State-of-the-Art Wind Energy Forecasting (and the Future of Forecasting)

Eric Grimit, Director of Forecasting
Cameron Potter, Power Prediction Engineer

International Wind Forecasting Workshop
July 24-25, 2008

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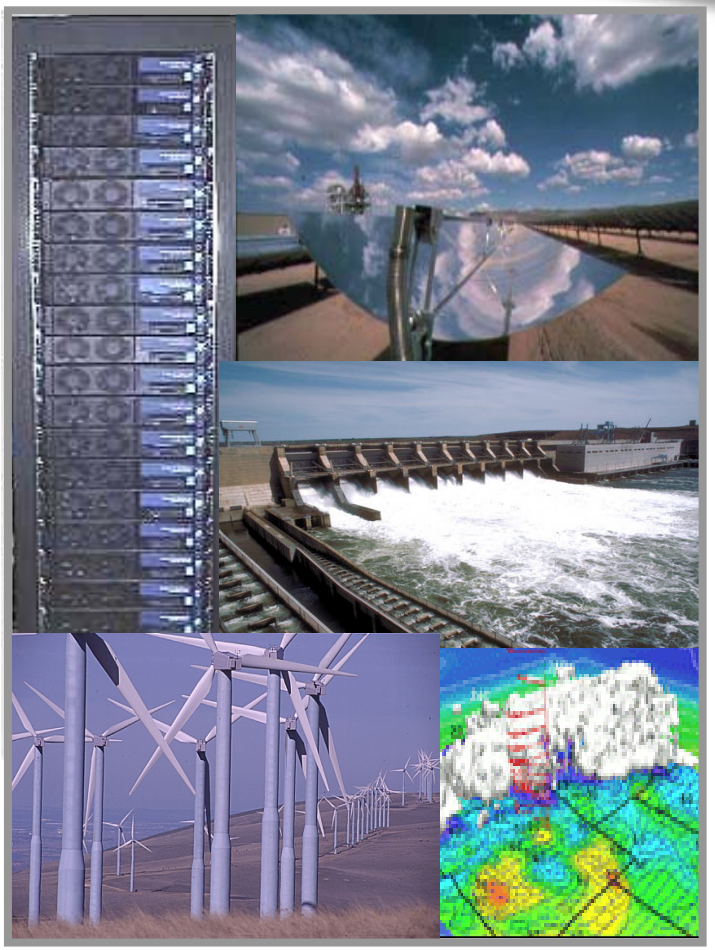
ABOUT 3TIER

- Founded in 1999

- Headquartered in Seattle
- Regional office in Panama City

- Founded and run by scientists and engineers to put the best of academic research into practice

- Focused on the renewable energy sector
  - → **~6,000 MW** wind energy forecasting
  - → **~3,500 MW** hydropower forecasting
  - → Extensive international wind resource assessment
  - → Solar assessment & forecasting



