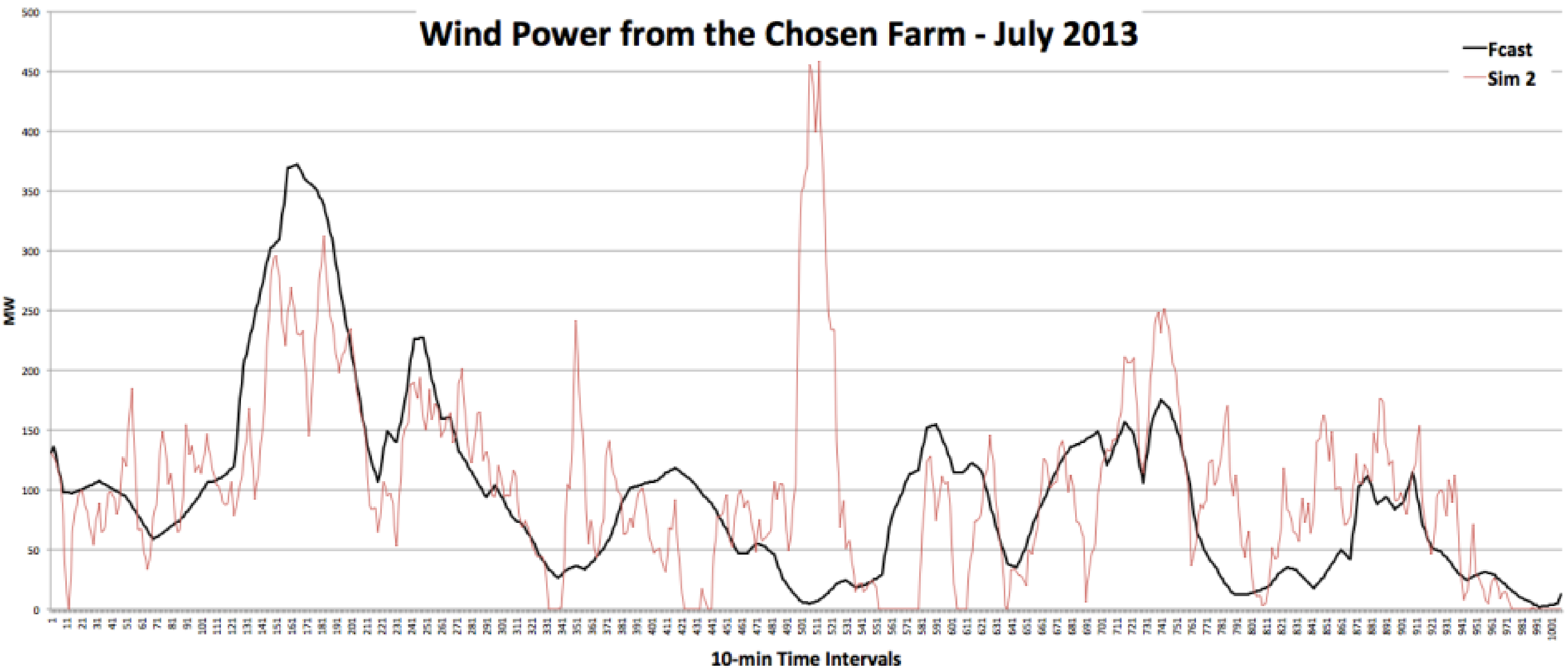
Simulating onshore wind

- ❑ Simulated time series #1 (chosen farm only):



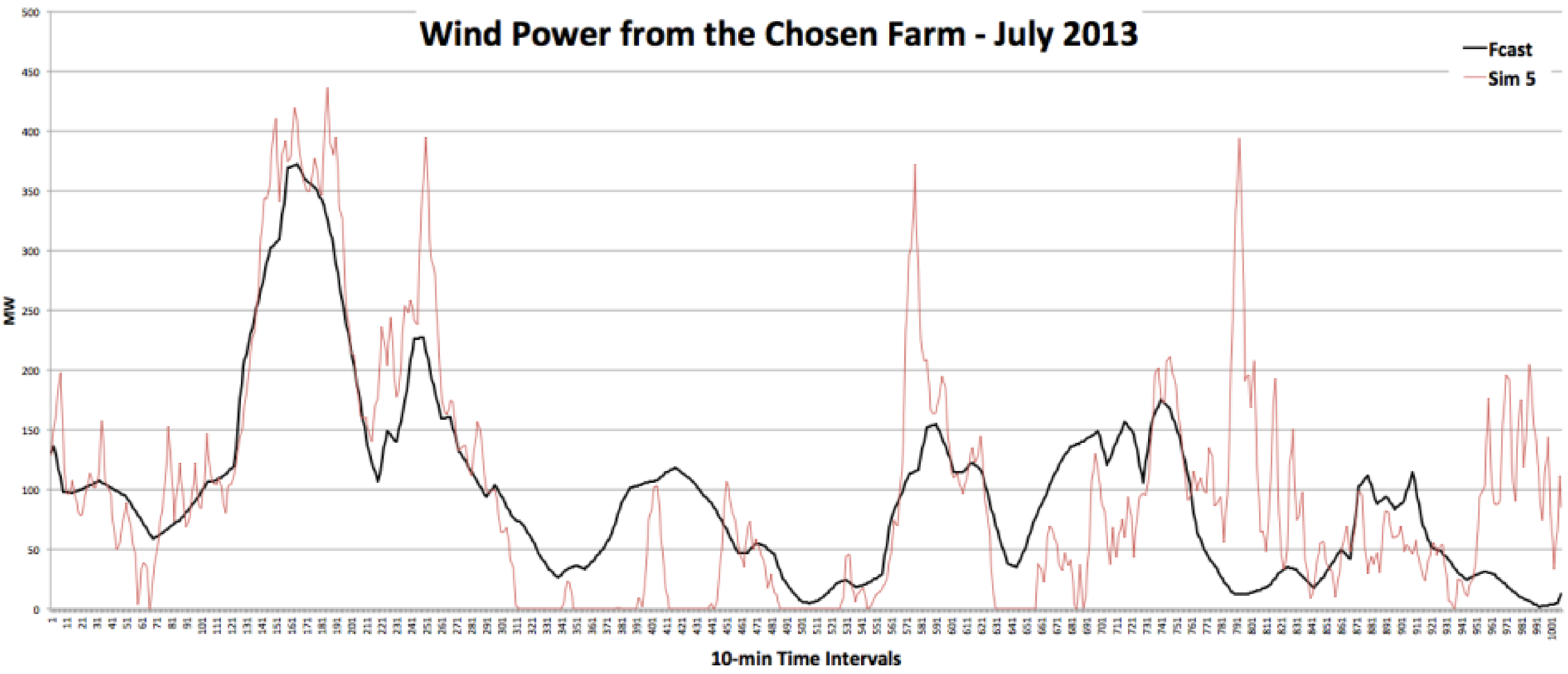
Simulating onshore wind

- Simulated time series #2 (chosen farm only):



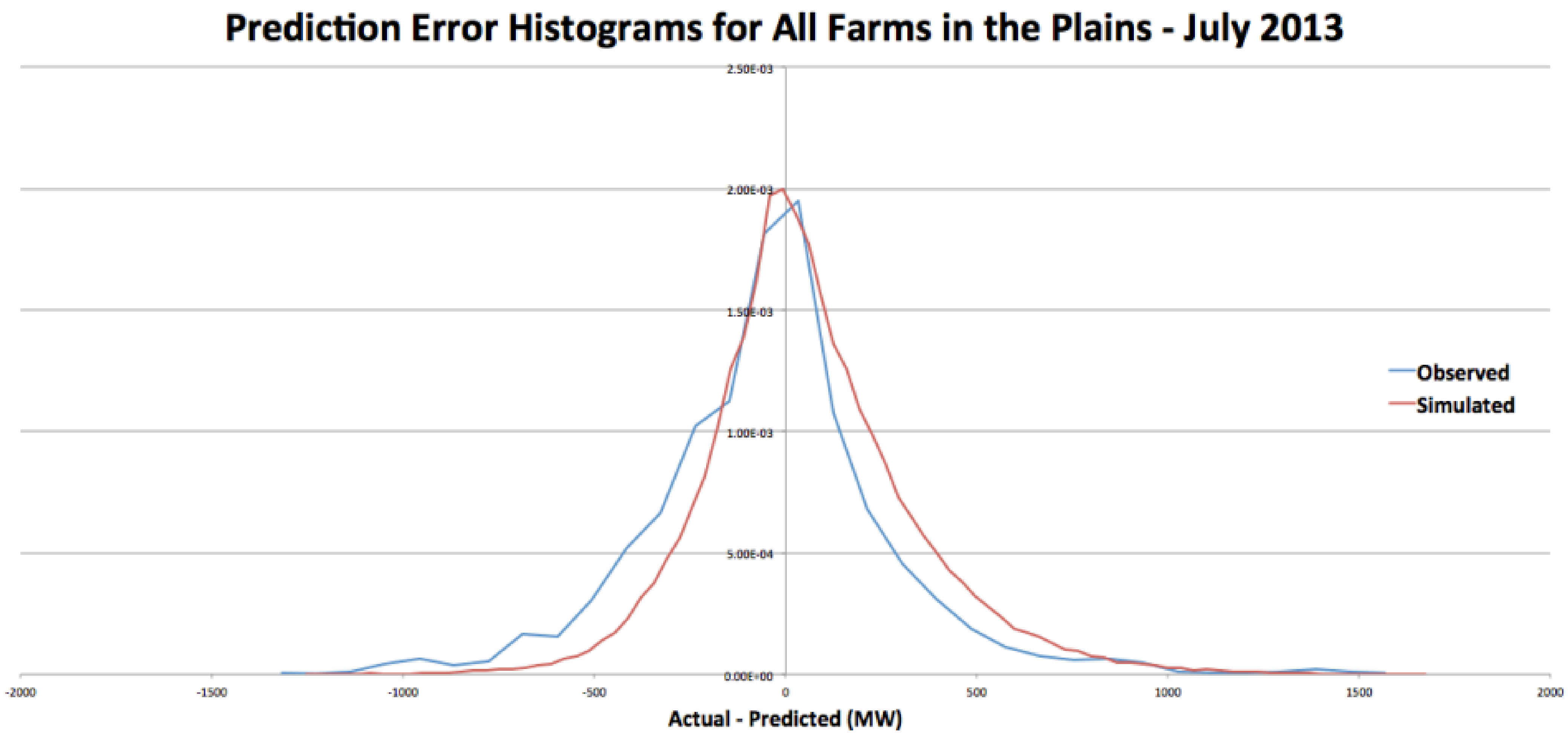
Simulating onshore wind

- Simulated time series #5 (chosen farm only):



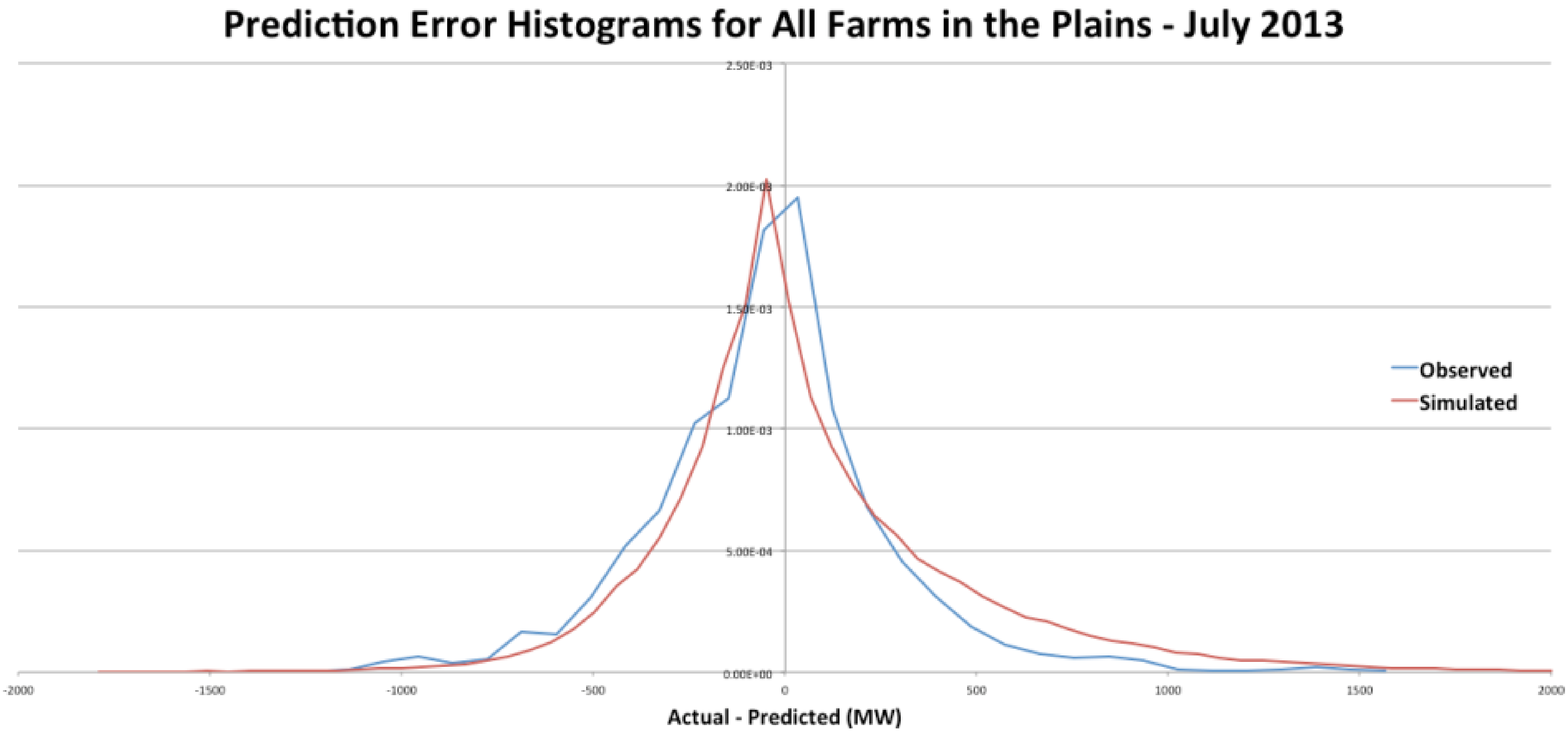
Simulating onshore wind

- Histogram of the prediction error (observed/simulated – forecast) for all farms in the Plains, *before* scaling up the correlation function:



