Estimating Reserve Costs for Wind Power

Andrew Mills

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Purpose of Presentation

- Provide conceptual overview of how system operators can manage increased variability and uncertainty due to wind
- Summarize simple methods for estimating impacts and costs of reserves
- Highlight important questions that should be the focus in more detailed studies

Presentation Outline

- Description of reserves and practices for procuring reserves
- Estimating the cost of holding and deploying reserves as a function of imbalances
- Estimating imbalances for the net load
- Balancing reserves estimates with increased wind and associated costs from literature

Resources that Can Provide Reserves

- **Spinning Resources:**
  - **Spare capacity on committed units that are operating at part-load**
  - **Portion of spinning resources can be dispatched by system operator, other portion is under automatic generation control (AGC)**
- **Standing Resources:**
  - **Plants that are not scheduled to be online, but can be started quickly (or are kept "hot" in a standby mode) in case additional energy is needed**
- **Availability of these resources to system operators:**
  - ***Active provision:* system operator schedules unit to ensure adequate reserves are available**
  - ***Inherent provision:* normal schedule may inherently leave room to maneuver dispatchable plants upward or downward**

Reasons to Procure Reserves

- *Contingency reserves:* maintained in case of emergency
  - Many system operators keep enough emergency reserves to cover the loss of the single largest contingency (loss of power plant or transmission line)
  - At least half of contingency reserves are typically from spinning resources
- *Balancing reserves:* deployed during normal operation in order to maintain balance between scheduled generation and load
  - Balance forecast errors and variations from flat schedules (*imbalances*)
  - Short-term imbalances must be met by spinning resources, but longer-term imbalances can be managed from be spinning or standing resources
  - Classifying imbalances as “Short-term” vs. “Long-term” depends on how fast standing resources can be available to meet imbalance

Increased variability and uncertainty

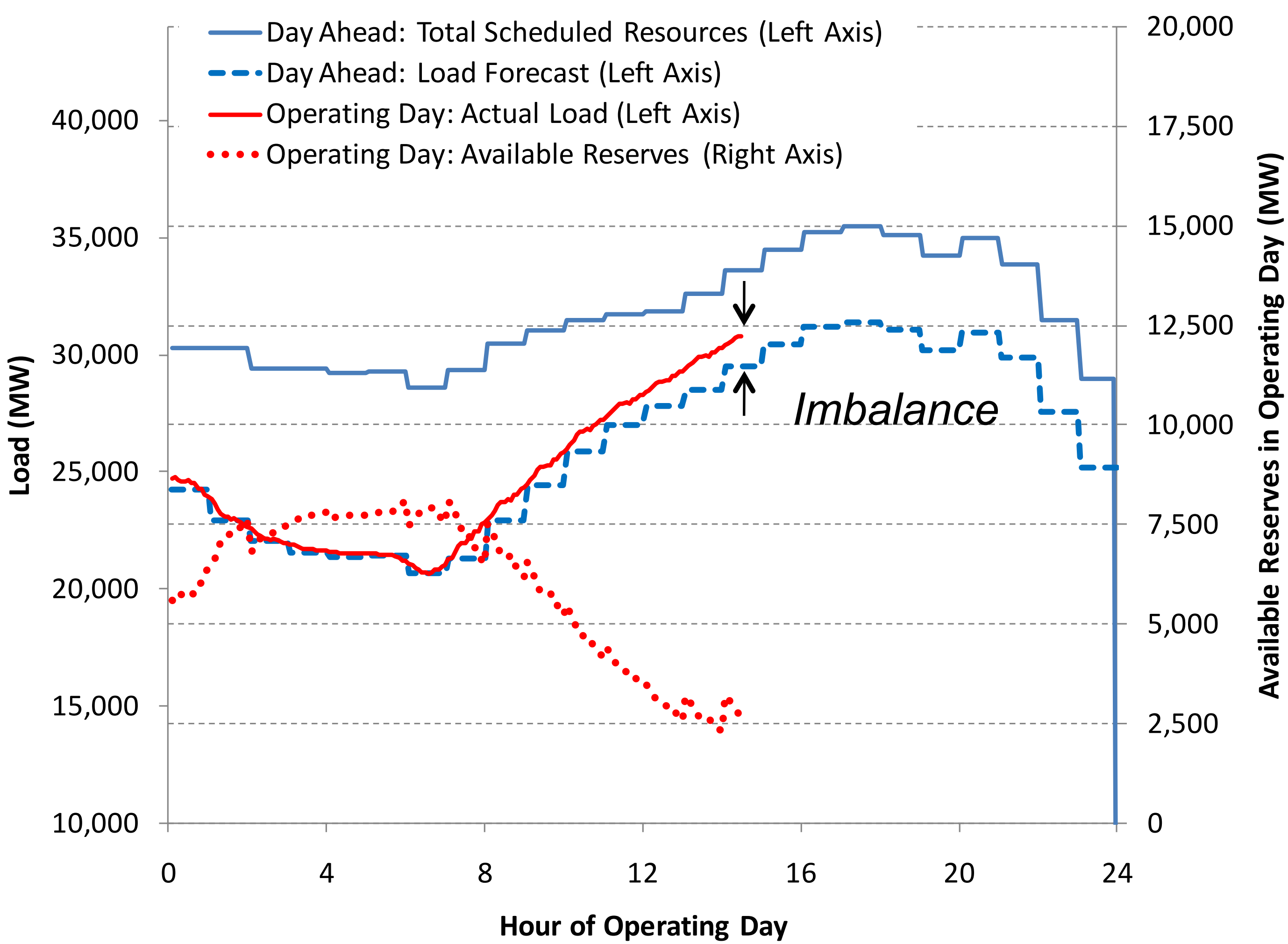
- Balancing reserves managed by system operator
  - Adequate balancing reserves ensure that contingency reserves are maintained during normal operation
- Increased variability and uncertainty will increase deployment of balancing reserves
  - Existing balancing reserve rules/practices may not be adequate with increasing wind
- Integration studies are used to quantify increase in balancing reserves and identify associated costs

NORMAL OPERATION: LOAD ONLY

Assumed Practices

- **Day-ahead load forecasts are used to create hourly generation and reserve schedules for the next operating day**
- **Balancing reserves can be *deployed* during the operating day to manage difference between day-ahead schedules and actual load**

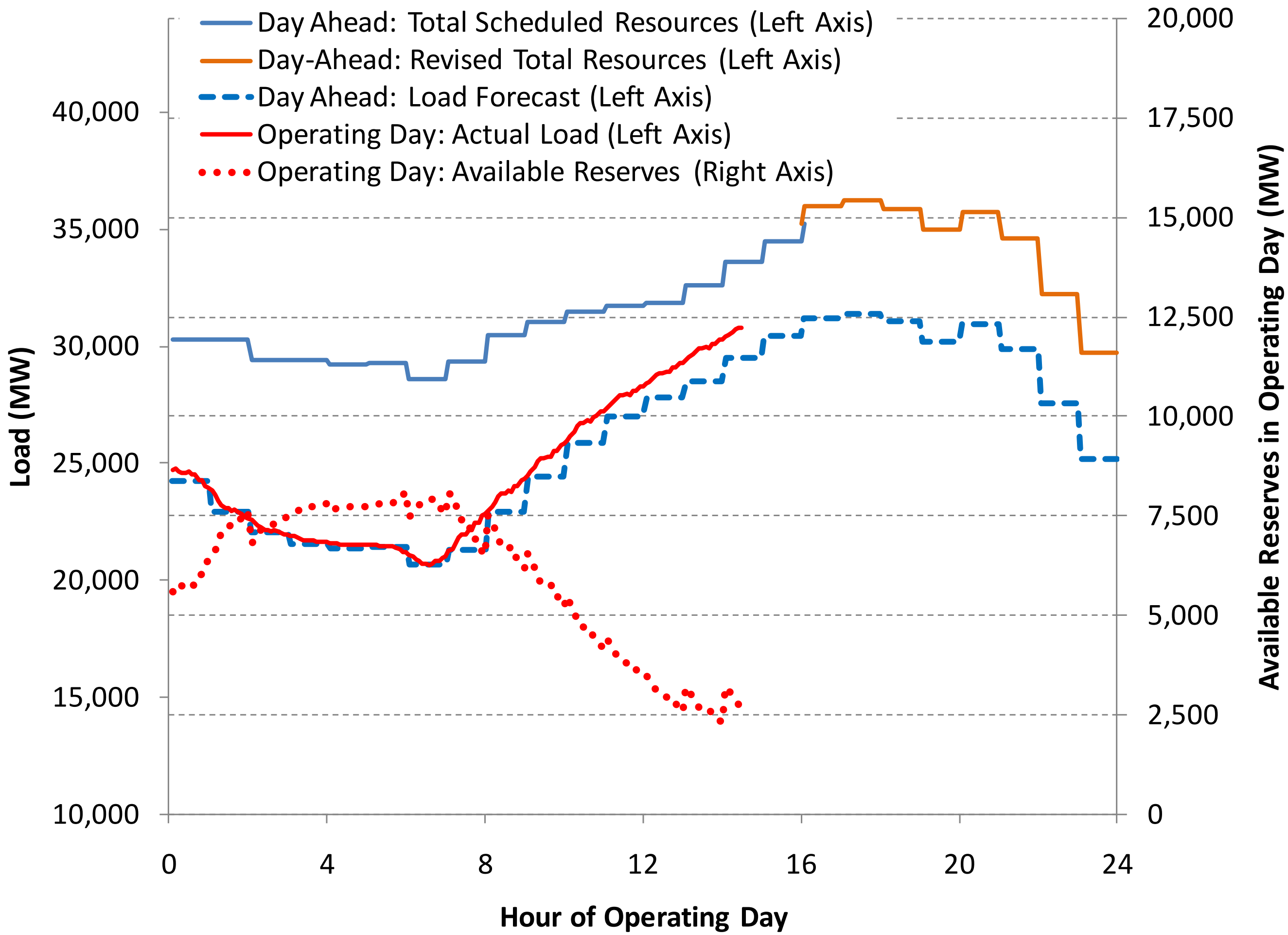
System Operation with Day Ahead Forecast