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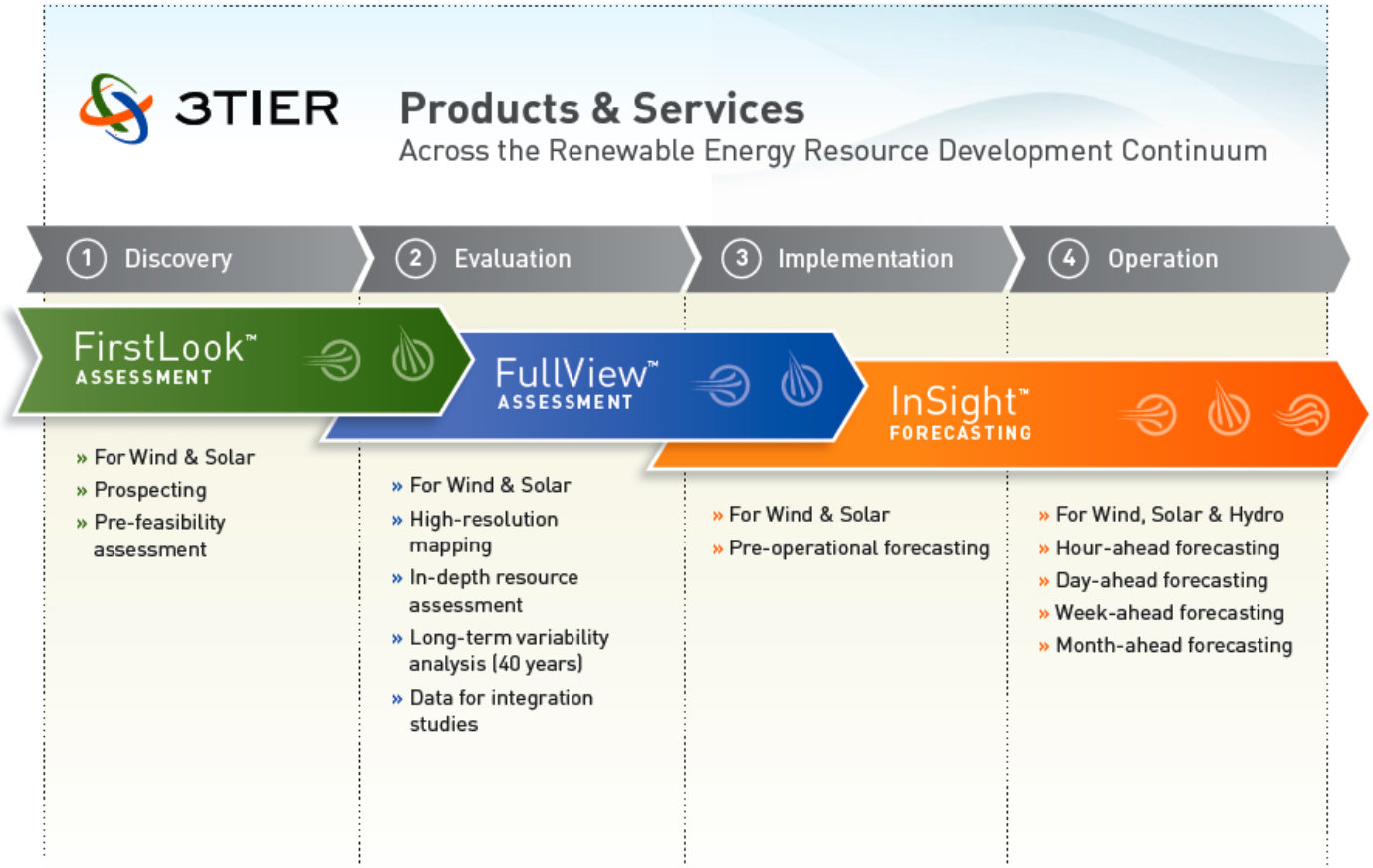
3TIER's products