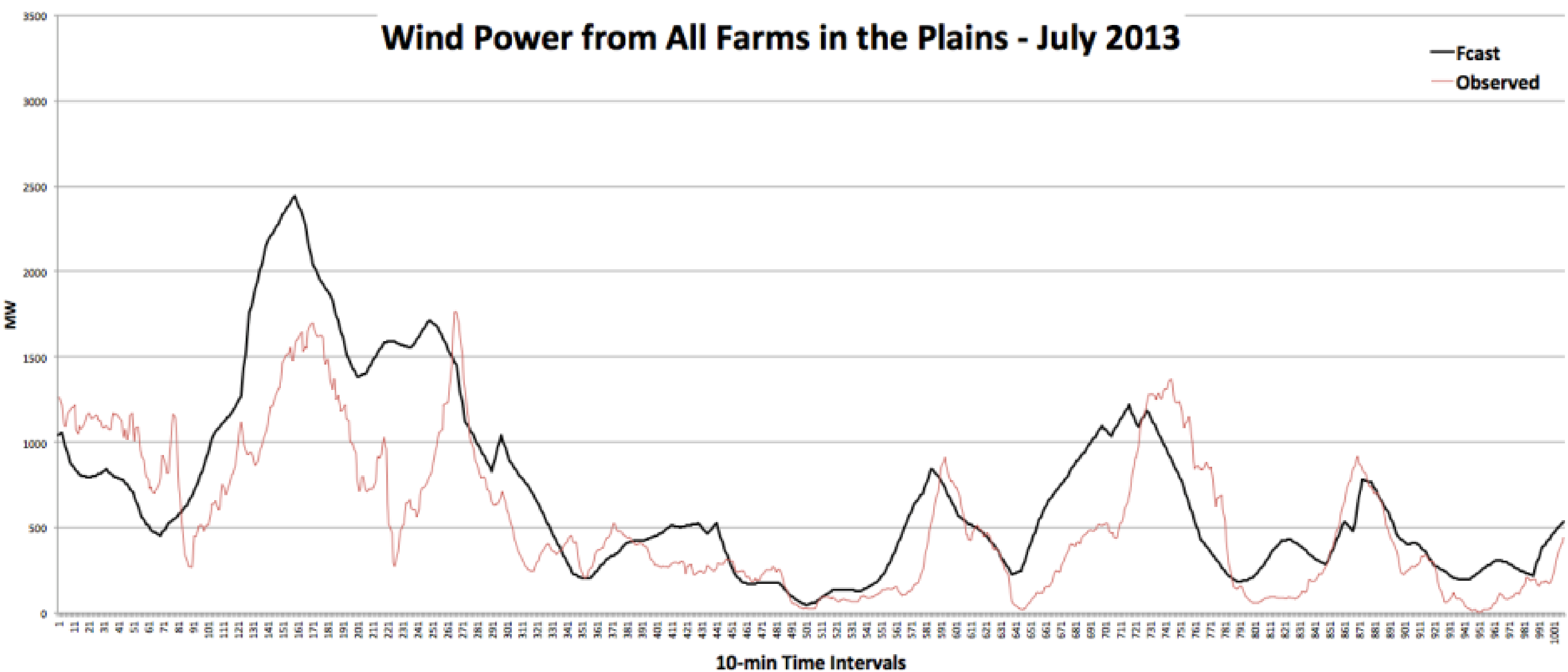
Simulating onshore wind

- Histogram of the prediction error (observed/simulated – forecast) for all farms in the Plains, *after* scaling up the correlation function:



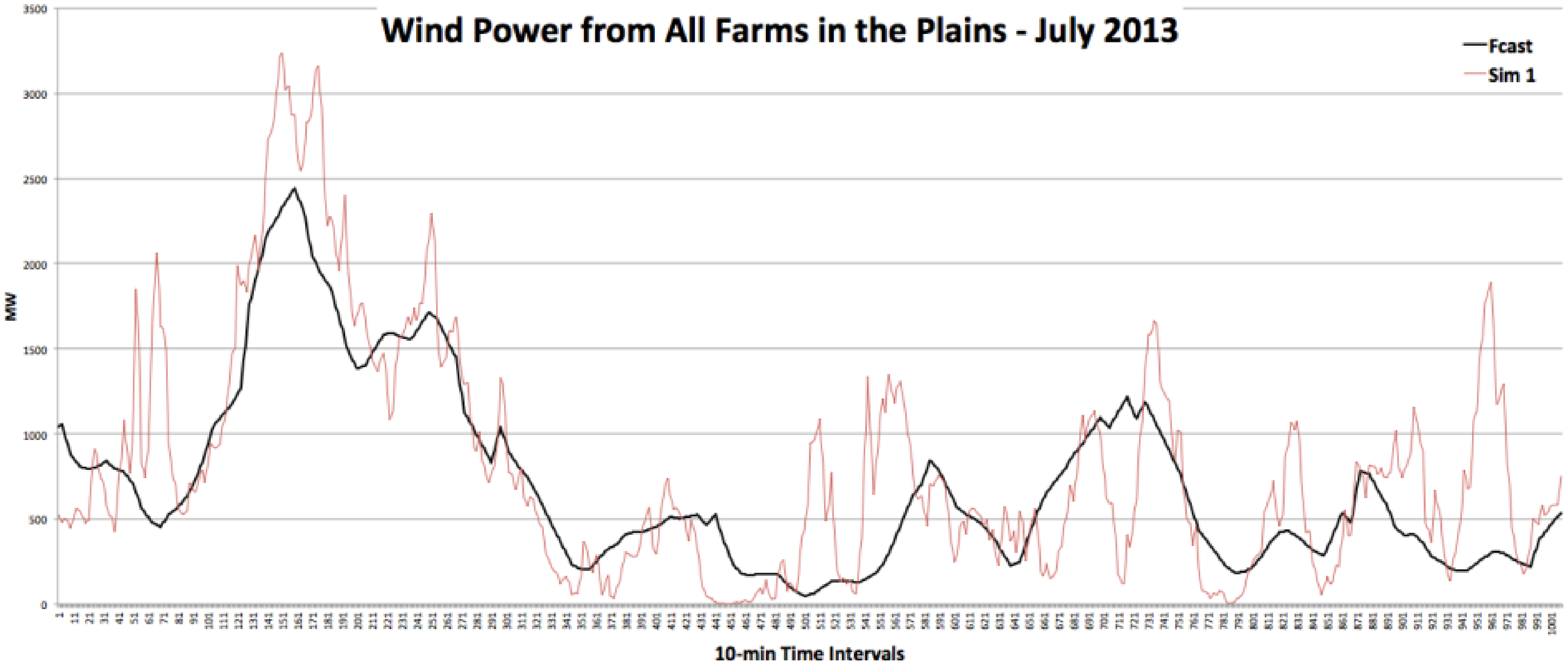
Simulating onshore wind

- Actual (observed) time series (all farms in the Plains):



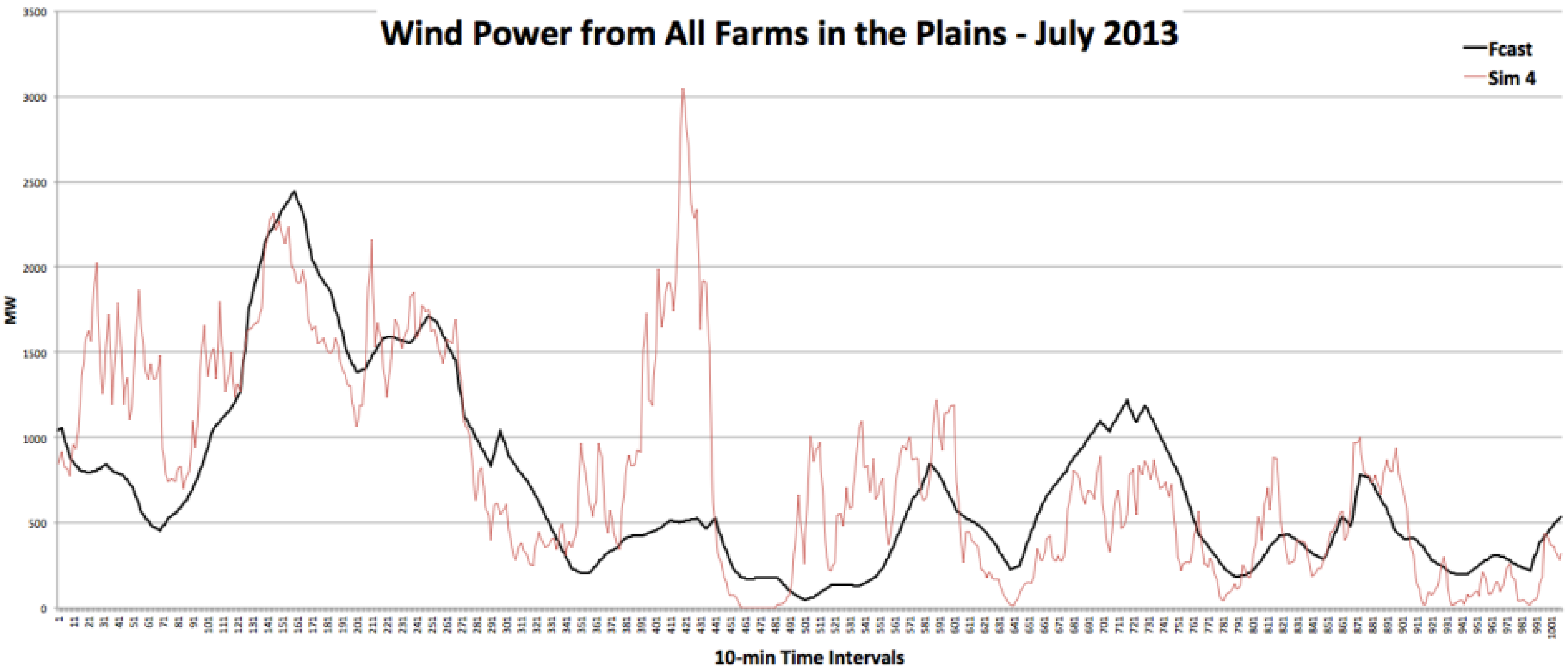
Simulating onshore wind

- Simulated time series #1 (all farms in the Plains):



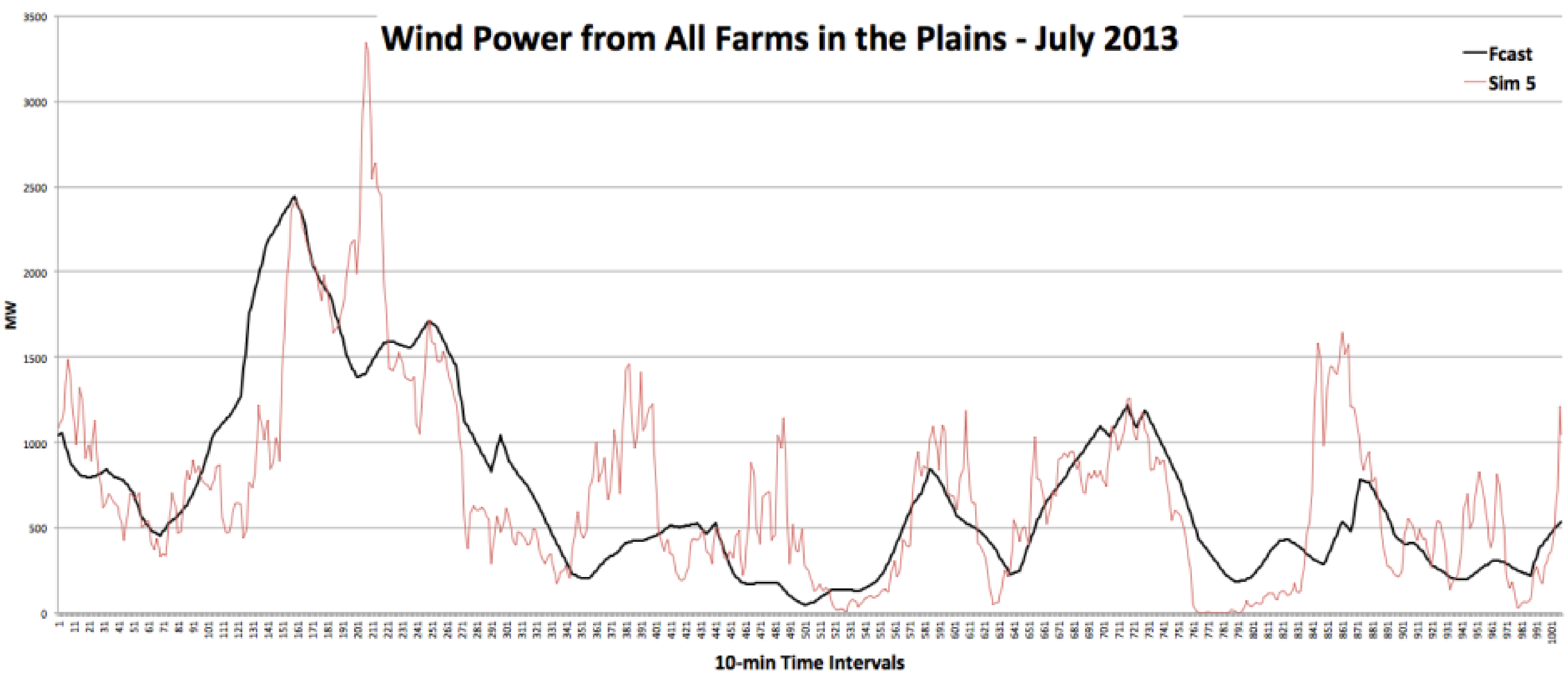
Simulating onshore wind

- Simulated time series #4 (all farms in the Plains):