Assumed Reserve Rule:
Schedule 4% of peak load for day-ahead load forecast error and within-day variability and 2,500 MW for contingencies

System operator has deployed nearly all balancing reserves when pre-contingency reserve levels near 2,500 MW

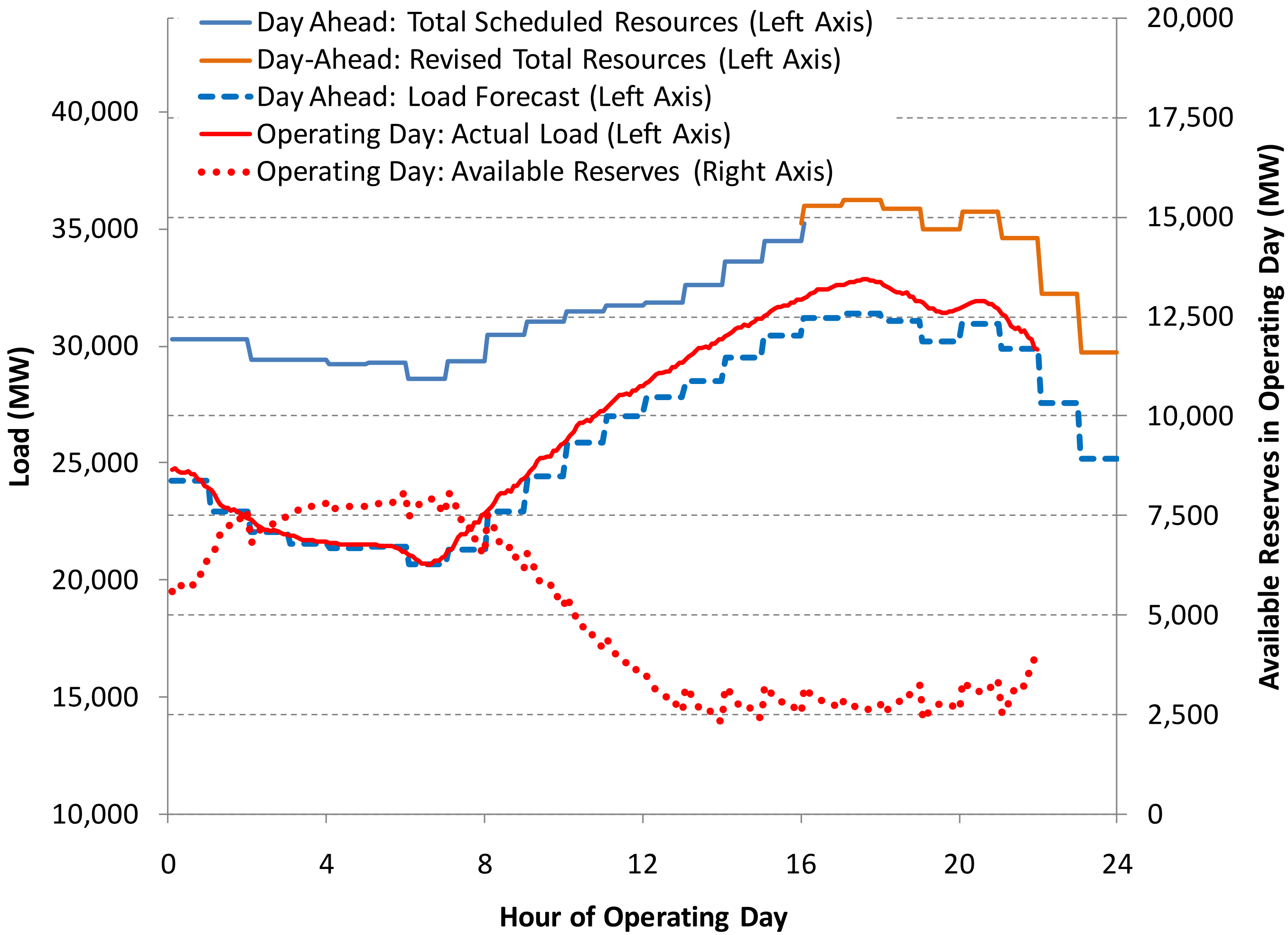
More Balancing Reserves are Required to Meet Imbalances



If it looks like balancing reserves would be depleted, then increase the reserves by scheduling more resources in the day ahead (increase to 6% of peak load).

In this case the reserves are only short during the afternoon peak load, the morning has sufficient inherent reserves

Balancing Reserves are Now Adequate



Section Summary

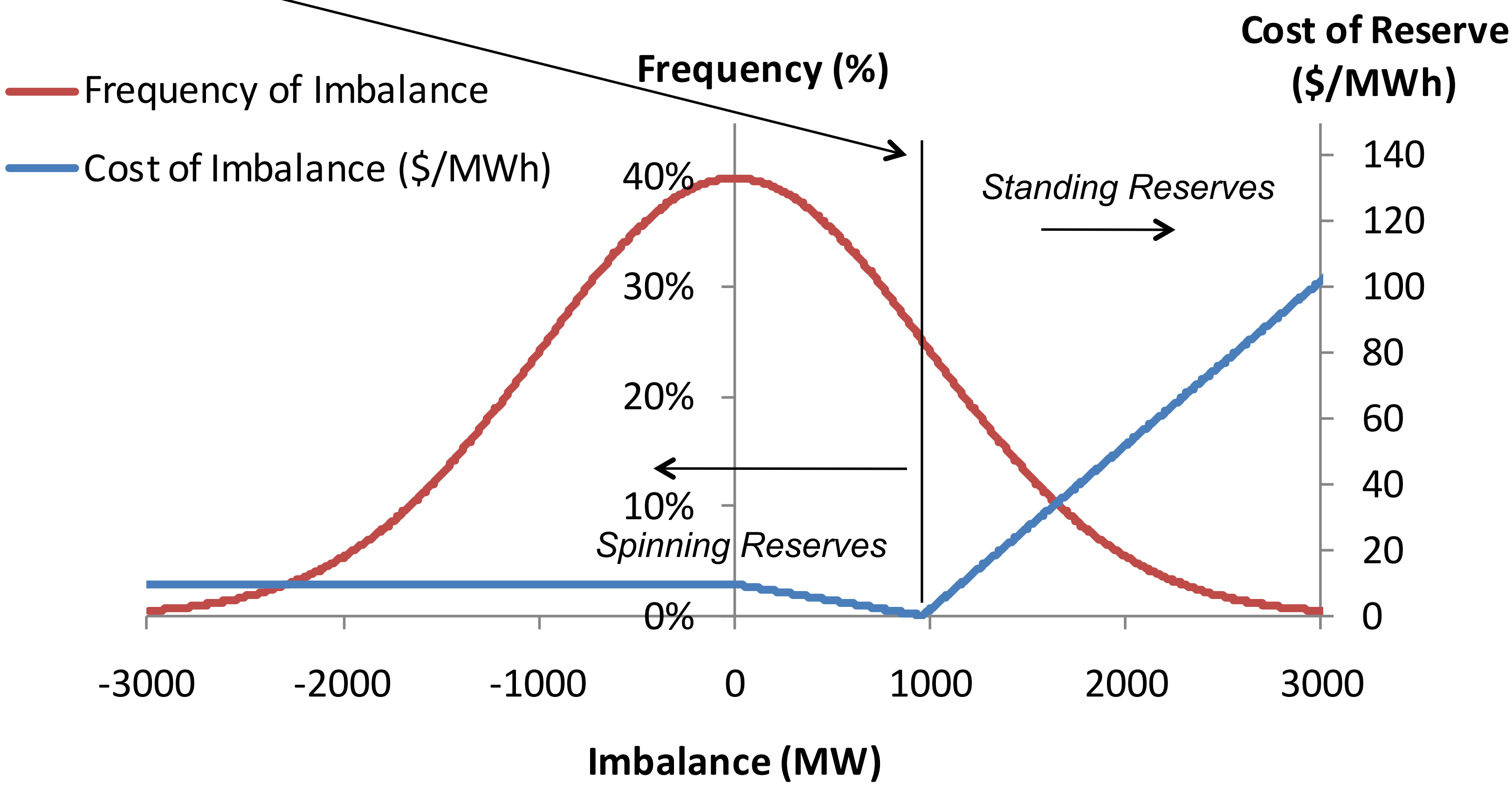
- **Generation resources are scheduled to meet the expected load**
- **System operators keep resources in reserve for unexpected events, or *contingencies***
- **Additional *balancing reserves* are used by the system operator to maintain a balance between load and generation, including imbalance caused by normal load forecasting errors and within-schedule variability**
- ***Balancing reserves* must be adequate so the system operator can maintain contingency reserves during normal operation**