…cover the entire life of a project, from inception through operation



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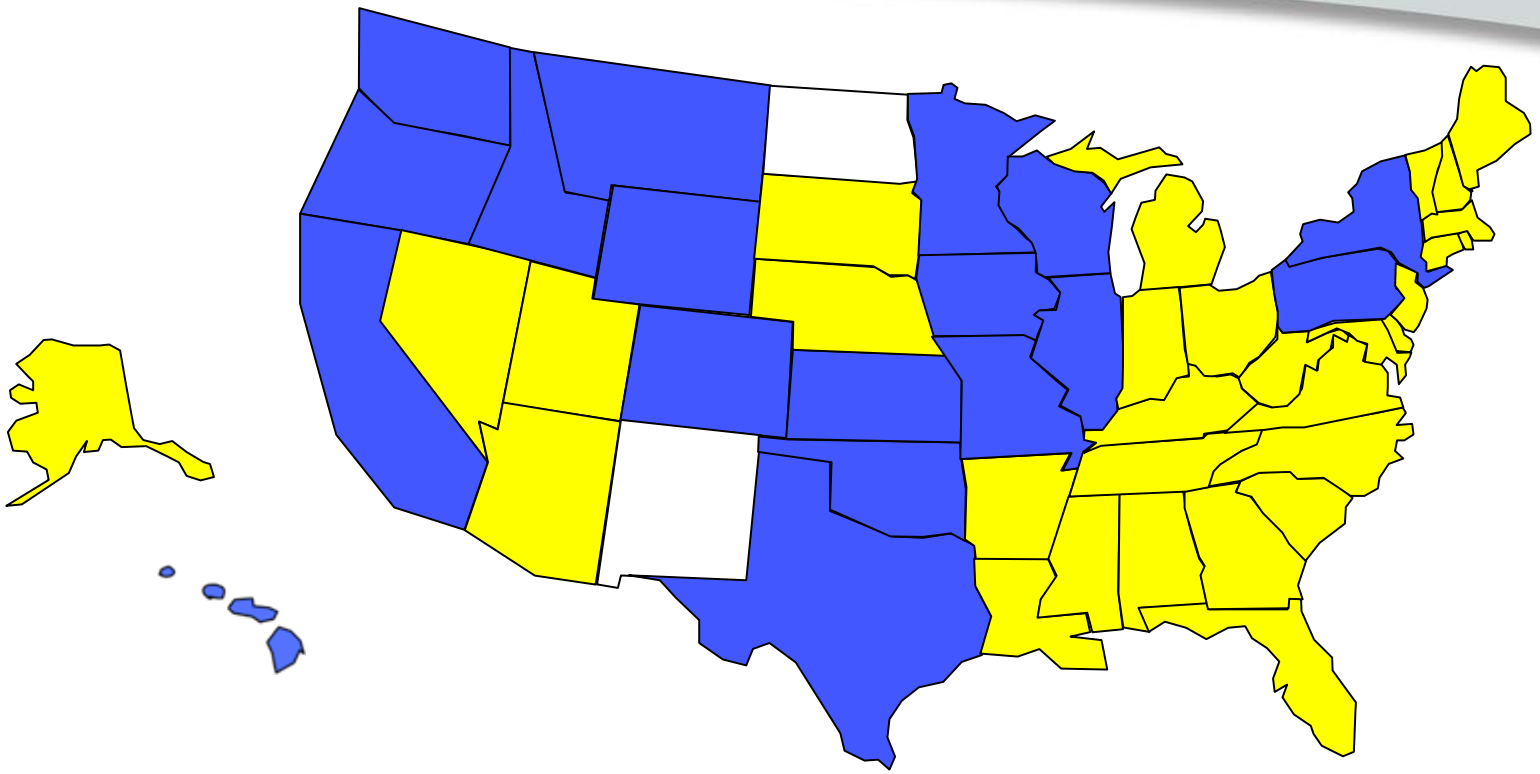
3TIER forecasting experience



3TIER wind forecast experience in state

States with less than 100 MW of projects

3TIER not forecasting in states with more than 100 MW of projects

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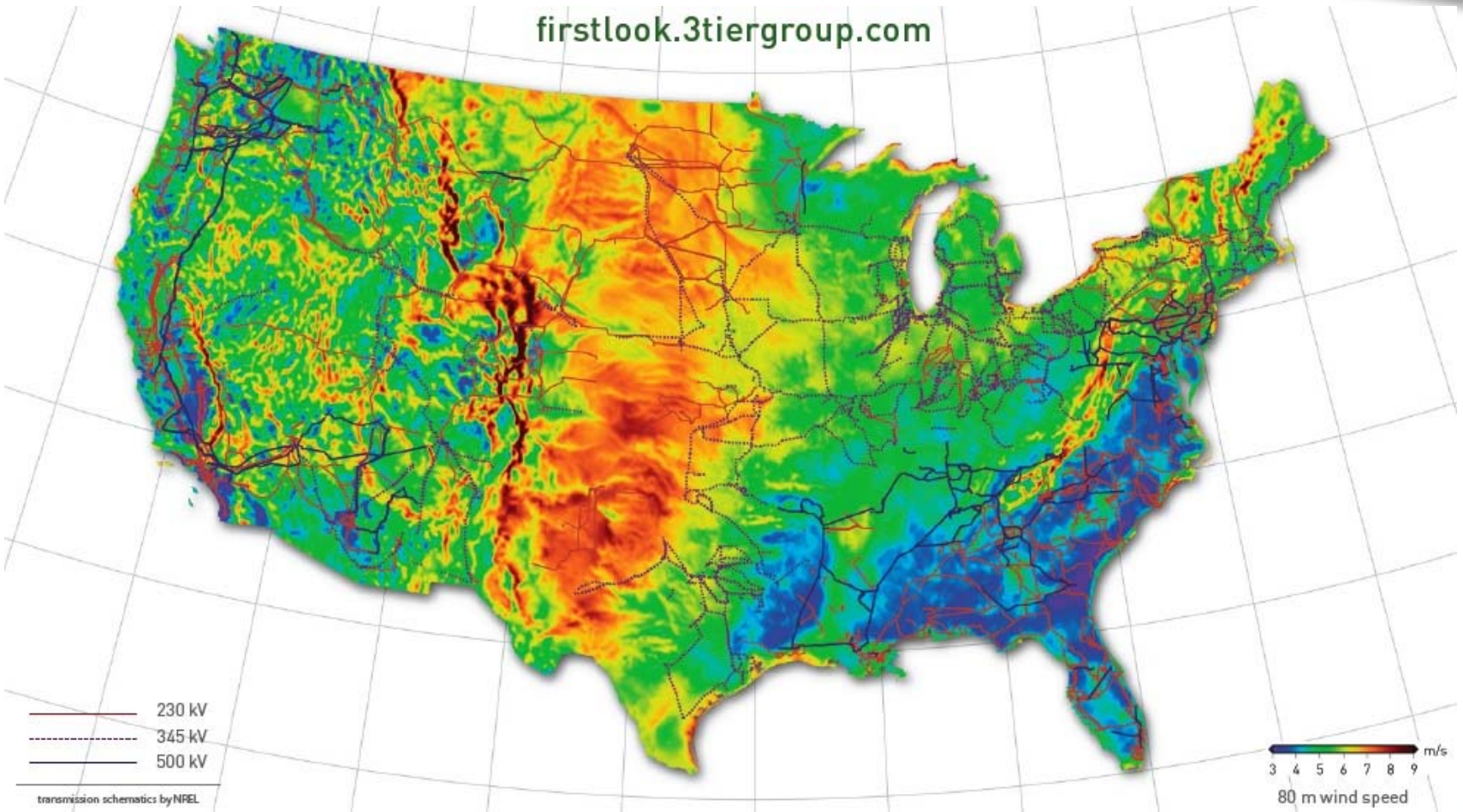
We are familiar with forecasting over a variety of terrain types