Simulating onshore wind

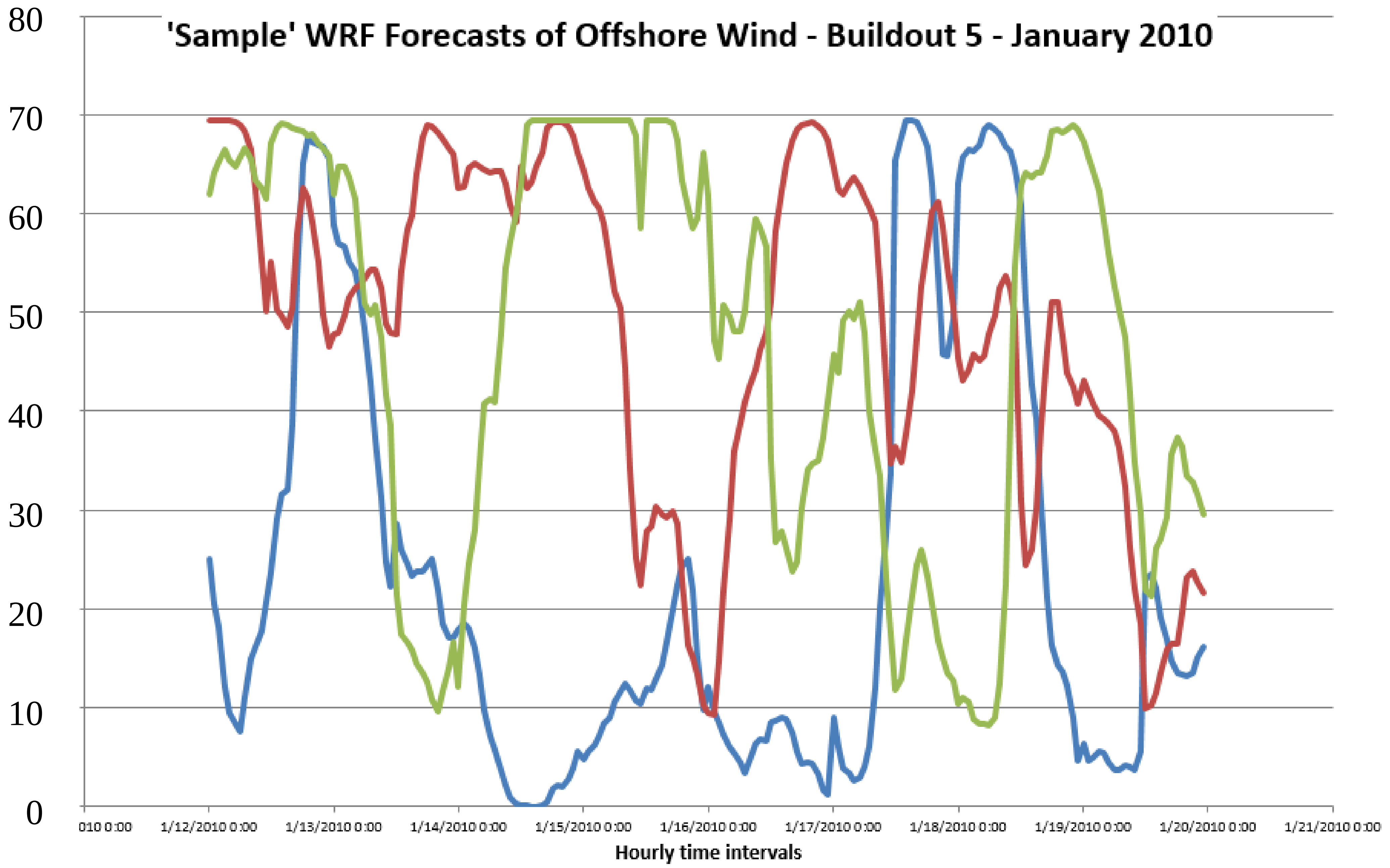
- ❑ Simulated time series #5 (all farms in the Plains):



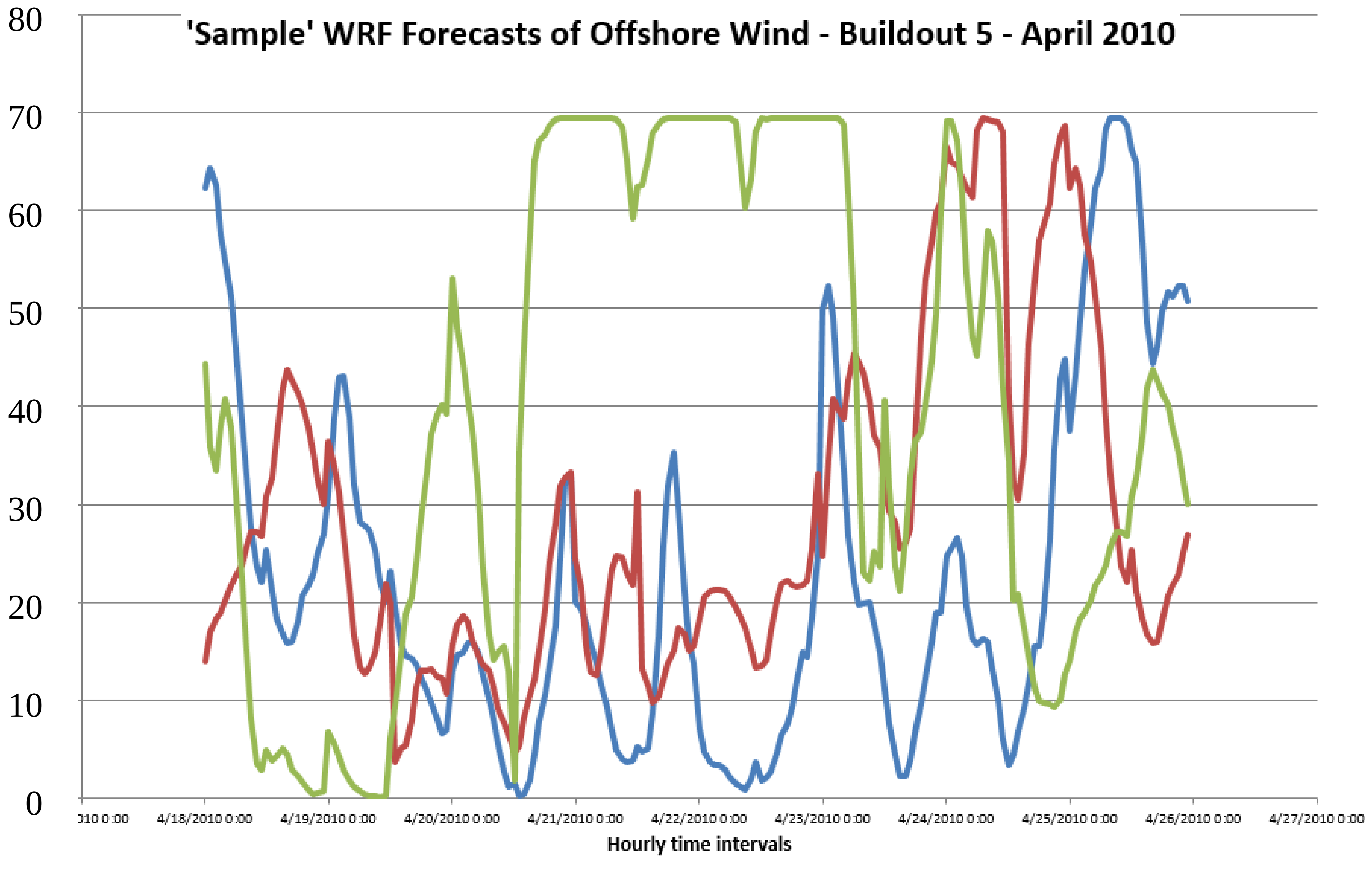
Lecture outline

- The PJM grid and planning process
- SMART-ISO – Model validation
- Modeling wind
  - Onshore error model
  - Offshore sample paths
- Designing a robust policy
- Experiments