COST OF HOLDING AND DEPLOYING BALANCING RESERVES

Simplified Cost of Holding and Deploying Reserves (Black and Strbac, 2007)

$$\text{Spinning Reserve (MW)} = \lambda\sigma$$

σ = Standard deviation of imbalances, MW (1000 MW in this case)
λ = Number of σ met with spinning reserve



Balancing Reserve Costs

- **For imbalances < 0:**
  - **On-line units are part-loaded or backed down from optimal set point (spinning resources)**
    - c_f = fuel consumption cost of on-line unit at *full* load ($/MWh)
    - c_p = fuel consumption cost of on-line unit at *part* load ($/MWh)
  - **Balancing reserve costs are associated with lower efficiency of plants operated at part load:**

$$\text{holding cost } (\$/\text{h}) = (c_p - c_f)\,\lambda\sigma$$

Balancing Reserve Costs

- **For imbalances > 0 but less than $\lambda\sigma$:**
  - **Spinning resources are deployed**
  - **Plants that were providing spinning resources now operate more efficiently and balancing reserve costs are reduced**
    - r_i= magnitude of imbalance during particular instance, *i*

$$\text{spinning cost (\$/h)} = (c_p - c_f)\lambda\sigma + (c_f - c_p)r_i$$

Balancing Reserve Costs

- **For imbalances > $\lambda\sigma$:**
  - **Standing reserves are deployed.**
  - **The cost of deploying standing reserves is based on the higher fuel cost of the standing reserves relative to the plant that would otherwise be scheduled.**
    - c_o= fuel consumption cost of deploying standing unit ($/MWh)

$$\text{standing cost}(\$/\text{h}) = (c_f - c_o)\lambda\sigma + (c_o - c_f)r_i$$

Balancing Reserve Costs

- **Balancing reserve costs are minimized when inefficiency of part-loading on-line resources are balanced with high cost of deploying standing resources**
- **The fraction of the standard deviation of imbalances that should be met with spinning resources (λ) is found as:**

$$\lambda = \Phi^{-1}(p)$$

$$p = (c_o - c_f)/(c_p + c_o - 2c_f)$$

Where $\Phi^{-1}(p)$ is the inverse cumulative standard normal distribution

Simple Numerical Example

- Cost of fuel from fully loaded on-line plant:
  - c_f = \$50/MWh
- Cost of fuel from part-loaded on-line plant:
  - c_p = \$60/MWh
- Cost of deploying standing plant:
  - c_o = \$100/MWh

p = (\$100/MWh - \$50/MWh)/ (\$60/MWh + \$100/MWh - 2*\$50/MWh) = 0.833

$\lambda = \Phi^{-1}(0.833)$ = NORMSINV(0.833) = 0.97

If standard deviation of imbalances are 1000 MW, then this result shows you should schedule 970 MW of spinning reserves, and meet rest of imbalances by deploying standing reserves.

Comparison to Cost of Existing Reserves in China

- System operators in dispatch centers schedule operating reserves for contingencies and for balancing load
- Compare costs of balancing reserves for load calculated by Black & Strbac (2007) method to cost of existing balancing reserves in China
- Method can then be expanded to cover imbalances in the *net load* due to both load and wind
  - Following section details approach for expanding analysis to include wind

OPERATION WITH INCREASED DAY AHEAD IMBALANCES

Balancing Reserves are Based on the Estimated Imbalances

- System operator only needs to follow the *net load*
  - Net load = Load – Wind Generation
  - *Unnecessary, and potentially costly to balance wind alone*
- Estimating imbalances needs estimate of day-ahead net load forecasts and actual net load (load – wind generation)
- Imbalance is difference between day-ahead schedule to meet expected net load and actual minute by minute net load

Statistical Methods to Estimate Imbalances of the Net Load

- If time series of net load imbalance is not available, statistical approximations can be used:
  - Assume load and wind imbalances are uncorrelated
  - Standard deviation of net load imbalances (σ_N) can then be calculated from an estimate of the standard deviation of the imbalances of the each the load (σ_L) and the aggregate of all wind plants (σ_W)

$$\sigma_N = \sqrt{\sigma_L^2 + \sigma_W^2}$$

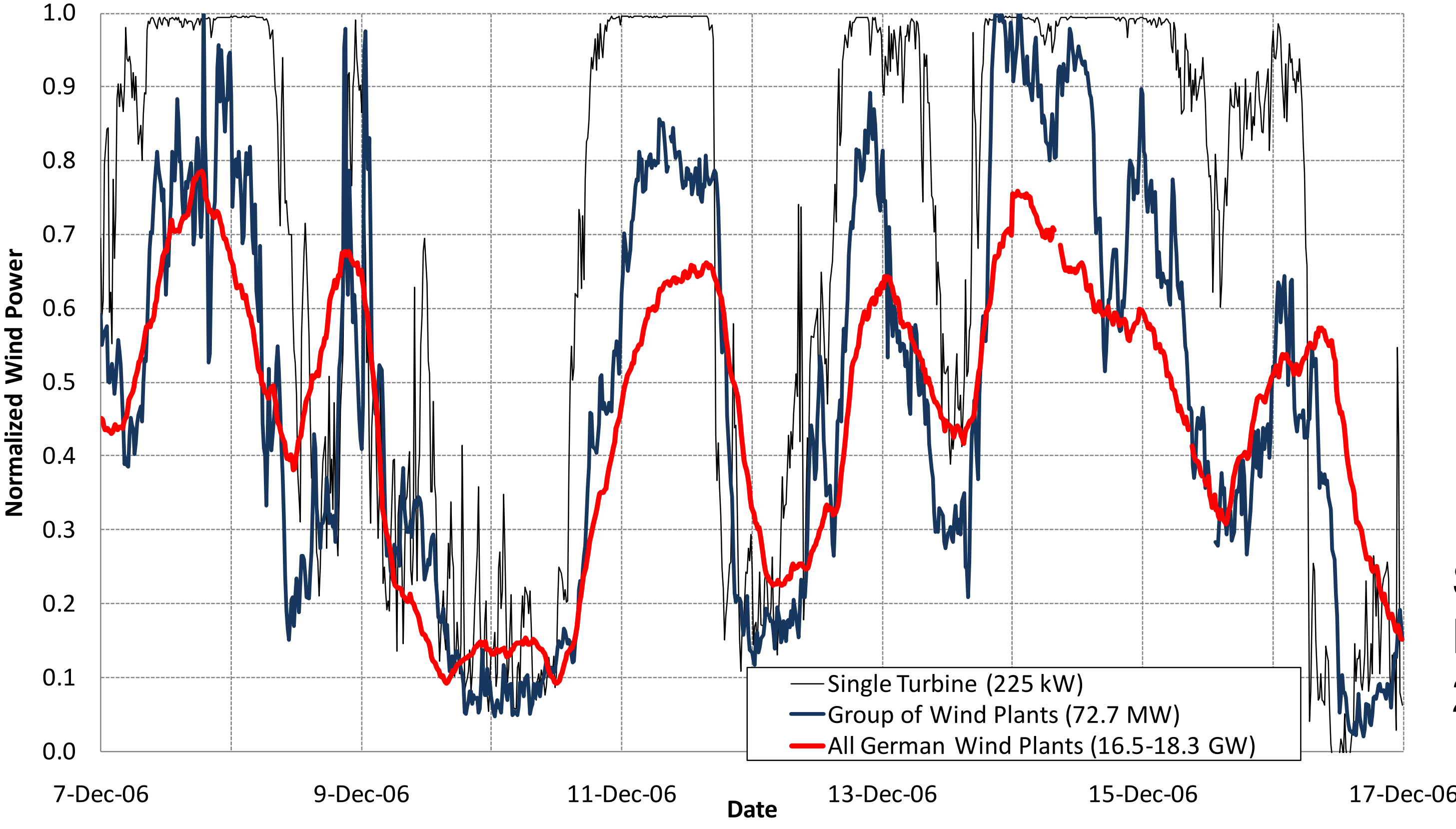
Imbalances of Load

- **Load imbalances are managed by a balancing authority**
  - **Does within-day balancing of load occur at the provincial or regional level? If so, look at balancing reserves they currently use for load**
- **Say balancing authorities currently carry about 6% of peak load as balancing reserves for worst load imbalances, then estimate standard deviation of day-ahead load imbalances as:**

$$3\sigma_L = 6\% * \text{peak load} \Rightarrow \sigma_L = 2\% * \text{peak load}$$