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We are familiar with handling very large quantities of data

- Ingesting approx. 10,000 pieces of data every 10 minutes in real-time from operational wind energy projects:
  - About 60,000 per hour
  - About 525,000,000 per year
- Creating at least 400,000,000 data values from in-house NWP simulations 4 times per day
- NREL Western Wind and Solar Integration Study:
  - 3,784,320 maps of 1,200,000 grid points each
  - 32,000 wind point time series (each one holding 157,680 values)
  - 8,000 solar point time series (each one holding 26,280 values)

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3TIER forecasting philosophy

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3TIER's wind forecast capabilities

- 3TIER recognizes the need for seamless forecasts across horizons from minutes to months in the future.
- Our standard forecast services provide hourly wind energy forecasts out to a maximum horizon of 168 hours (7 days).
- We also provide forecasts with a monthly resolution for longer-term planning of 12-18 months ahead.
  - This requires at least 30 years of wind resource variability analysis at the site.
  - Forecasts are based on climate indices and show estimated deviations from the long-term capacity factor.

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Standard forecast deliverables

Forecast Type	Time Issued (approximate)	Update Frequency	Span	Granularity
Hour-Ahead	3 min after new data received	5, 10, or 15 min	~10 hr	1 hr
Day-Ahead	5-8 AM EST 8-11 AM EST 2-5 PM EST 8-11 PM EST	4 times/day	24 hr	1 hr
Week-Ahead	5-8 AM EST	daily	168 hr	1 hr
Weather	5-8 AM EST 8-11 AM EST 2-5 PM EST 8-11 PM EST	4 times/day	84 hr	1 hr

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Data for the most accurate forecasts

Project

- Power output, 10-min averages/intervals

Meteorological data

- Towers o.k., Turbines better (also 10-minutely)
  - Wind speed
  - Wind direction
  - Pressure
  - Temperature

Turbine

- Power output and availability status (10-minutely)