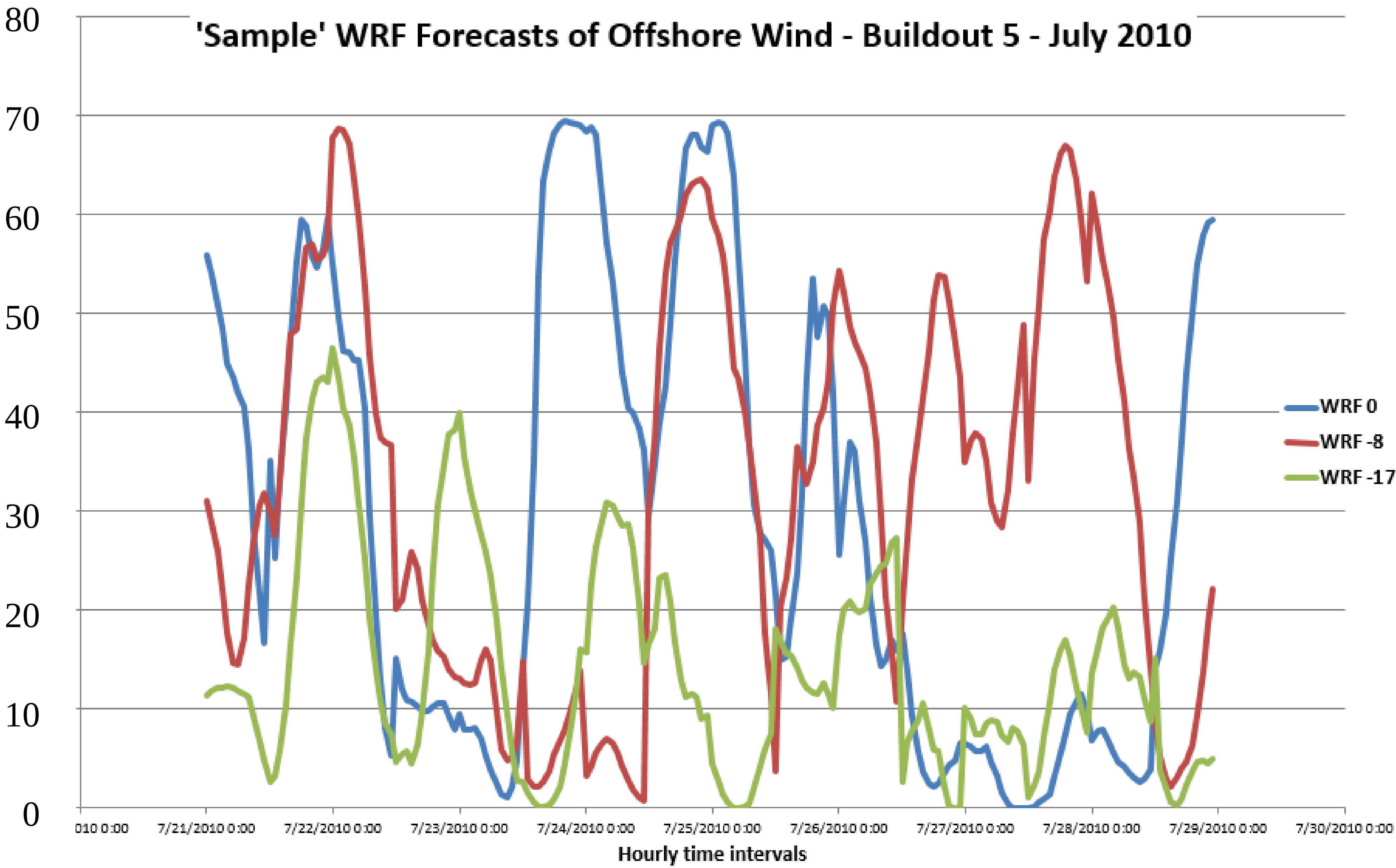
Wind forecast samples



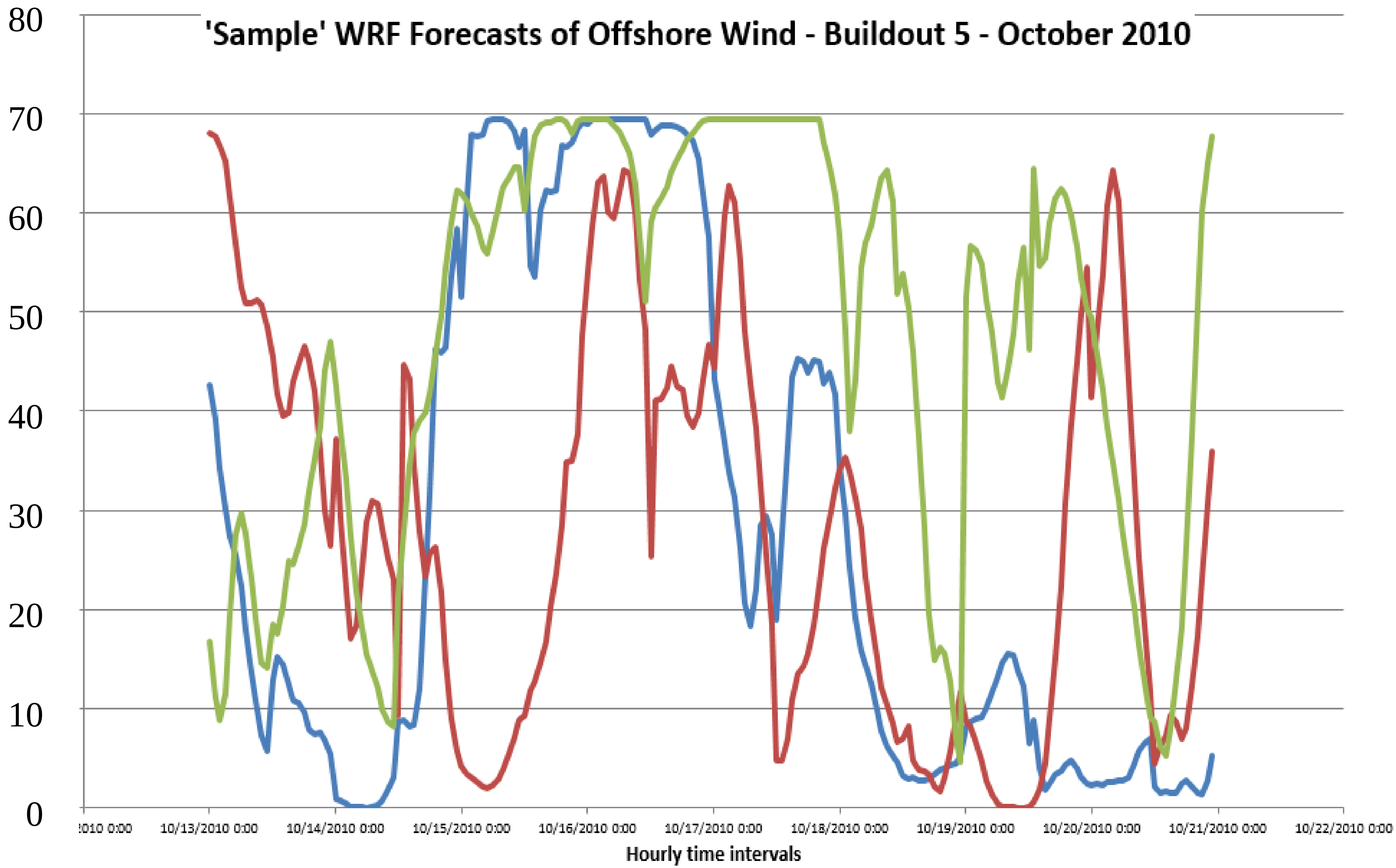
Wind forecast samples



Wind forecast samples

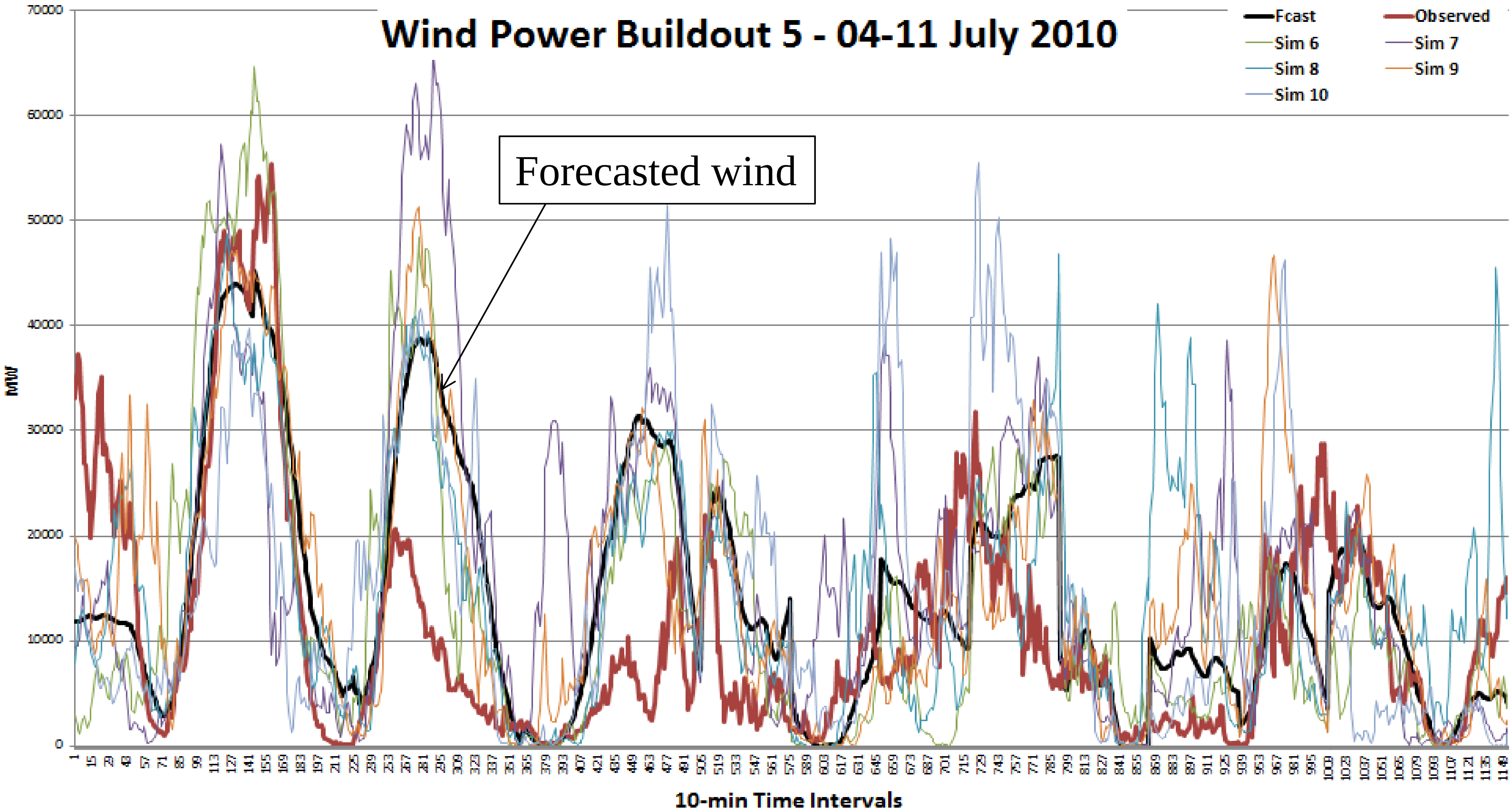


Wind forecast samples



Simulating offshore wind

- ❑ Offshore wind – Buildout level 5



Lecture outline

- The PJM grid and planning process
- SMART-ISO – Model validation
- Modeling wind
  - Onshore error model
  - Offshore sample paths
- Designing a robust policy
- Experiments

Designing a policy

- Dealing with uncertainty
  - » We have to design policies to manage the different forms of uncertainty.
  - » We do this by looking for *robust policies*, which are rules for making decisions.
  - » We write our optimization problem in the form:

$$\min_{\pi} E^{\pi} \left\{ \sum_{t=0}^{T} \gamma^t C\left(S_t, X^{\pi}(S_t)\right) \right\}$$

Search for the best policy

Averaging over multiple samples

Day-ahead, hour-ahead and real-time decisions

Objective function where $S_{t+1} = S^M\left(S_t, X^{\pi}(S_t), W_{t+1}\right)$

Designing a policy

- Dealing with uncertainty
  - » We have to design policies to manage the different forms of uncertainty.
  - » We do this by looking for *robust policies*, which are rules for making decisions.
  - » We write our optimization problem in the form:

$$\min_{\pi} E^{\pi}\left\{\sum_{t=0}^{T}\gamma^{t}C\left(S_t, X^{\pi}(S_t)\right)\right\}$$

  - » We refer to this as the *base model* which is typically calculated as a simulation:

$$\min_{\pi} \bar{F}^{\pi} = \frac{1}{N}\sum_{n=1}^{N}\sum_{t=0}^{T}\gamma^{t}C\left(S_t(\omega^n), X_t^{\pi}(S_t(\omega^n))\right)$$

where $S_{t+1} = S^M\left(S_t, x_t, W_{t+1}(\omega)\right)$

Four classes of policies

1) Policy function approximations (PFAs)

- » Lookup tables, rules, parametric functions

2) Cost function approximation (CFAs)

- » $X^{CFA}(S_t \mid \theta) = \arg\min_{x_t \in \bar{\mathcal{X}}_t(\theta)} \bar{C}^{\pi}(S_t, x_t \mid \theta)$

3) Policies based on value function approximations (VFAs)

- » $X_t^{VFA}(S_t) = \arg\min_{x_t} \left(C(S_t, x_t) + \gamma \bar{V}_t^{x}\left(S_t^{x}(S_t, x_t)\right)\right)$

4) Lookahead policies

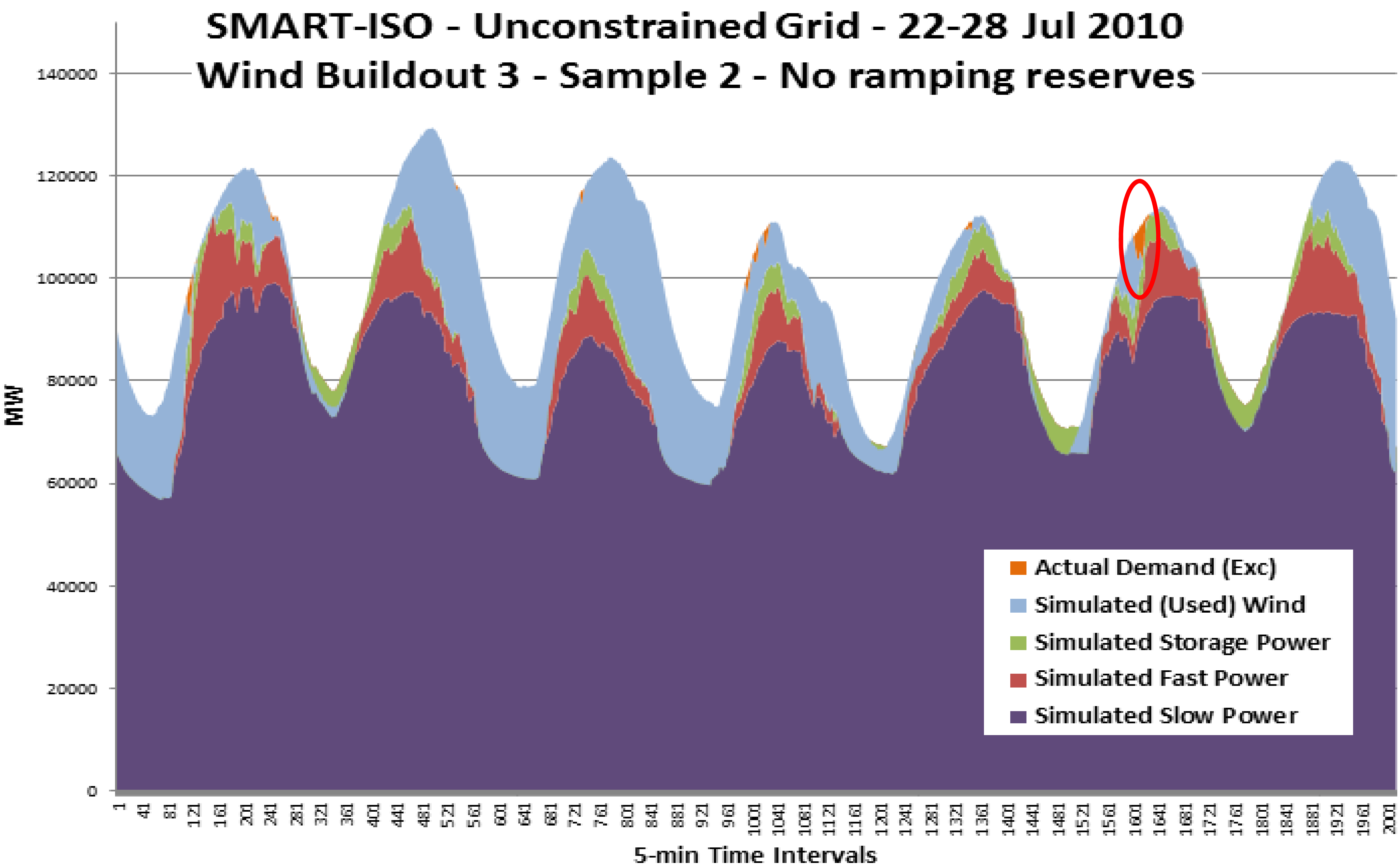
- » ***Deterministic lookahead:***

$$X_t^{LA-D}(S_t) = \arg\min_{\tilde{x}_{tt}, \tilde{x}_{t,t+1}, \ldots, \tilde{x}_{t,t+T}} C(\tilde{S}_{tt}, \tilde{x}_{tt}) + \sum_{t'=t+1}^{T} \gamma^{t'-t} C(\tilde{S}_{tt'}, \tilde{x}_{tt'})$$