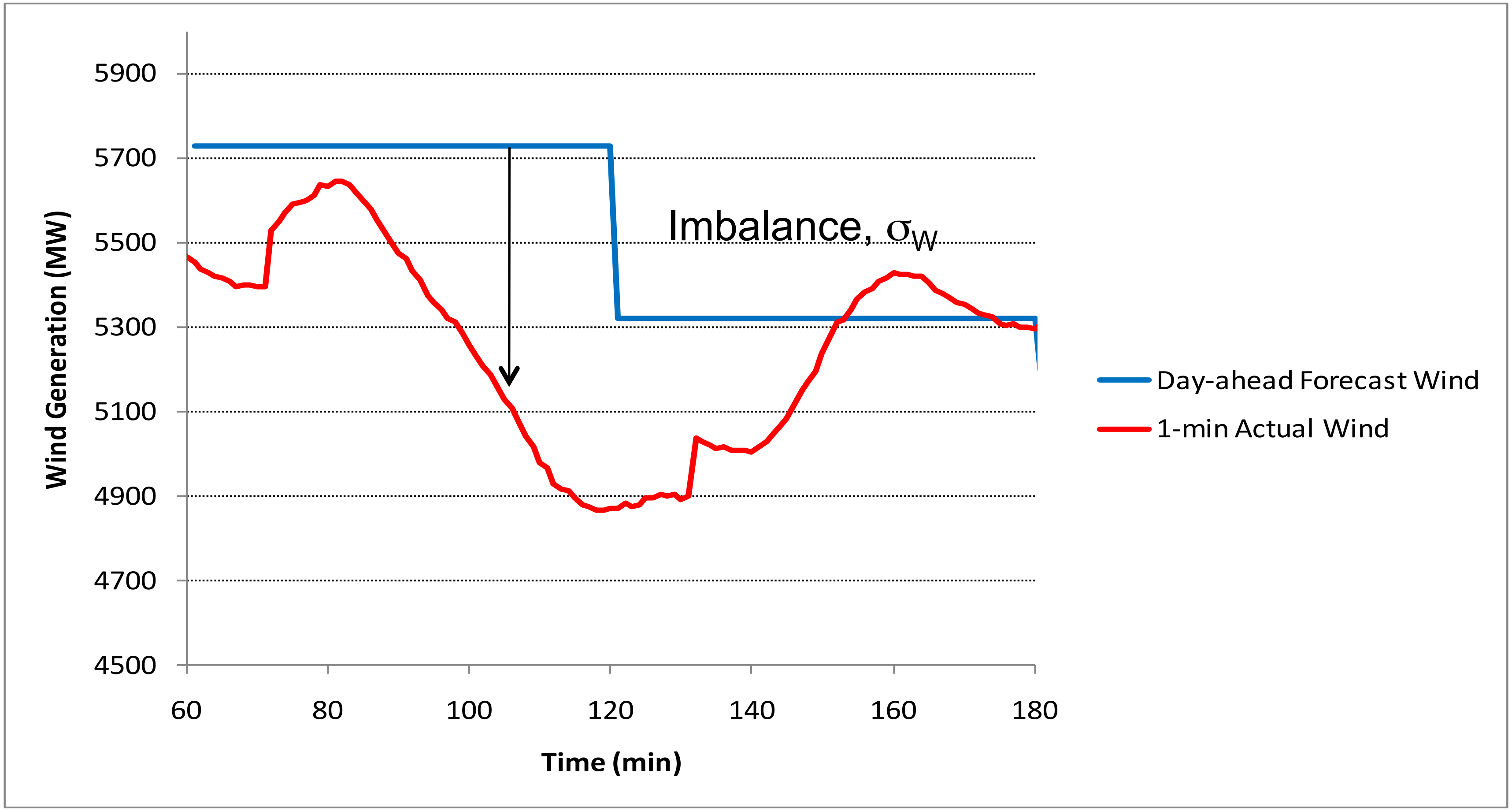
Imbalances from Wind

- **Balancing authority does not balance each individual wind plant**
- **Aggregating the output of several individual wind plants will substantially smooth the variability and uncertainty of the wind output (particularly over shorter time scales)**