Future Availability Schedules

- Hour by hour projections of the expected availability

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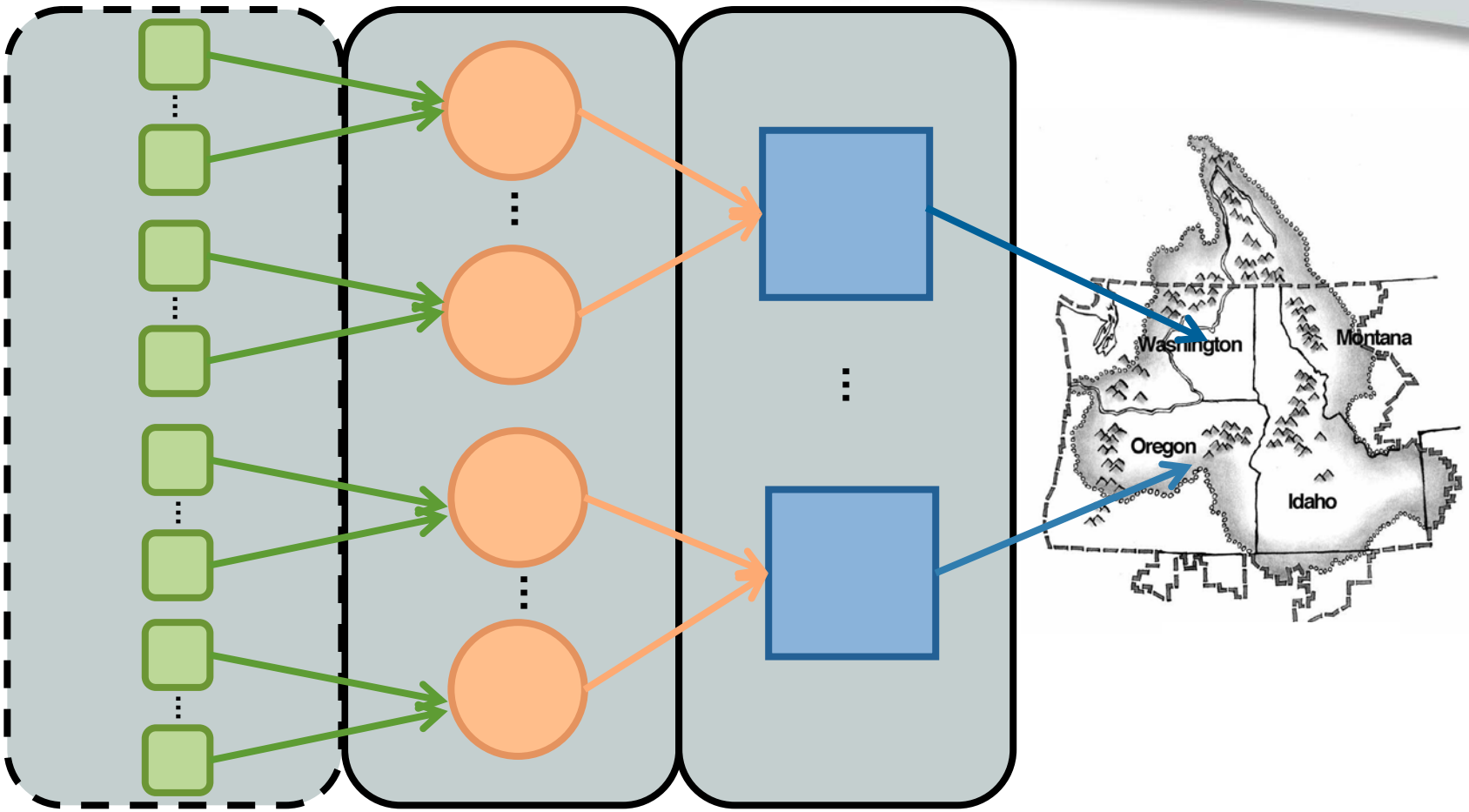
Forecast Aggregations