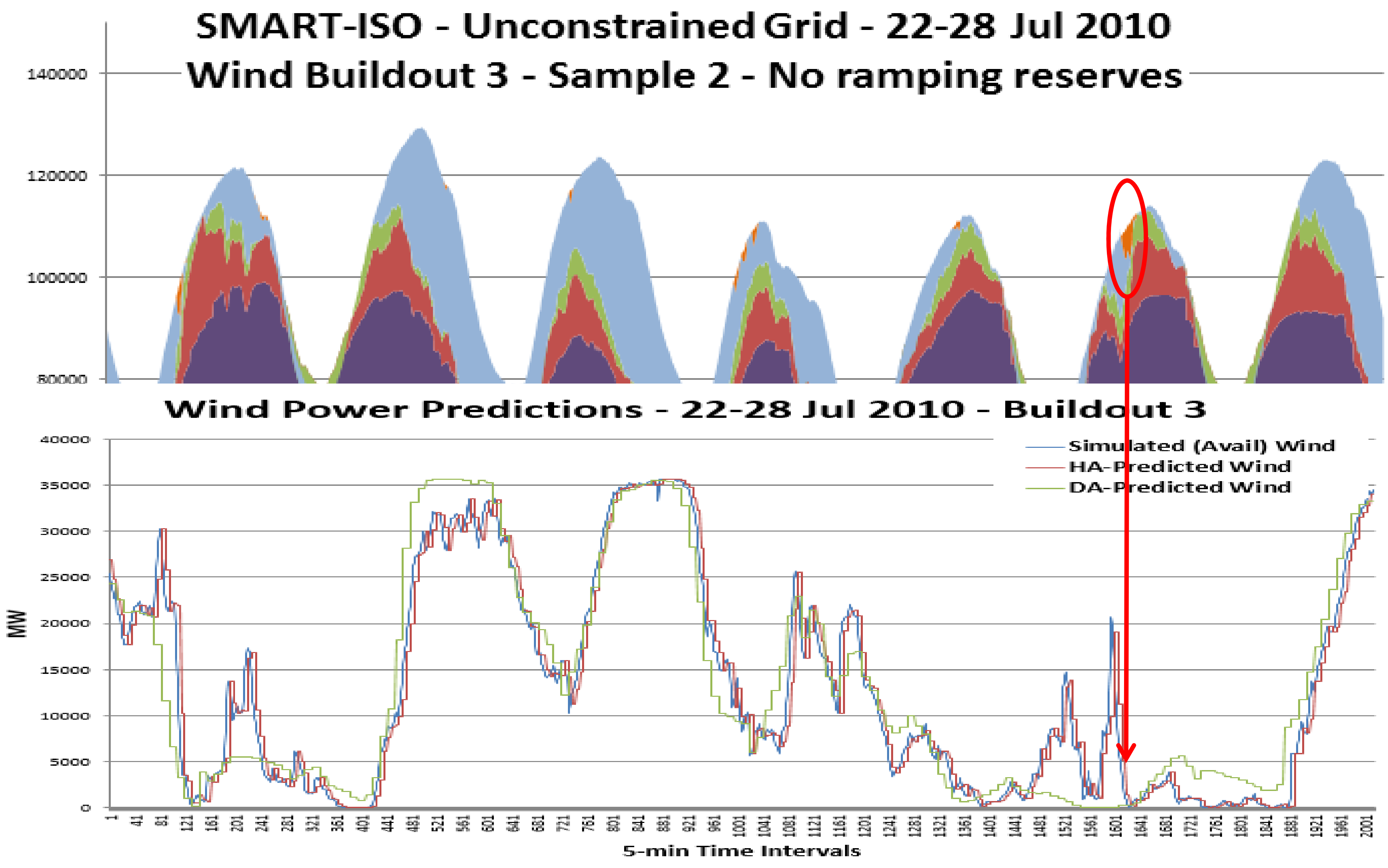
- » ***Stochastic lookahead (e.g. stochastic trees)***

$$X_t^{LA-S}(S_t) = \arg\min_{\tilde{x}_{tt}, \tilde{x}_{t,t+1}, \ldots, \tilde{x}_{t,t+T}} C(\tilde{S}_{tt}, \tilde{x}_{tt}) + \sum_{\omega \in \tilde{\Omega}_t} p(\omega) \sum_{t'=t+1}^{T} \gamma^{t'-t} C(\tilde{S}_{tt'}(\omega), \tilde{x}_{tt'}(\omega))$$

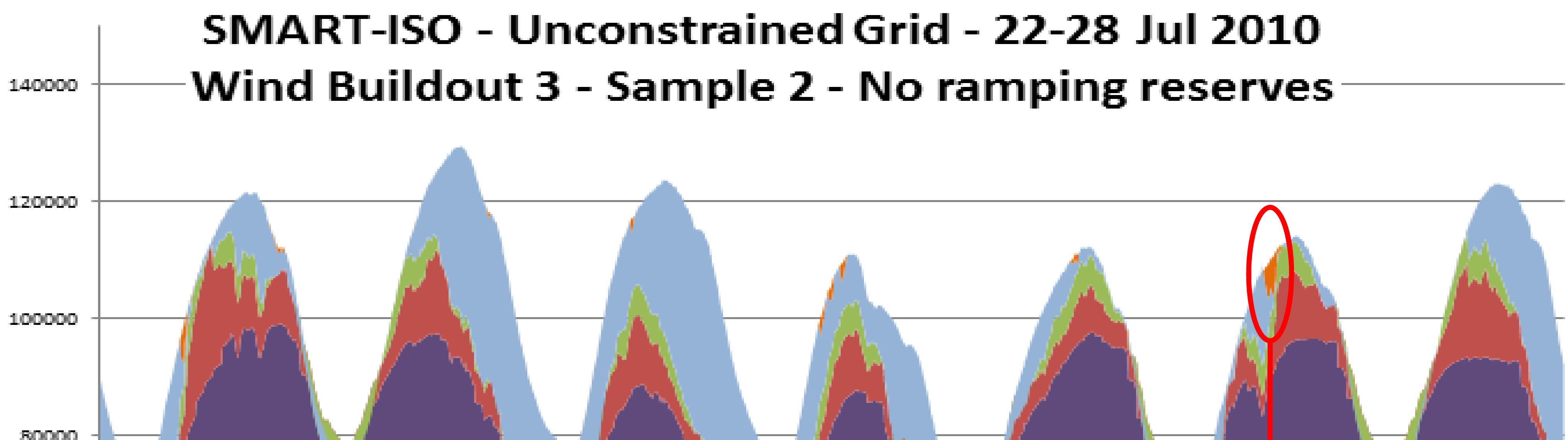
Stochastic lookahead policies

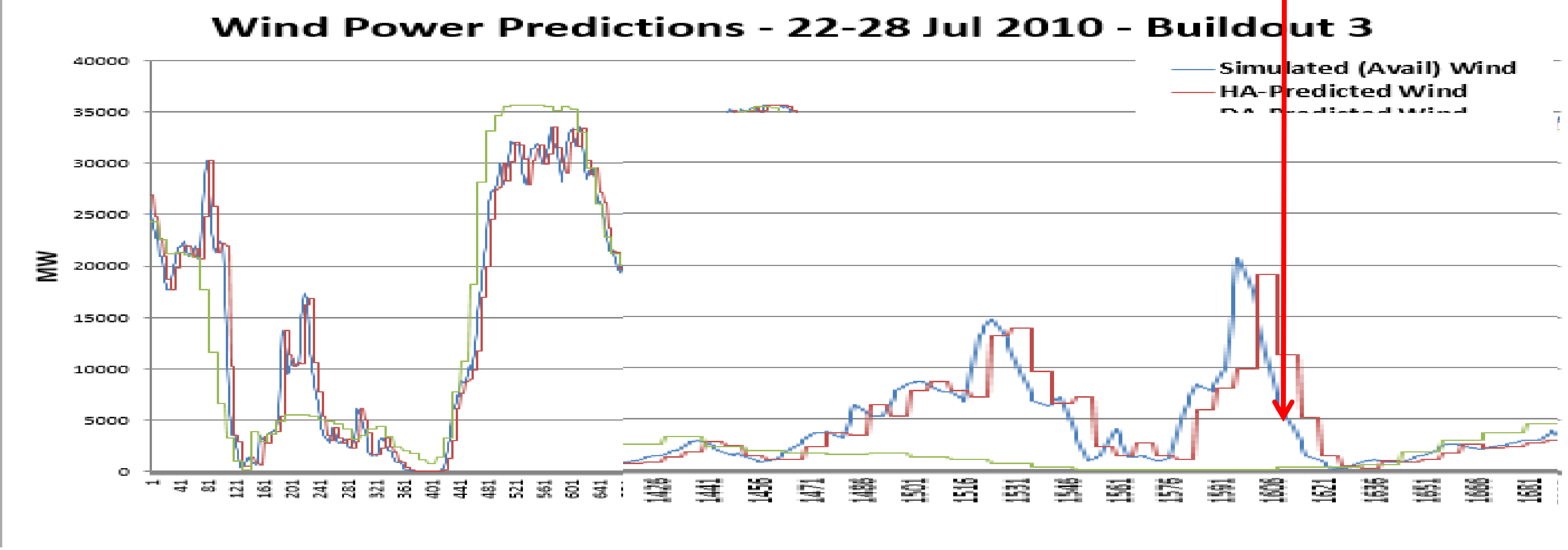


Stochastic lookahead policies



Stochastic lookahead policies





A hybrid lookahead-CFA policy

- A deterministic lookahead model
  - » We use a point forecast of the future

$$\min_{\substack{(x_{tt'})_{t'=1,\dots,24} \\ (y_{tt'})_{t'=1,\dots,24}}} \sum_{t'=t}^{t+48} C(x_{tt'}, y_{tt'})$$

Steam generation ($x_{tt'}$)   Gas turbines ($y_{tt'}$)

- » These decisions need to made with different horizons
  - Steam generation is made day-ahead
  - Gas turbines can be planned an hour ahead or less

A hybrid lookahead-CFA policy

- A deterministic lookahead policy
  - » We use a point forecast of the future

$$X^{\pi}(S_t) = \arg \min_{\substack{(x_{tt'})_{t'=1,\dots,24} \\ (y_{tt'})_{t'=1,\dots,24}}} \sum_{t'=t}^{t+48} C(x_{tt'}, y_{tt'})$$

  - » This would be very sensitive to forecast errors.

A hybrid lookahead-CFA policy

- A robust cost function approximation
  - We add in up and down fast ramping reserves

$$X^{\pi}(S_t|\theta) = \arg\min_{\substack{(x_{tt'})_{t'=1,\dots,24} \\ (y_{tt'})_{t'=1,\dots,24}}} \sum_{t'=t}^{t+48} C(x_{tt'}, y_{tt'})$$

$$x^{\max}_{t,t'} - x_{t,t'} \geq \theta^{up} L_{tt'}$$ Up-ramping reserve

$$x_{t,t'} - x^{\max}_{t,t'} \geq \theta^{down} L_{tt'}$$ Down-ramping reserve

  - This is a (parametric) cost function approximation, parameterized by the ramping parameters θ .

Designing a policy

- We then have to tune the parameters of this policy in our *stochastic base model*.

$$\min_\pi E^\pi \left\{ \sum_{t=0}^{T} \gamma^t C\left(S_t, X^\pi(S_t \mid \theta)\right) \right\}$$

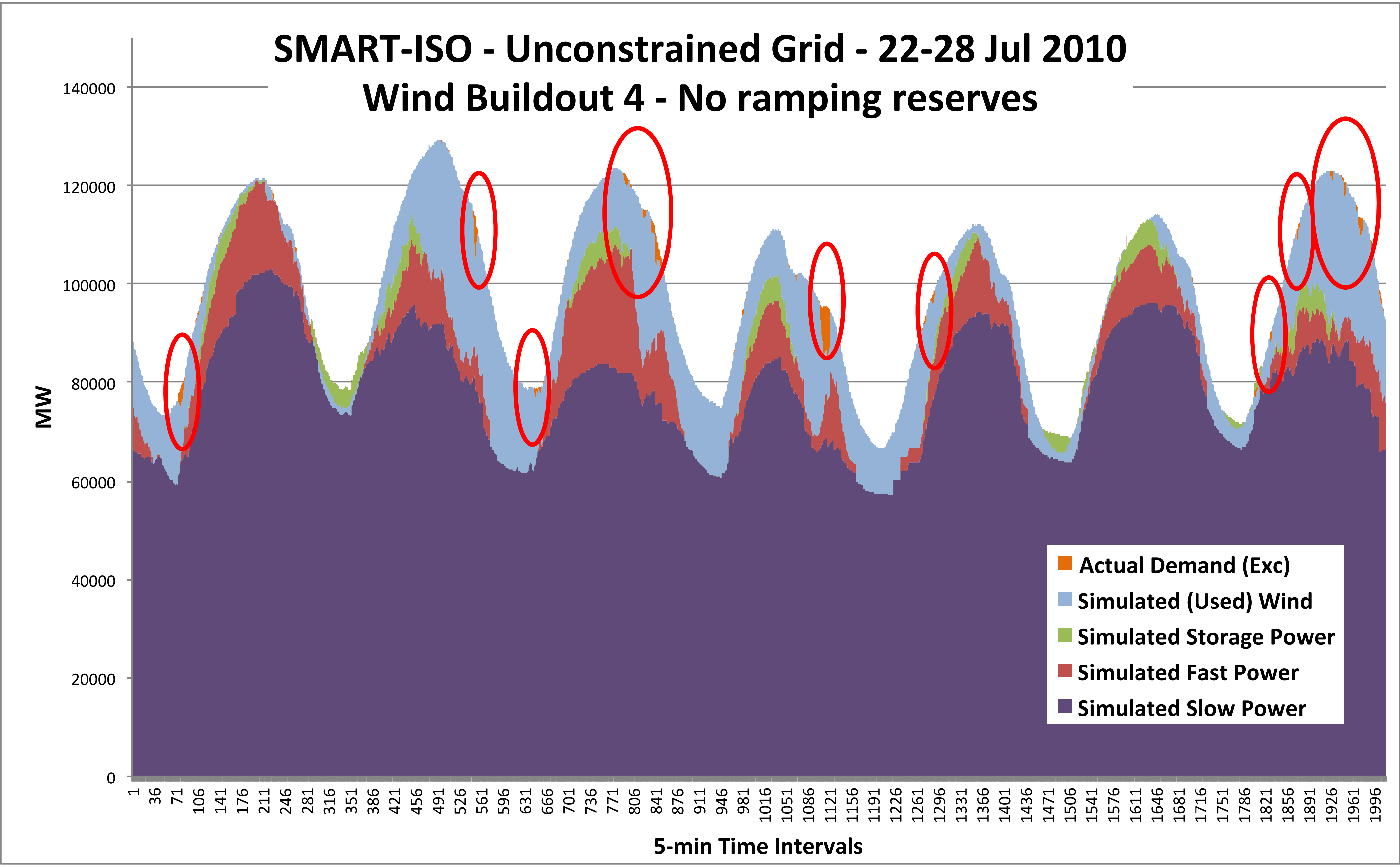
$\pi = \theta = \left(\theta^{up}, \theta^{down}\right)$