Source: Holttinen et al. 2009

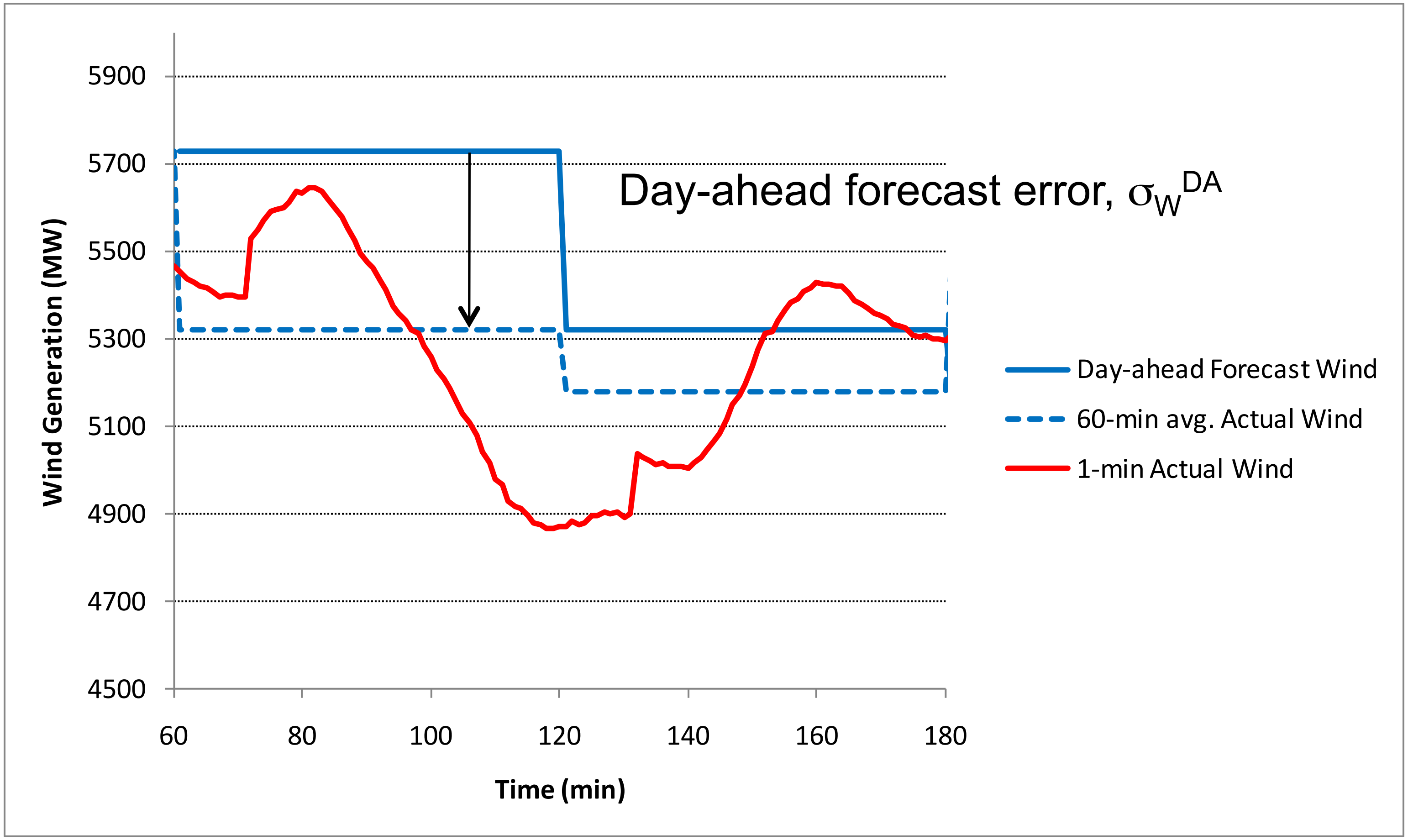
Imbalance from day-ahead schedule



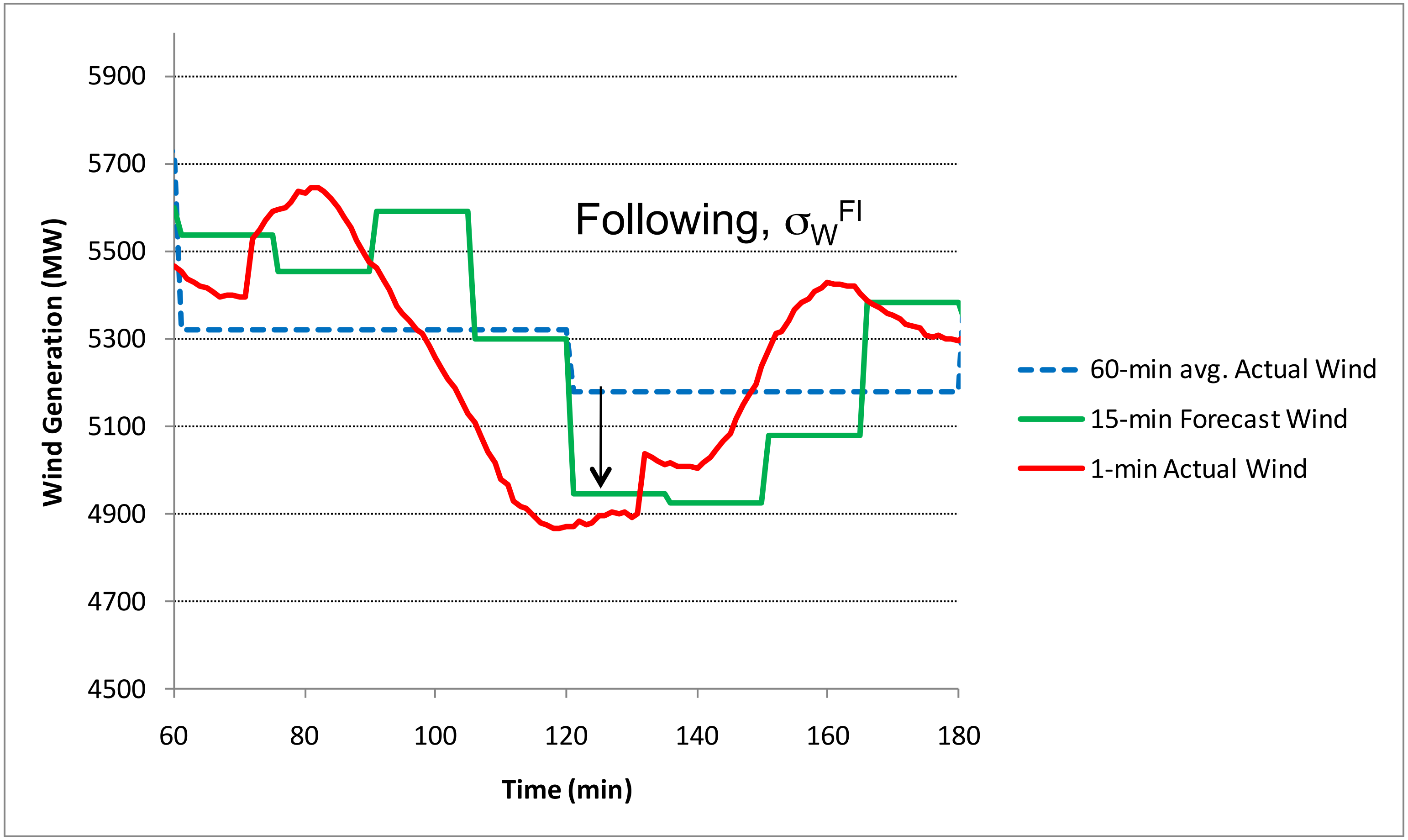
Imbalance from day-ahead schedule

- **Estimating standard deviation of wind imbalances requires:**
  - **Day-ahead wind schedules for aggregate of all wind plants in the balancing area**
  - **Minute-by-minute actual wind generation for all wind plants in the balancing area**
- **If that is not available, then statistical methods can again be used to break the wind imbalances into components that can be estimated**
  - **Day-ahead forecast error component**
  - **Following component**
  - **Regulation component (short-term forecast and variability)**

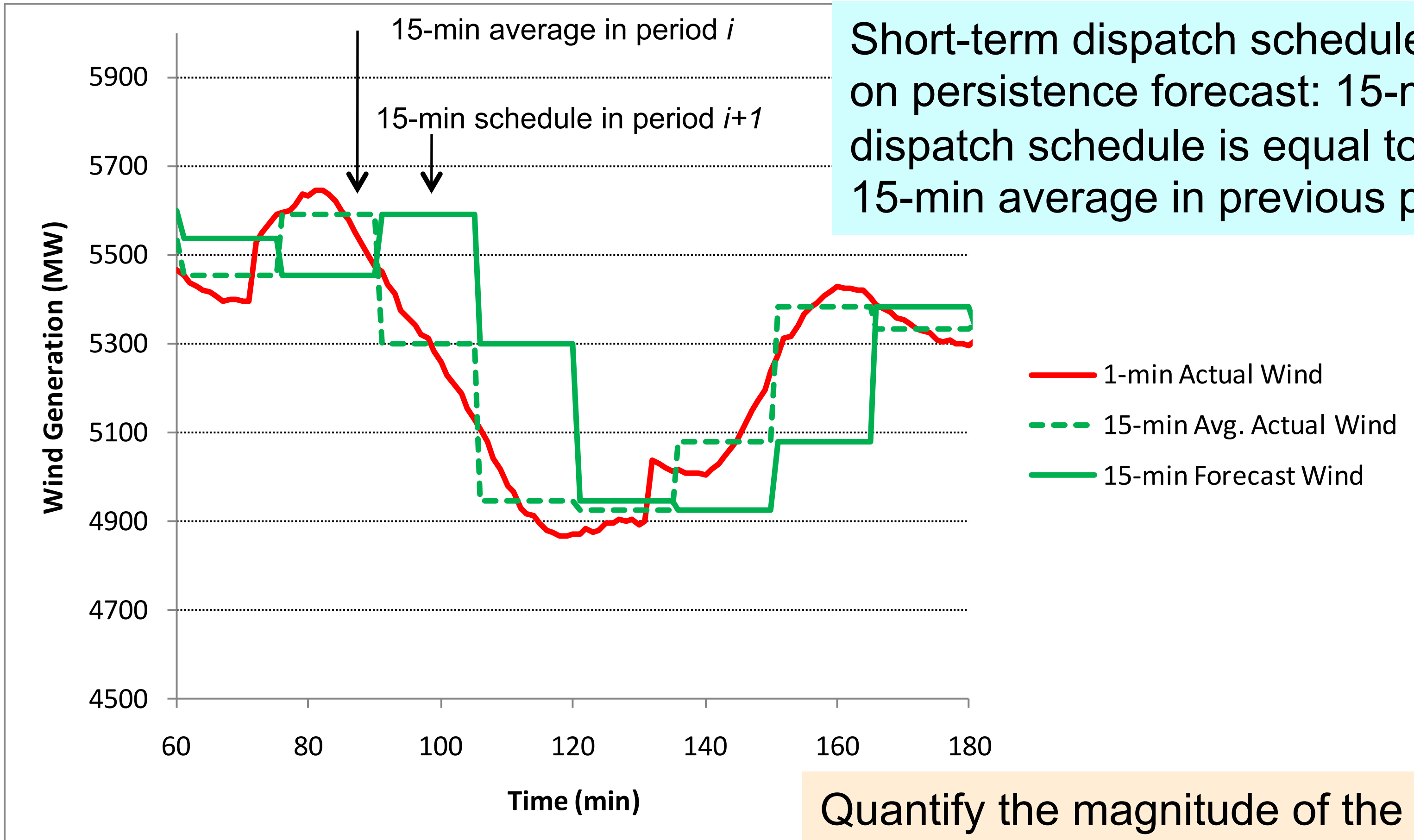
Imbalance: day-ahead forecast error component