Wind Plants* Nodes Regions System

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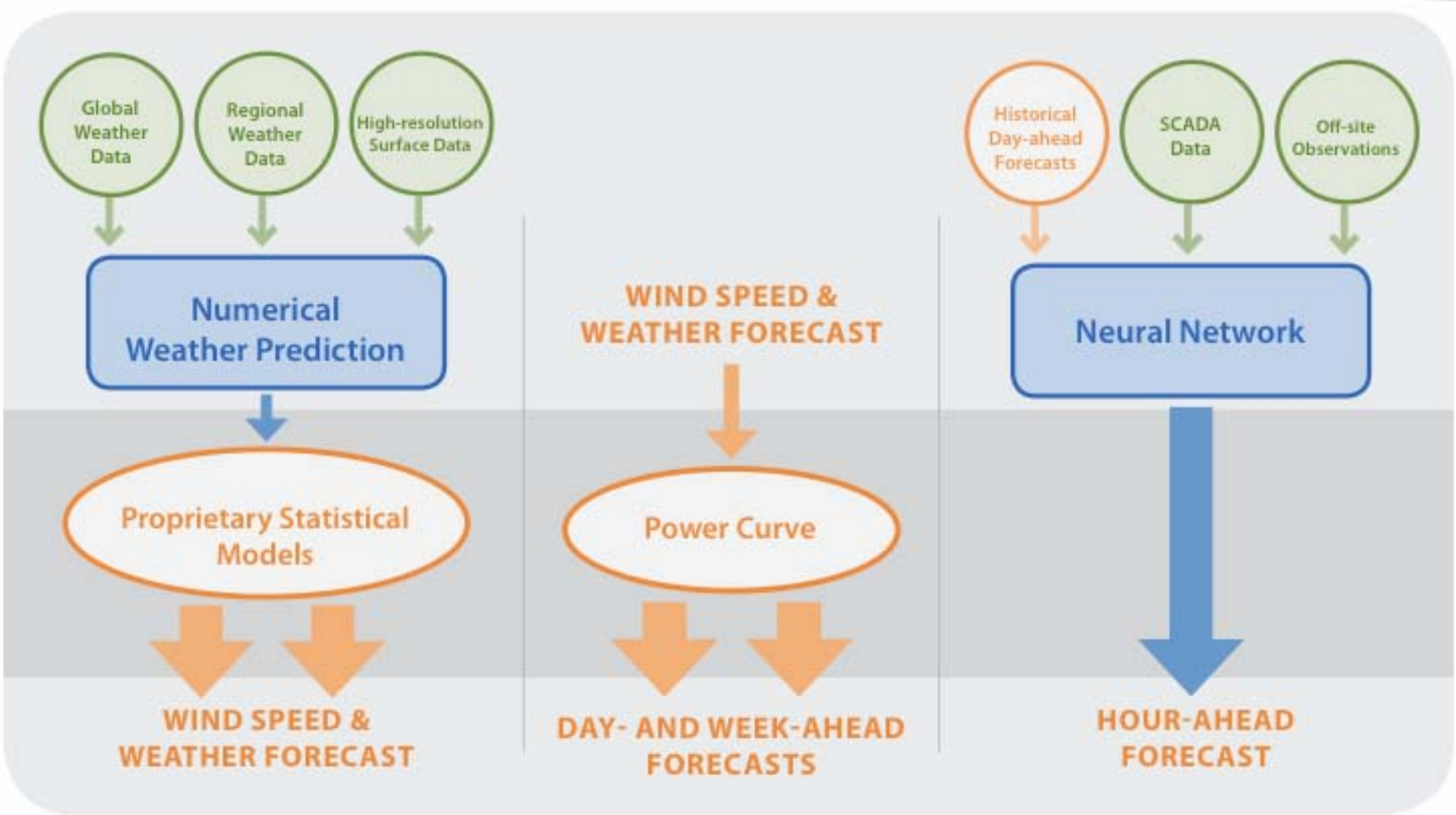
*better with plant-level and turbine-level data (power, met)

A complex forecasting system is required using both models and data



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LIVE DEMONSTRATION
(3TIER NWP animations)

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ACCURACY DEPENDENCIES

- Data (The More, The Better)
  - Need Quality, Frequency, and Timeliness!
- Horizon (Lead Time)
  - Forecast Skill Diminishes – The Butterfly Effect
- Weather Type (It's Been Known to Change!)
  - The Time Limit of Forecast Skill Fluctuates
- Scope (Individual Wind Plant or Regional Aggregate?)
  - Forecasts for the Many are Better Than for the One
- Location (Location, Location!)
  - Forecast Accuracy Varies Substantially By Real Estate
- Metric (Ruler or Scale?)
  - Accuracy is in the Eye of the Beholder: What Matters to You?