Robust CFA policy

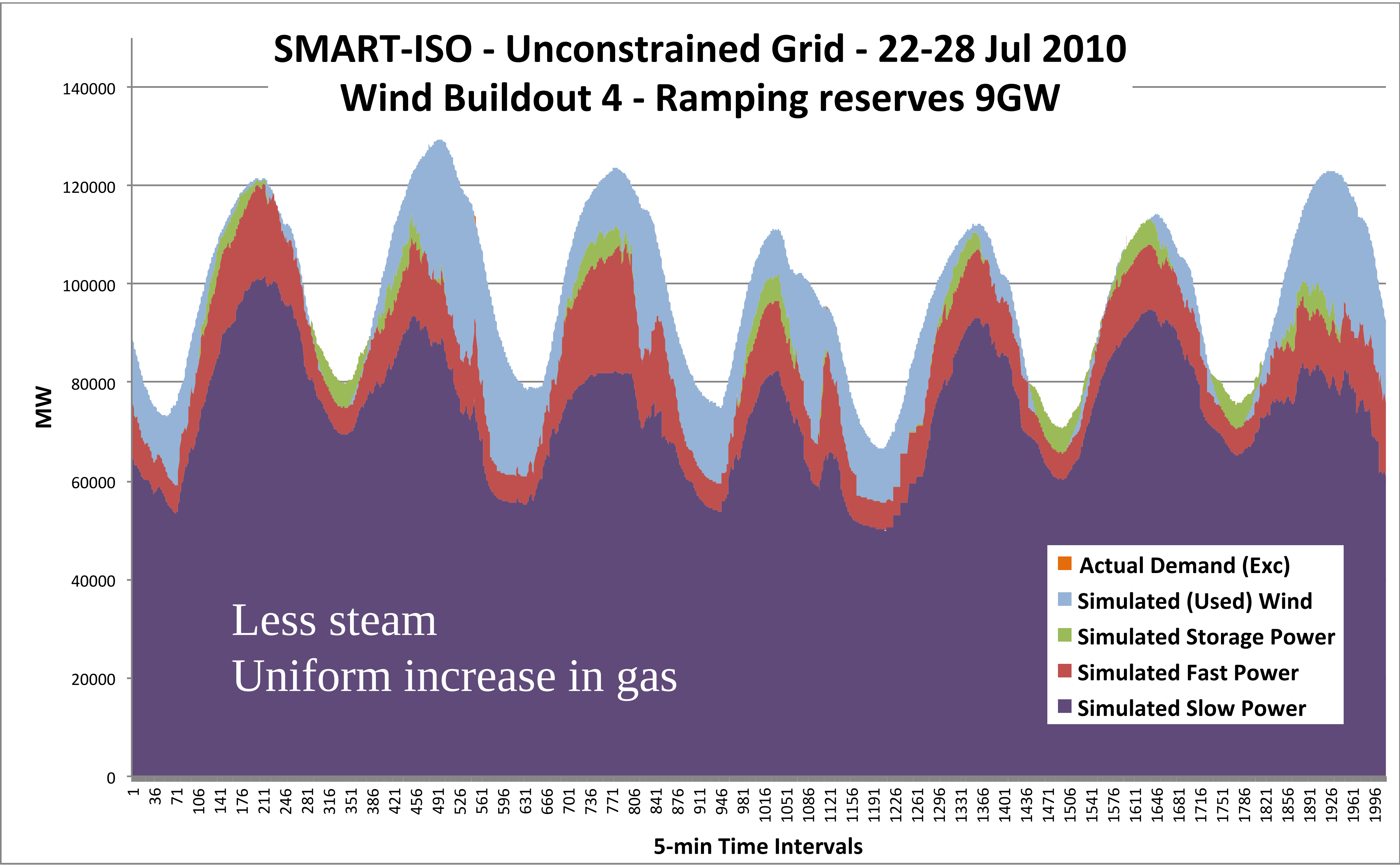
Stochastic base model

» The challenge now is to adaptively estimate the ramping constraints $\theta = \left(\theta^{up}, \theta^{down}\right)$.

SMART-ISO: Offshore wind study



SMART-ISO: Offshore wind study



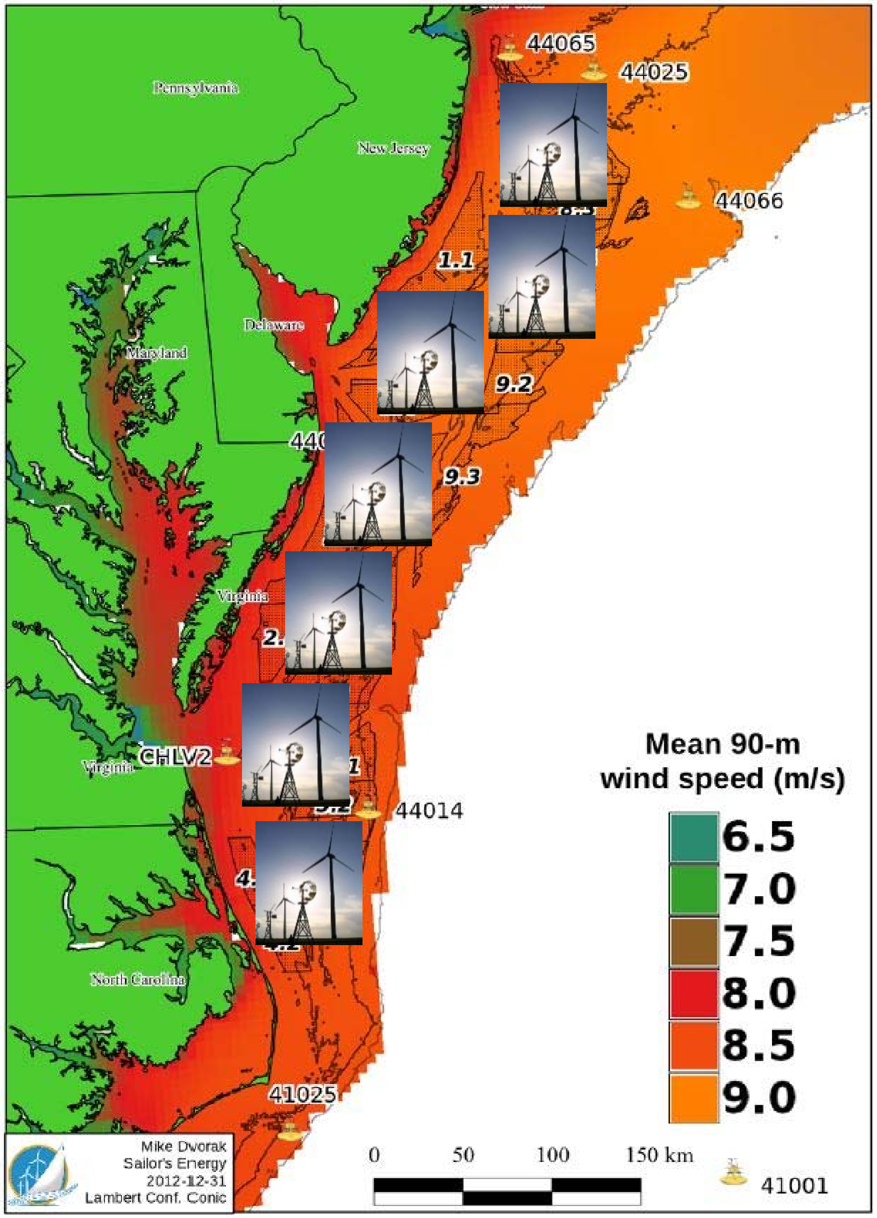
Lecture outline

- The PJM grid and planning process
- SMART-ISO – Model validation
- Modeling wind
    - Onshore error model
    - Offshore sample paths
- Designing a robust policy
- Experiments

SMART-ISO: Offshore wind study

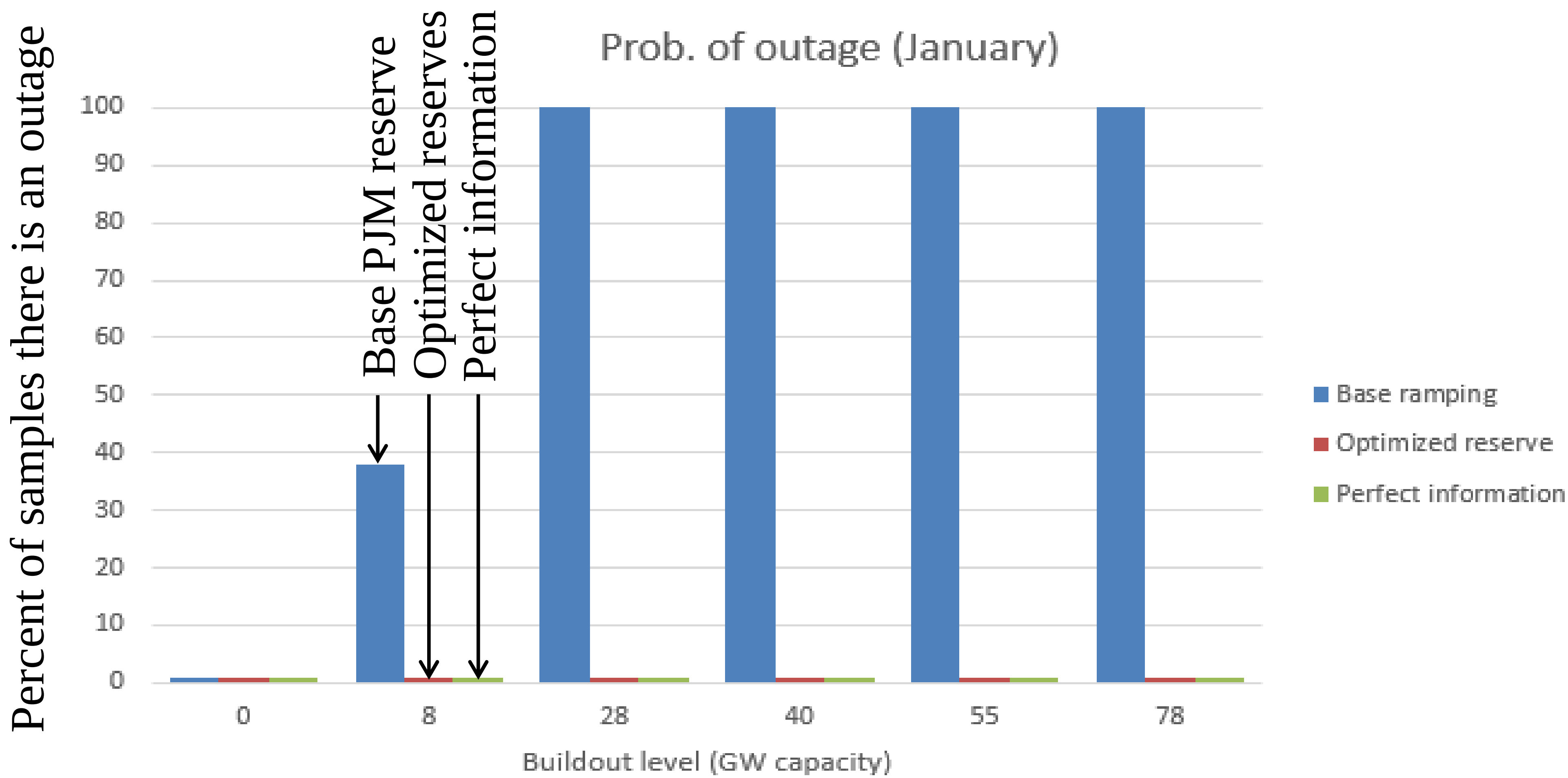
- Mid-Atlantic Offshore Wind Integration and Transmission Study (U. Delaware & partners, funded by DOE)

- 29 offshore sub-blocks in 5 build-out scenarios:
  - » 1: 8 GW
  - » 2: 28 GW
  - » 3: 40 GW
  - » 4: 55 GW
  - » 5: 78 GW