Imbalance: Following Component



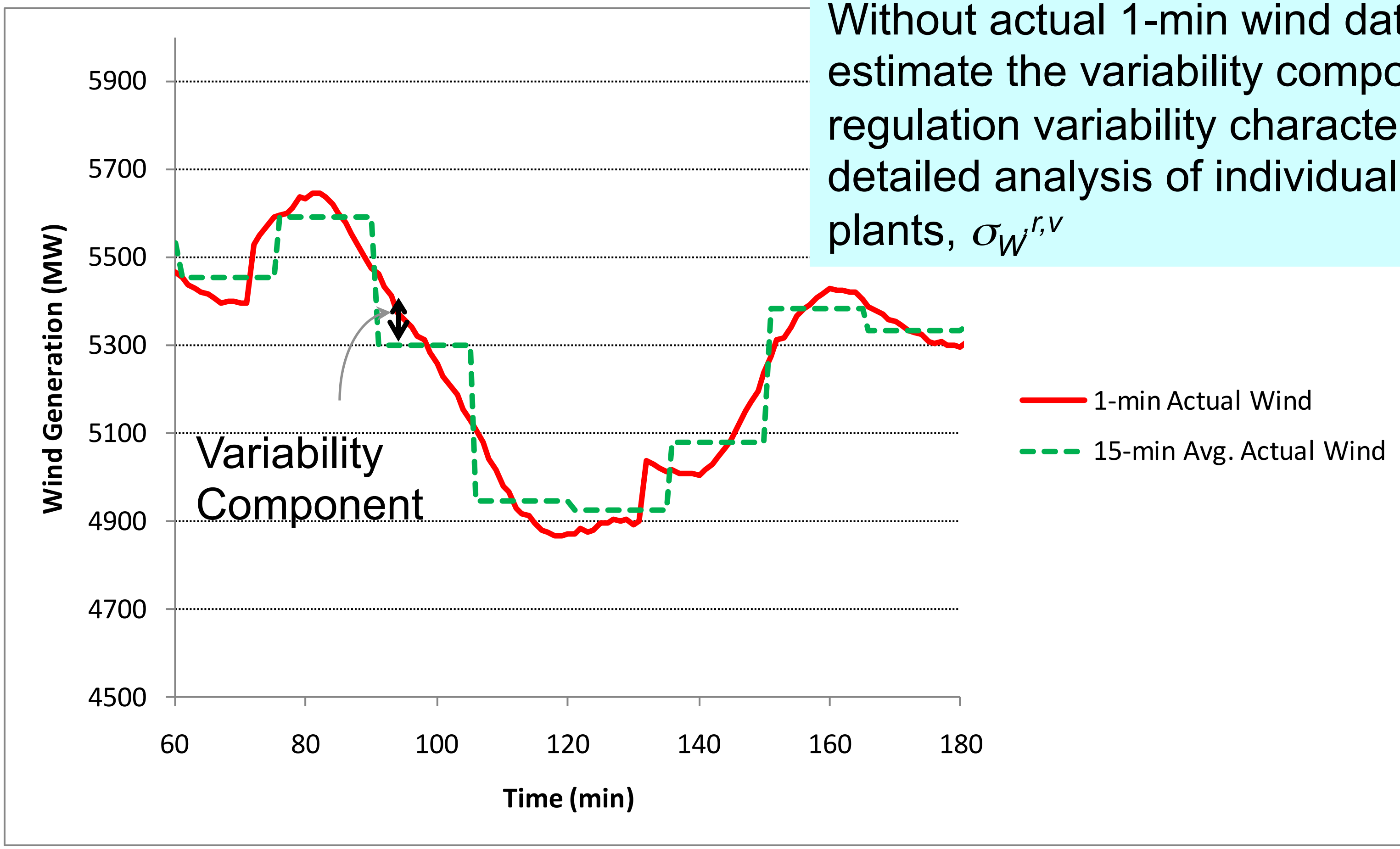
Imbalance: Forecast Component of Regulation



Short-term dispatch schedule based on persistence forecast: 15-min dispatch schedule is equal to actual 15-min average in previous period

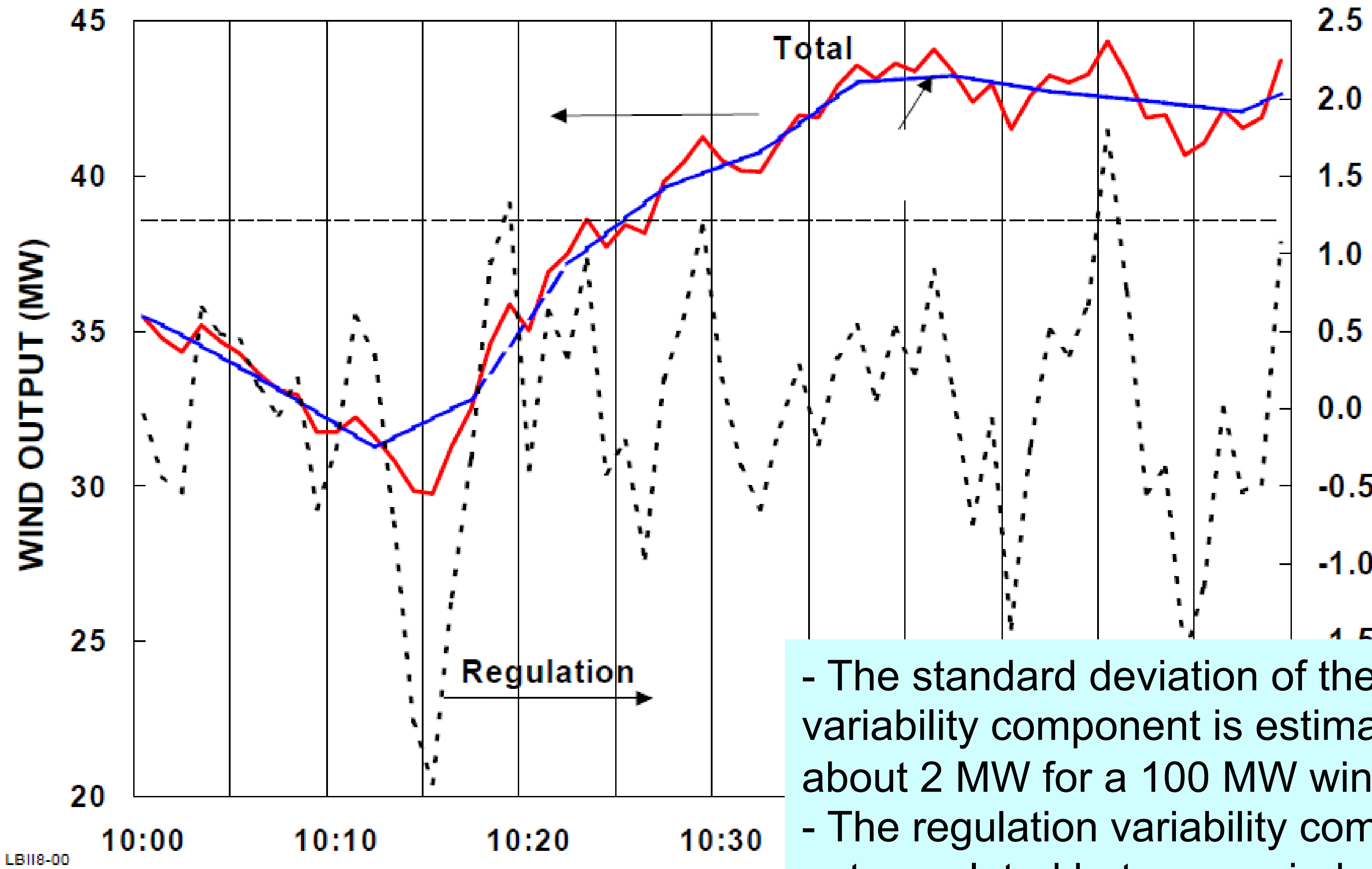
Quantify the magnitude of the forecast error as the standard deviation across all periods of the difference between the 15-min average in period *i* and the 15-min schedule in period *i* => $\sigma_{W}^{r,f}$

Imbalance: Variability component of regulation



Without actual 1-min wind data to estimate the variability component, use regulation variability characteristic from detailed analysis of individual wind plants, $\sigma_W^{r,v}$

Regulation: Variability Component



- The standard deviation of the regulation variability component is estimated to be about 2 MW for a 100 MW wind plant.
- The regulation variability component is not correlated between wind plants

Estimate of Total Wind Imbalance

$$\sigma_W = \sqrt{\left(\sigma_W^{DA}\right)^2 + \left(\sigma_W^{Fl}\right)^2 + \left(\sigma_W^{r,f}\right)^2 + \left(\sigma_W^{r,v}\right)^2}$$

- **Total imbalance can be estimated by constituent components**
  - Day-ahead forecast error estimates from other studies
  - Following and regulation forecast error component from 15-min data (correlated over high wind region, but uncorrelated for distances > 100 km)
  - Regulation variability component from U.S. experience (2 MW/100 MW wind plant), and all uncorrelated