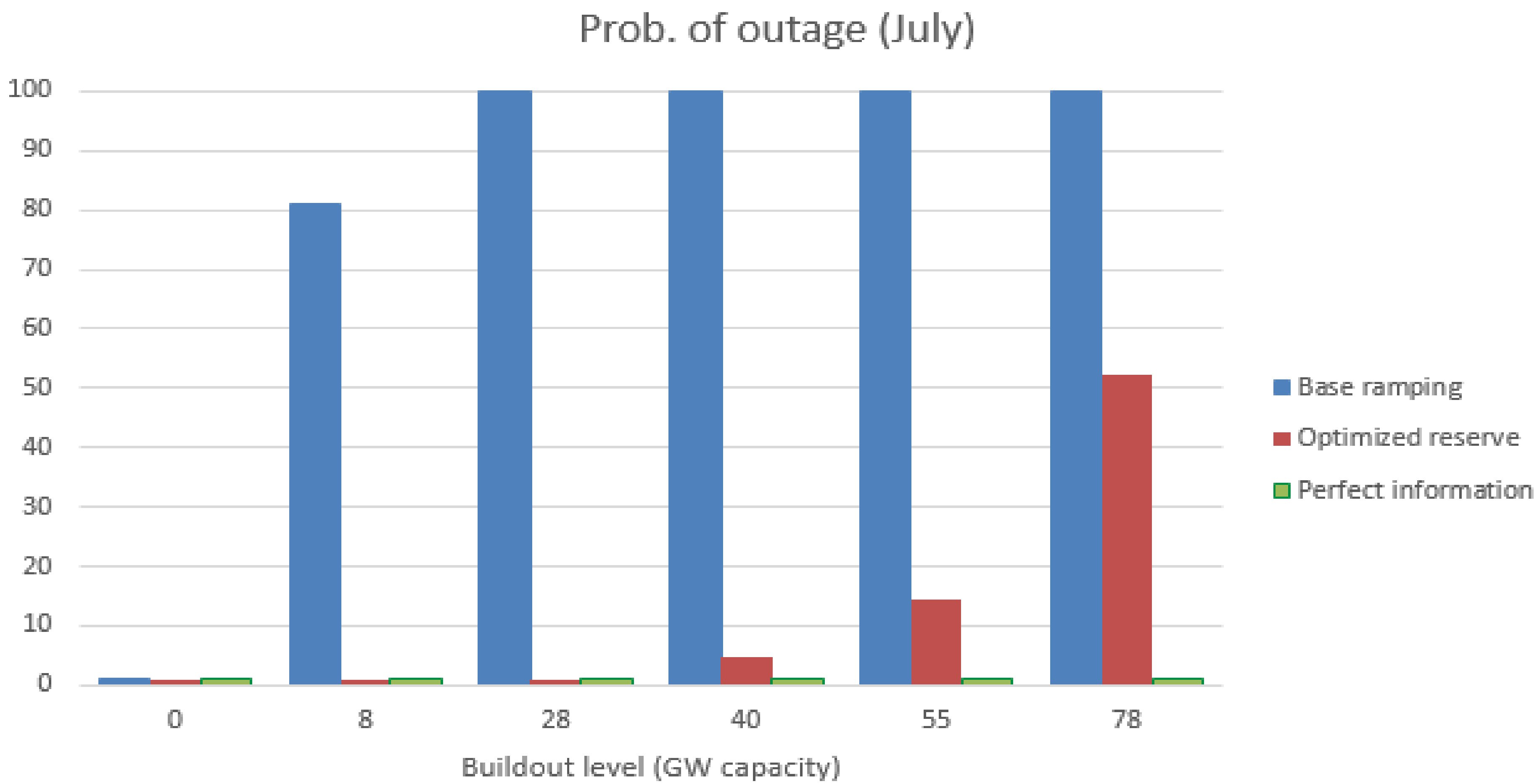
SMART-ISO: Offshore wind study

- Outage probabilities over 21 scenarios for January, April and October:



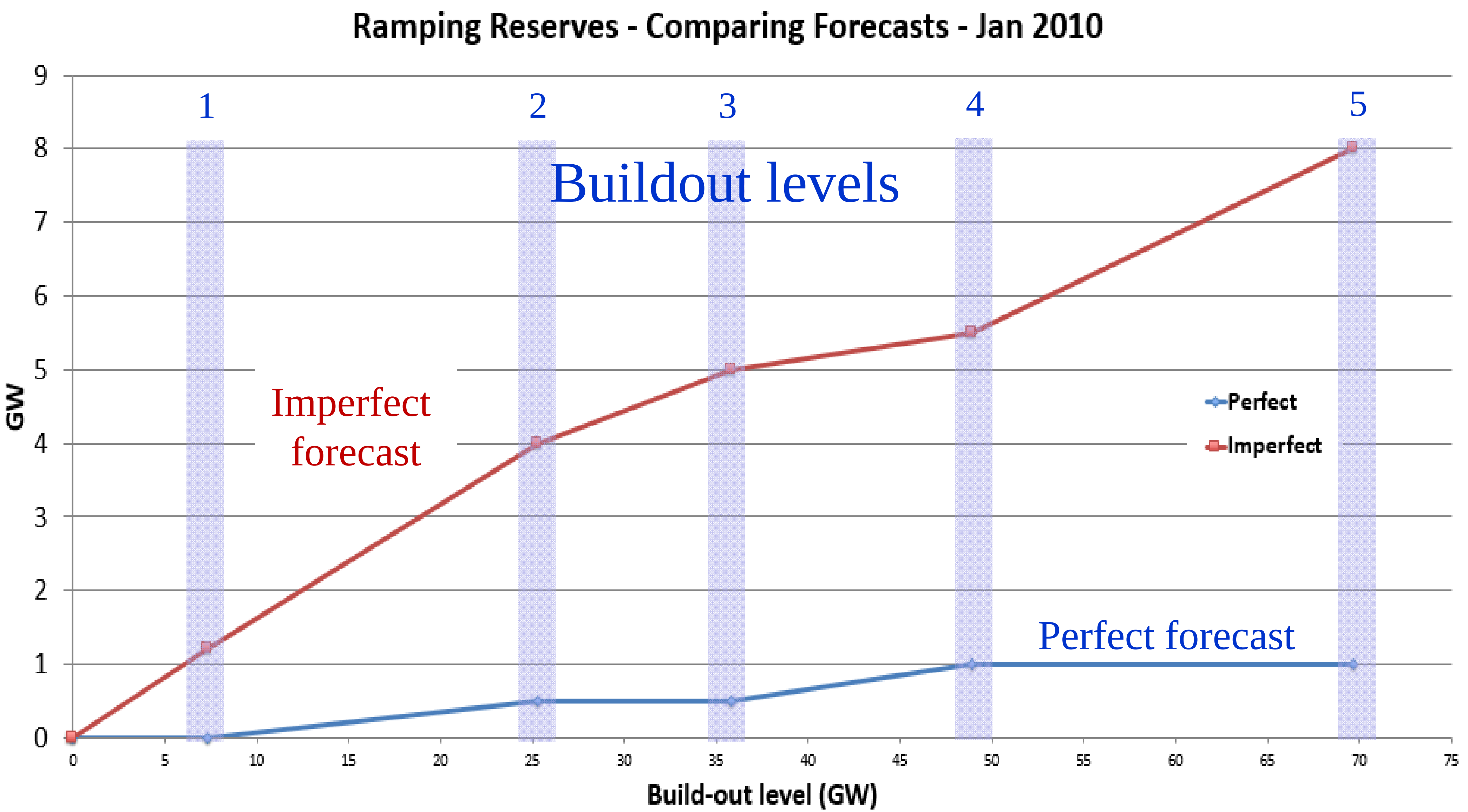
SMART-ISO: Offshore wind study

- ❑ Outage probabilities over 21 scenarios for July



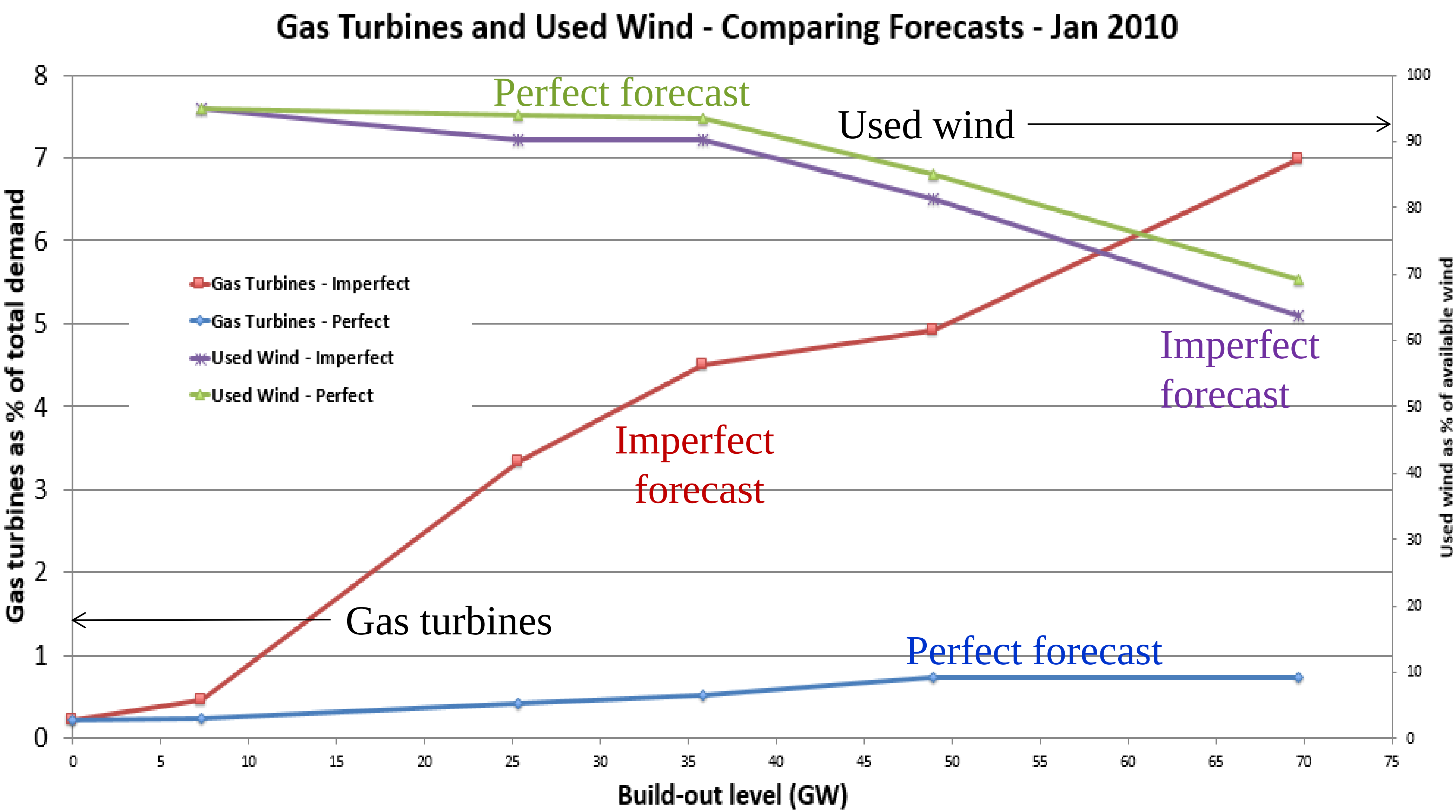
SMART-ISO: Offshore wind study

- January, 2010

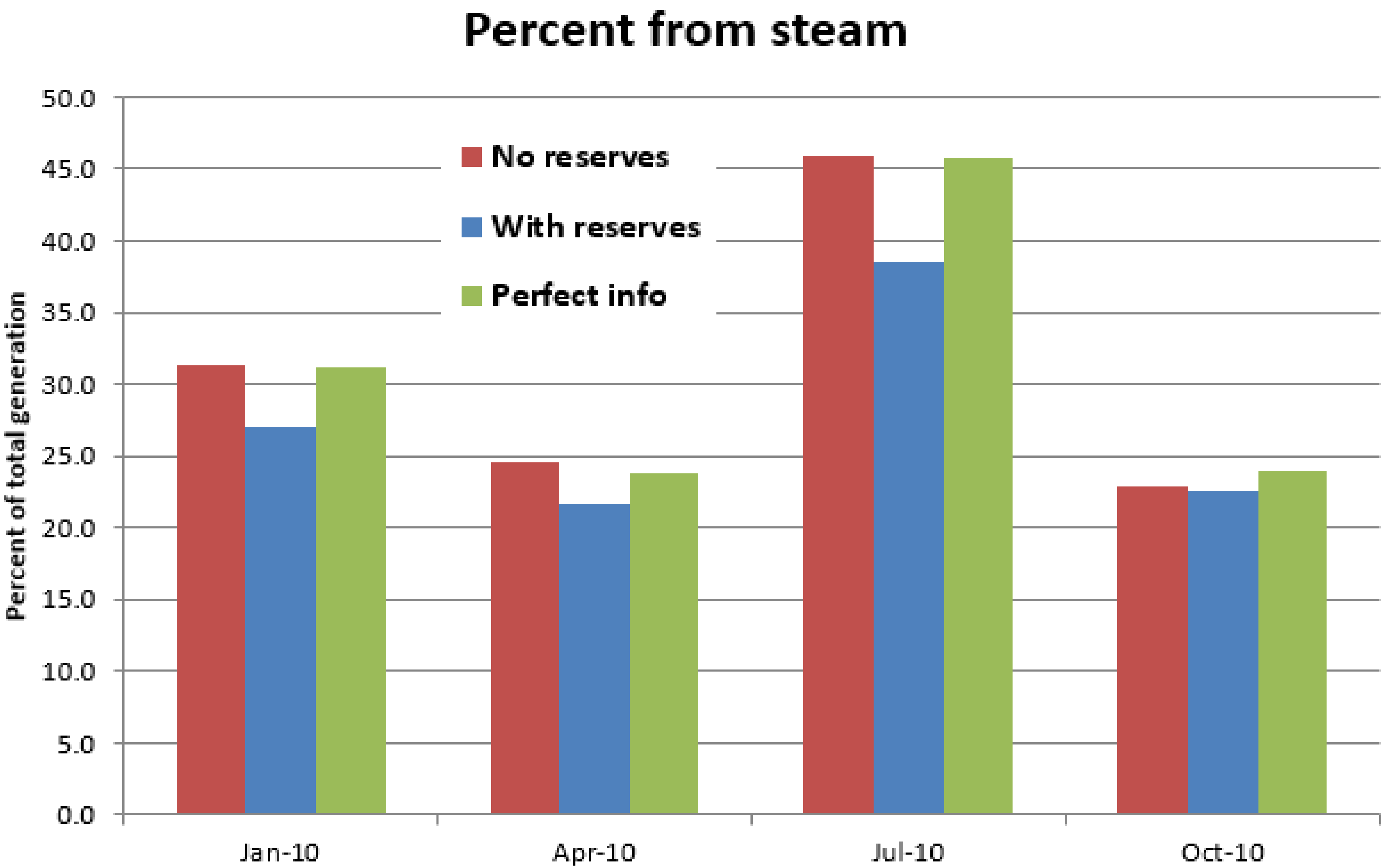


SMART-ISO: Offshore wind study

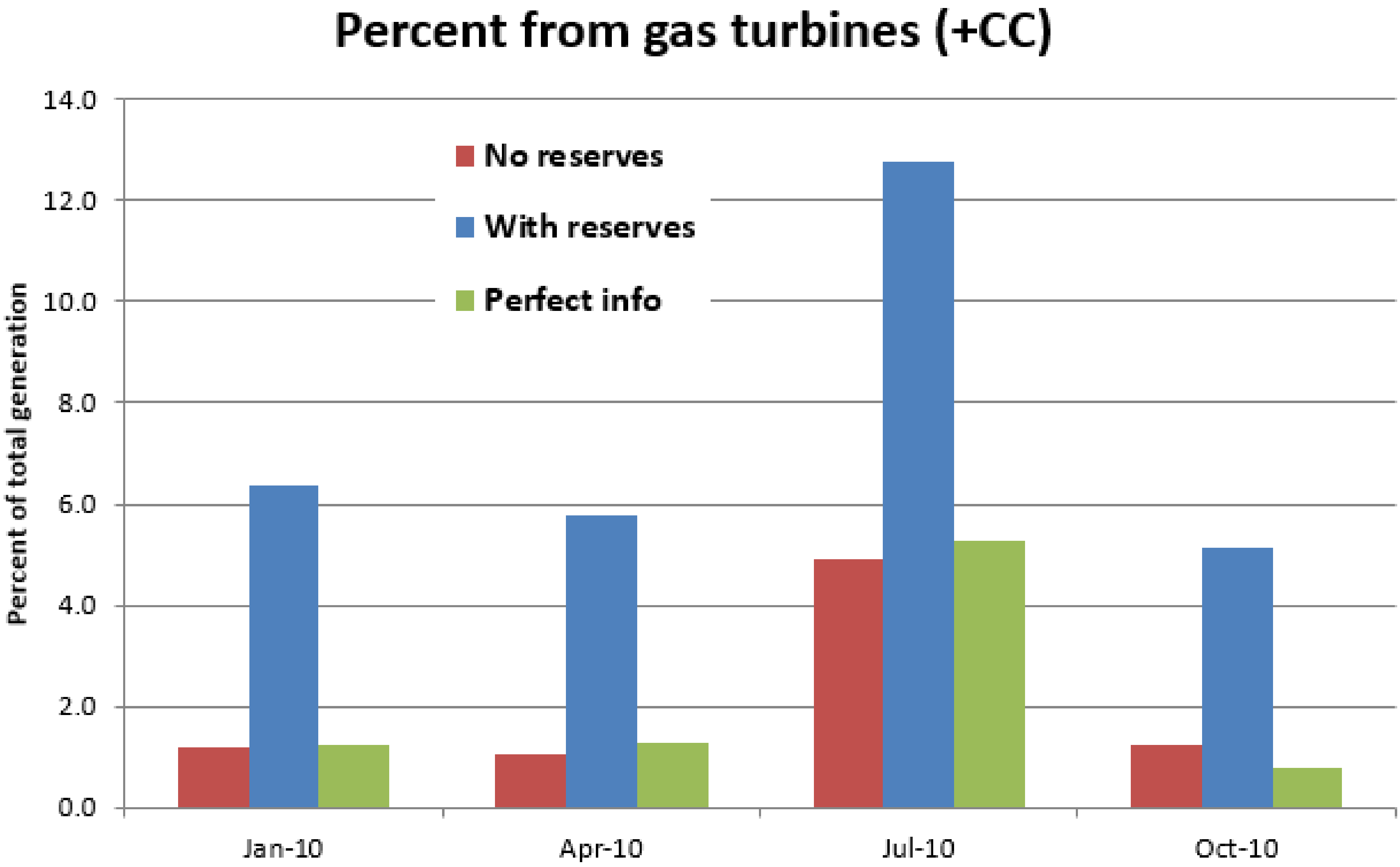
- January, 2010



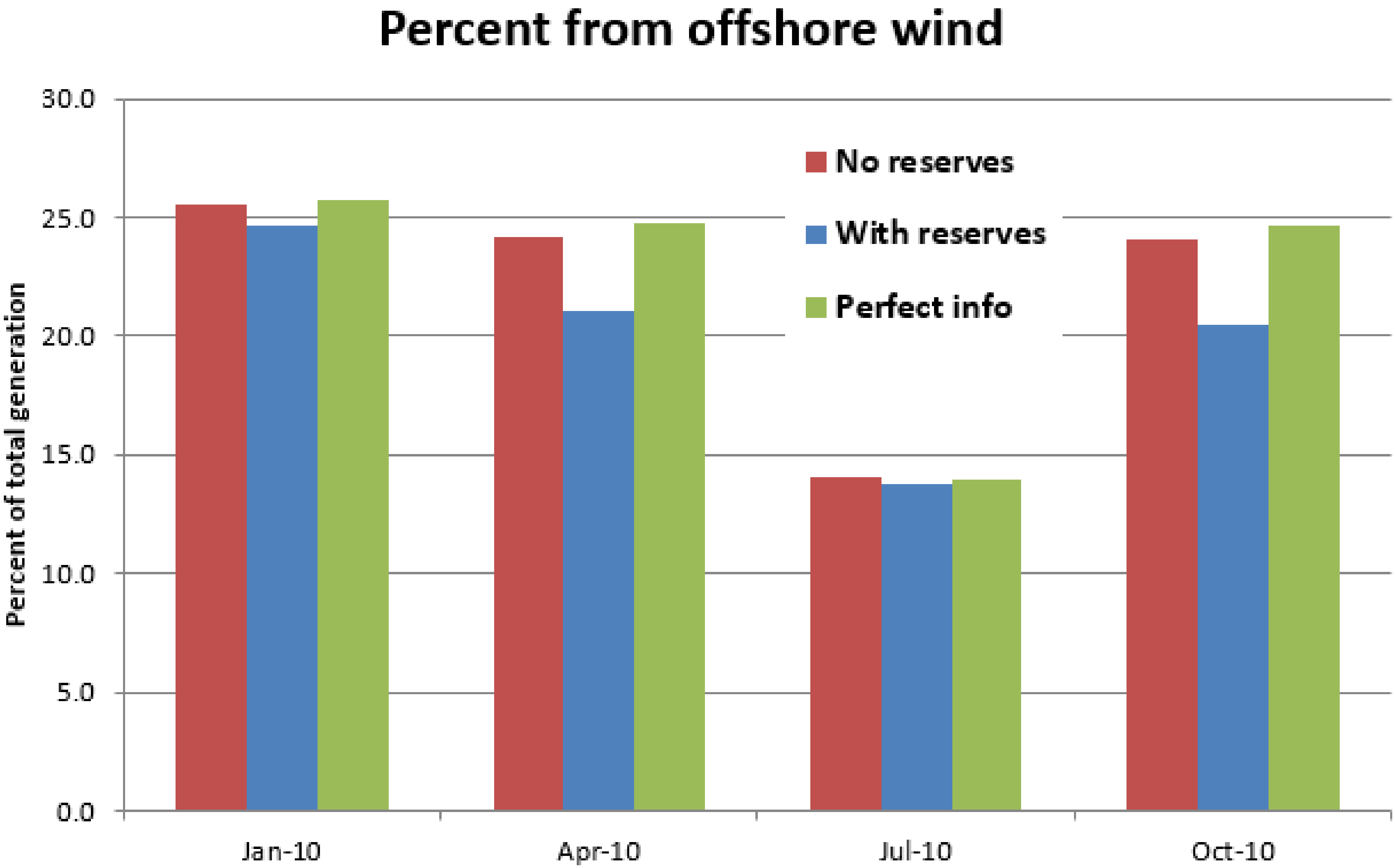
SMART-ISO: Results May 2014



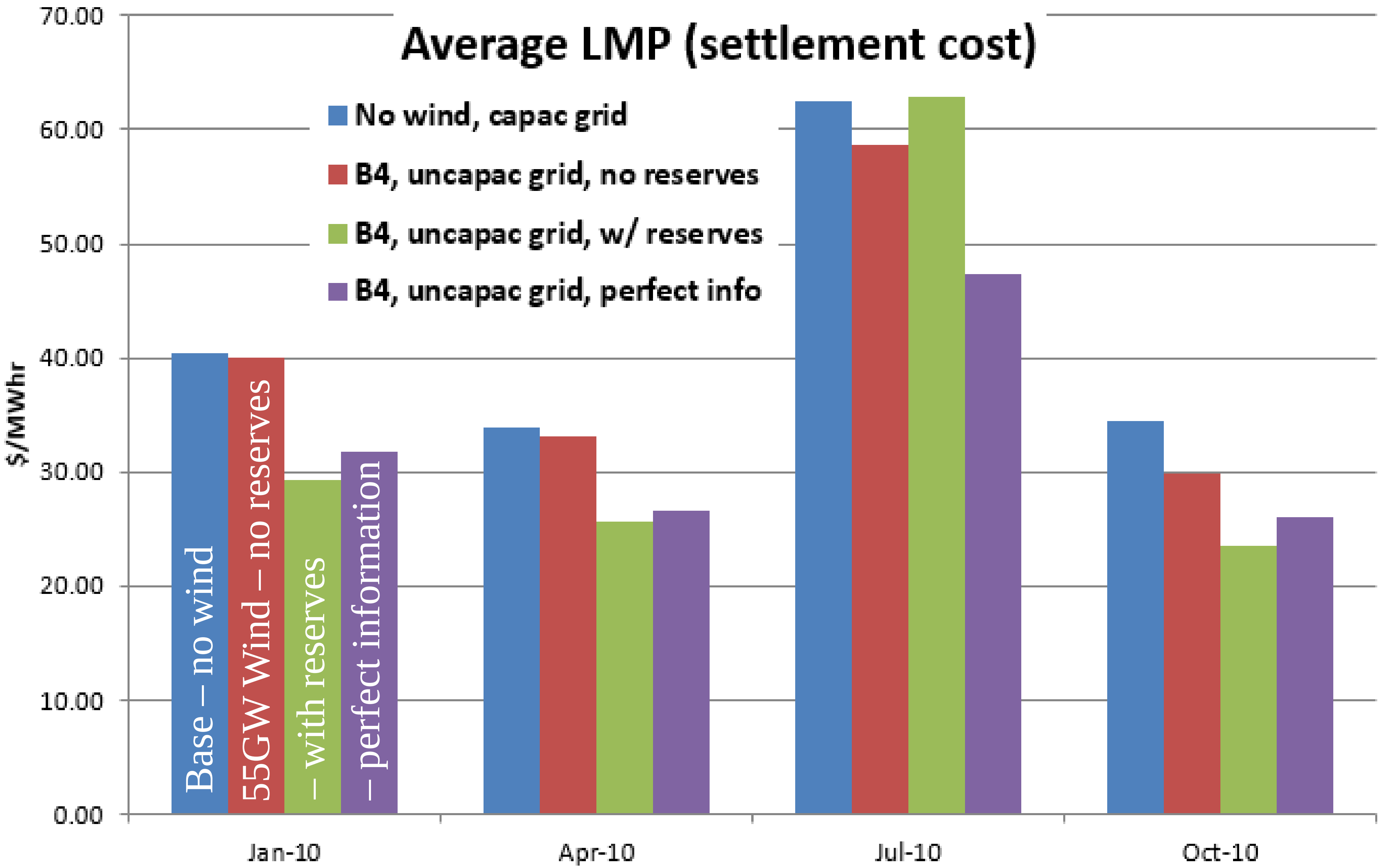
SMART-ISO: Results May 2014



SMART-ISO: Results May 2014



SMART-ISO: Offshore wind study



Observations

- Steps andceilings:
  - Grid capacity - The current grid does not have the capacity to handle significant levels of off-shore wind.
  - Reserve capacity - Uncertainty in forecasts requires significant levels of reserves, and increased use of gas turbines.
  - Faster planning – Transition IT-SCED to 10 or 15 minute updates; reduce the lag between run time and implementation.
  - Forecasting – Better day-ahead and intermediate forecasting.
  - Storage – Grid level battery storage can smooth both diurnal cycles as well as stochastic volatility.
  - Demand response – We can reduce the load on the network, but notification times are important.
  - Generator investments – More and faster-ramping generators.
  - Cross-ISO integration – Coordinate the entire eastern interconnect.