$(\sigma_W^{r,v})^2 = [N * (2\ \text{MW})^2]$ where *N* is number of 100 MW wind plants

Simple Numerical Example

- **Determine net load imbalance with 10,000 MW of wind from 100 plants (N = 100):**
- **Standard deviation of day-ahead forecast error (assume 10% of total wind nameplate):**
  - σ_W^{DA} **= 10% * 10,000 MW = 1000 MW**
- **Standard deviation of following (assume 20% of 100 MW wind plant and all uncorrelated)**
  - $\sigma_W^{Fl} = \sqrt{N}$ *** 20%*100 MW = 200 MW**
- **Standard deviation of regulation, forecast component (assume 10% of 100 MW wind plant and all uncorrelated)**
  - $\sigma_W^{r,f} = \sqrt{N}$ *** 10%*100 MW = 100 MW**
- **Standard deviation of regulation, variability component (assume 2% of 100 MW wind plant and all uncorrelated)**
  - $\sigma_W^{r,f} = \sqrt{N}$ *** 2%*100 MW = 50 MW**
- **Standard deviation of wind imbalance:** $\sigma_W = \sqrt{(1000^2 + 200^2 + 100^2 + 50^2)}$ **= 1,026 MW**
- **Standard deviation of load imbalance (assume 2% of 100,000 MW):** σ_L **= 2,000 MW**
- **Standard deviation of *net load* imbalance:** $\sigma_N = \sqrt{(2000^2 + 1026^2)}$ **= <u>2,247 MW</u>**

Estimates of day-ahead forecast error of wind (σ_W^{DA}) from literature

Study	Standard deviation of day-ahead wind forecast error (% wind nameplate)	Notes
Porter and Rogers (2010)	5% to <15%	Summary of performance in different regions of U.S.
Charles River Associates (SPP)	9-10%	Midwest U.S.
Holttinen et al. (2009)	6-7%	Germany

Estimate following and regulation forecast error from wind data

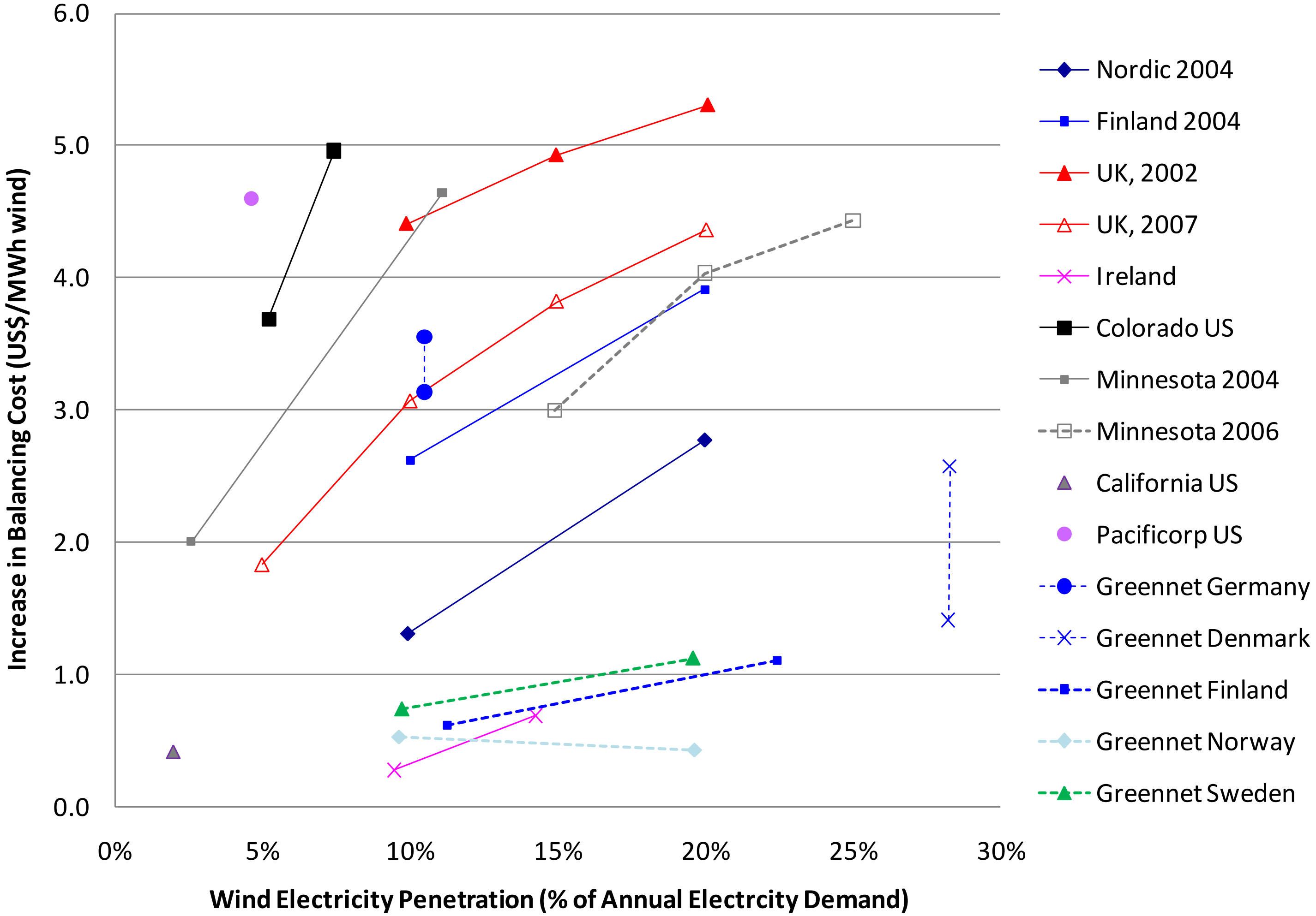
- Use time series of aggregate wind output from expected wind plants
  - Need to capture effects of diversity
- Synthesis methods (explained in extra slides at end) can be used to create additional wind time series from limited set of existing plants
- Or simply use existing plants and assume all additional plants will be uncorrelated (may overstate smoothing from diversity)
- DO NOT simply scale output of existing plants (ignores smoothing from diversity)

Data Needed to Estimate Increased Cost of Balancing Reserves

- Understand how system operators currently manage imbalances in load
  - When are schedules set? How large are load imbalances? What resources are used to manage normal imbalances? Very large imbalances?
- Estimate costs of balancing reserves to meet imbalances
  - How much less efficient are dispatchable plants when part loaded?
  - How much does it cost to deploy fast starting plants? Can coal plants be kept in “hot” standby to be started quickly? What would that cost?
- Estimate increased balancing reserves with wind energy
  - How large are day-ahead forecast errors?
  - How variable are diverse wind plants within the hour? Requires sub-hourly data from multiple wind plants

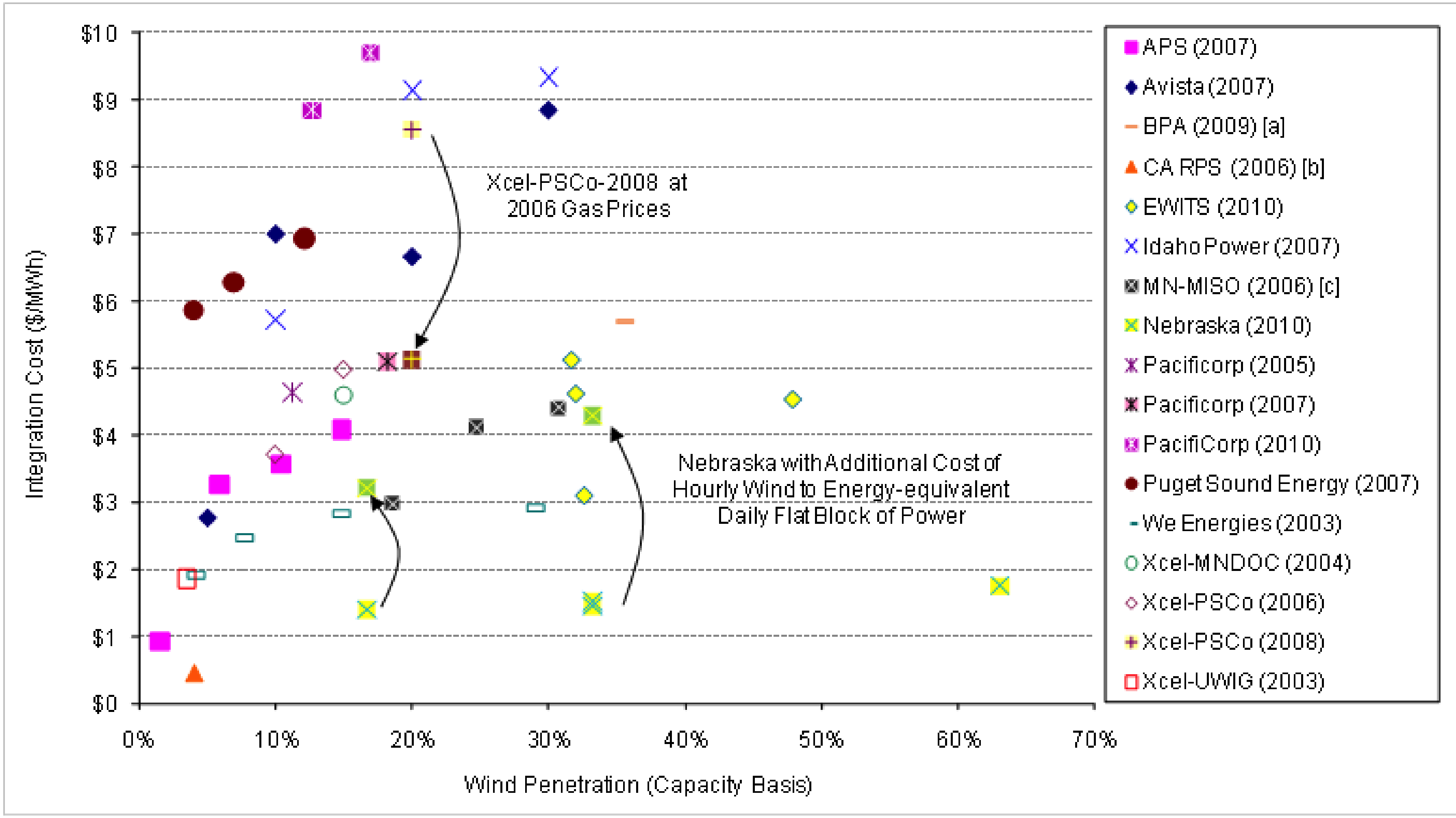
COMPARISON TO RESULTS FROM THE LITERATURE

Costs of Balancing Reserves from the Literature



Source: Holttinen et al 2009

Costs of Balancing Reserves from the Literature



Source: Wiser and Bolinger (2010)

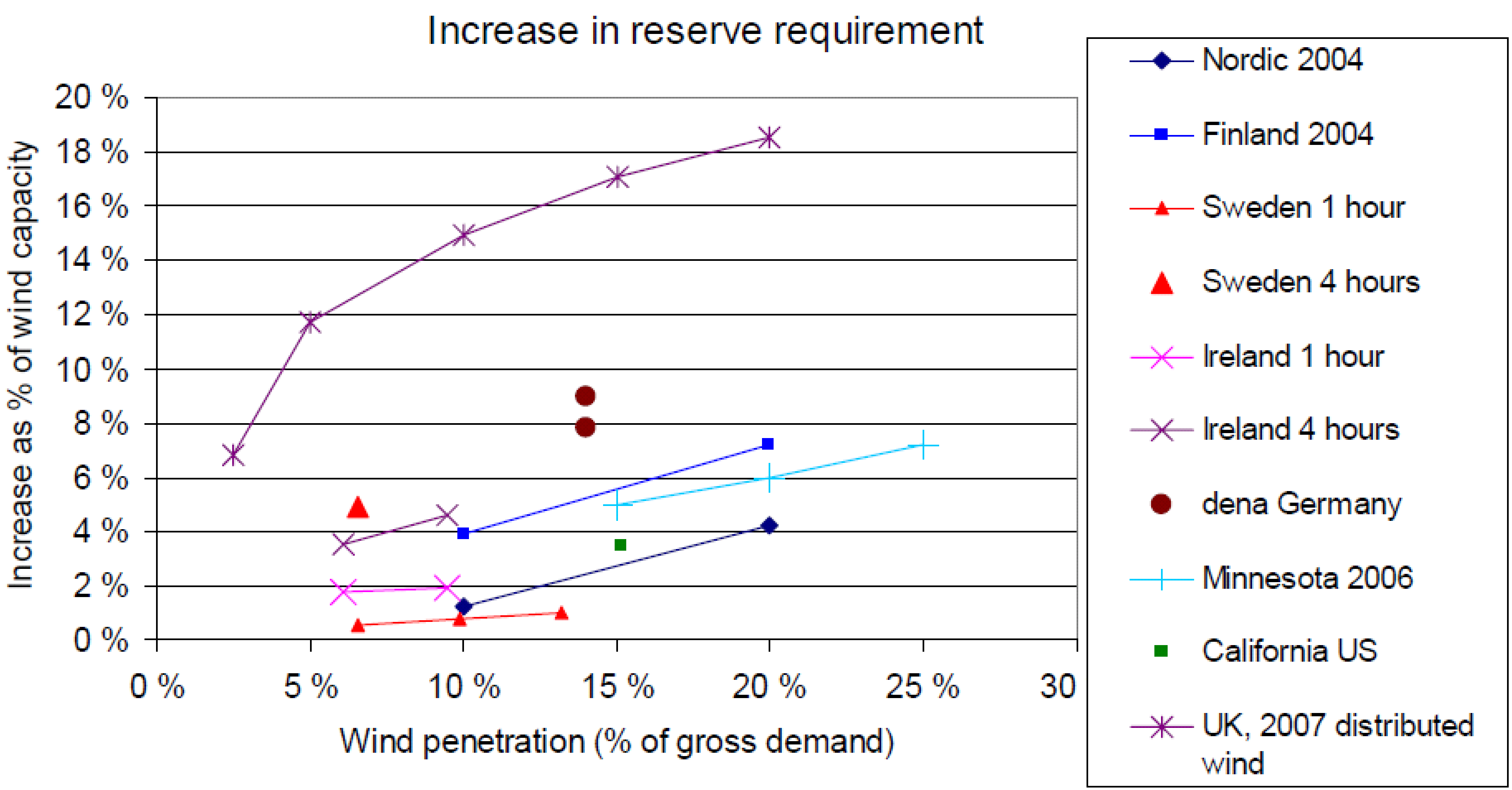
Estimates of day-ahead imbalance costs for wind from literature

Study	Wind	Cost of Day-ahead imbalances from wind (excluding following and regulation component)
California (2006)	7.5 GW (26 TWh)	$0.7/MWh
	12.5 GW (43 TWh)	$0.9/MWh
New York (2005)	3.3 GW (8.9 TWh)	$2.8/MWh
Texas (2008)	5 GW (18 TWh)	$1.1/MWh
	10 GW (38 TWh)	$1.6/MWh
	15 GW (54 TWh)	$0.2/MWh
WWSIS (2010)	27 GW (86 TWh)	$2.2/MWh
EWITS (2010)	230 GW (746)TWh	$1.8/MWh

Cost of Spinning Reserves in U.S.

- Spinning reserve costs vary with many factors:
  - Availability and characteristics of resources
  - Opportunity cost to holding reserves
  - Requirements for response time of reserves
- Cost of reserves in U.S. varies from region to region:
  - In 2008 costs of spinning reserves in major markets varied from $1.7/MW-reserves per hour (New England) to $27/MW-reserves per hour (ERCOT)
  - Mostly hovers around $10/MW-reserves per hour

Estimates of Balancing Reserve Increases from the Literature



Source: Holttinen et al 2009

Use Estimated Increase in Balancing Reserves with Costs of Reserves

- Simple method: estimate the increased costs of balancing reserves with wind using the increase in balancing reserves with wind from the literature and the cost of balancing reserves in China
- Example: If balancing reserves cost $10/MW per hour in China and 10,000 MW of wind requires an increase in balancing reserves of 8% of nameplate capacity of wind (using DENA Germany from previous slide), then:
  - Incremental balancing reserves = 8%*10,000 MW = 800 MW
  - Incremental balancing reserve cost = 800 MW * $10/MW-h * 8760h/yr = $70 million/yr
  - Assuming wind produces 27 TWh/yr at 30% capacity factor
  - Then incremental balancing reserve cost = $70 million/yr / 27 million MWh/yr = <u>$2.6/MWh</u>

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EXTRA SLIDES

Creating Wind Profiles: BPA approach

- Estimate time series of future project (Q_{new}) by using time series of existing project (Q_i) with time delay (τ)
- Use weighted average of multiple plants where future project is between two plants (sum of w_i over all plants used = 1)
- Scale existing wind plant output to future plant output with linear multiplier based on ratio of wind plant capacity (K)

$$Q_{new}(t) = \sum_i w_i \frac{K_{new}}{K_i} Q_i(t - \tau_i)$$

How do you estimate the lags?

- Determine the lag between existing sites on either side of a future site
  - Estimate the autocorrelation coefficient for all lags
  - Pick the lag with the greatest autocorrelation coefficient
- Interpolate the lags by the distance between the existing sites and the future sites