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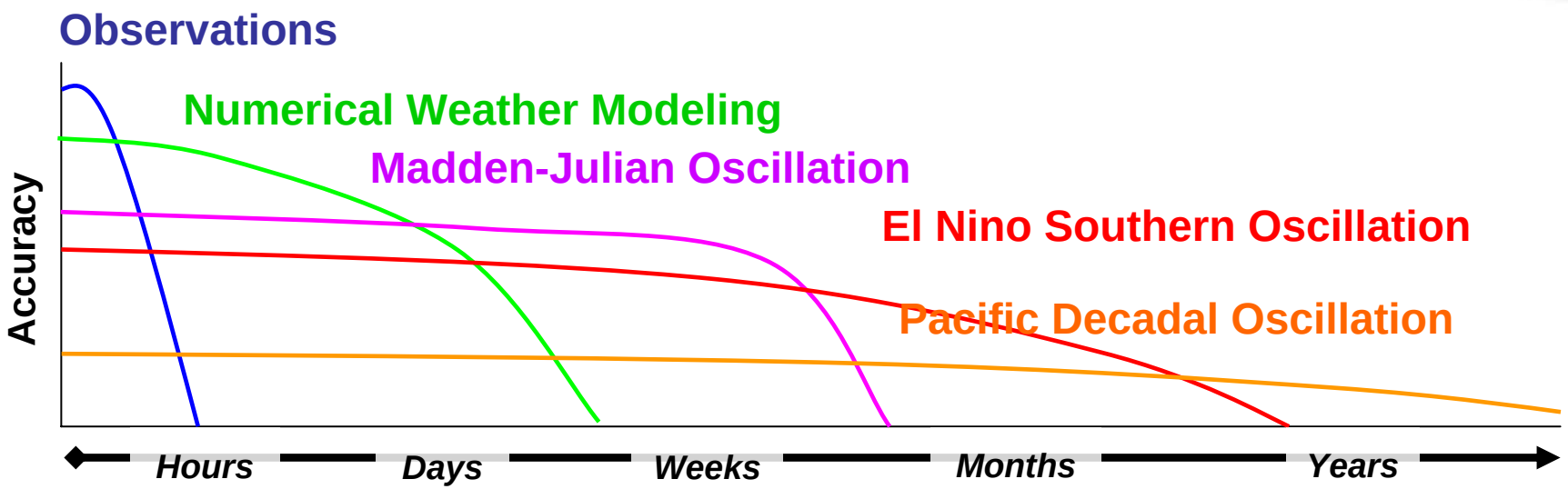
FORECAST HORIZONS



Short-range

- Spinning or firming reserves
- Load following
- Spot market

Medium-range

- Transmission scheduling
- Asset allocation
- Day ahead market

Long-range

- Asset optimization
- Futures market
- Hedging

Assessment

- Firm capacity
- Volumetric risk

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FORECAST HORIZONS

- Industry Requirements:
  - Next Unit Commitment Period (5-20 min. lead)
  - Next Operating/Trading Hour (1-3 hr. lead)
    - Lead varies by ISO/RTO (BPA = 30 min., CAISO = 105 min.)
  - Next Operating/Trading Day (1-3 day lead)
    - Closing varies (PJM = noon EST, CAISO = 5:30 am PPT)
  - Next Week (1-6 day lead)
  - Next Month/Quarter (10-30 day lead)

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METRIC

- What Matters to You?
  - Net Annual Production (Fixed PPA)
  - Imbalance / Operating Reserve Charges (Merchant)
  - Minimizing Over-Scheduling (Risk Management)
  - Grid Reliability (Risk Aversion)
- Some Standard Measures of Accuracy/Error:
  - Bias, Mean Error
  - Mean Absolute Error (MAE)
  - Root-Mean-Squared Error (RMSE)

$$\text{Bias} = \frac{1}{n}\sum_{i=1}^{n} p_i - o_i$$

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n} \left| p_i - o_i \right|$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (p_i - o_i)^2}$$

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METRIC

- Skill:
  - Measured by the Improvement (in %) Over a Benchmark Method

$$Skill = \frac{(RMSE_{benchmark} - RMSE_{forecast})}{RMSE_{benchmark}} \times 100\%$$

  - Common Benchmarks:
    - Persistence: forecast = current generation
    - Climatology: forecast = historical average generation
    - Another Forecast (e.g., National Weather Service)
- Cumulative Advantage/Disadvantage:
  - The summed difference (in MW) between forecast error and benchmark errror over time (e.g., one month)

$$\text{Cumulative Advantage of p over pb} = \sum_{i=1}^{n} \left(\left| pb_i - o_i \right| - \left| p_i - o_i \right| \right)$$

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TYPICAL FORECAST ACCURACY

- Standard accuracy/error and skill metrics
- Hourly average generation at individual wind facilities
- Monthly evaluation time periods
- Hour- and day-ahead predictions

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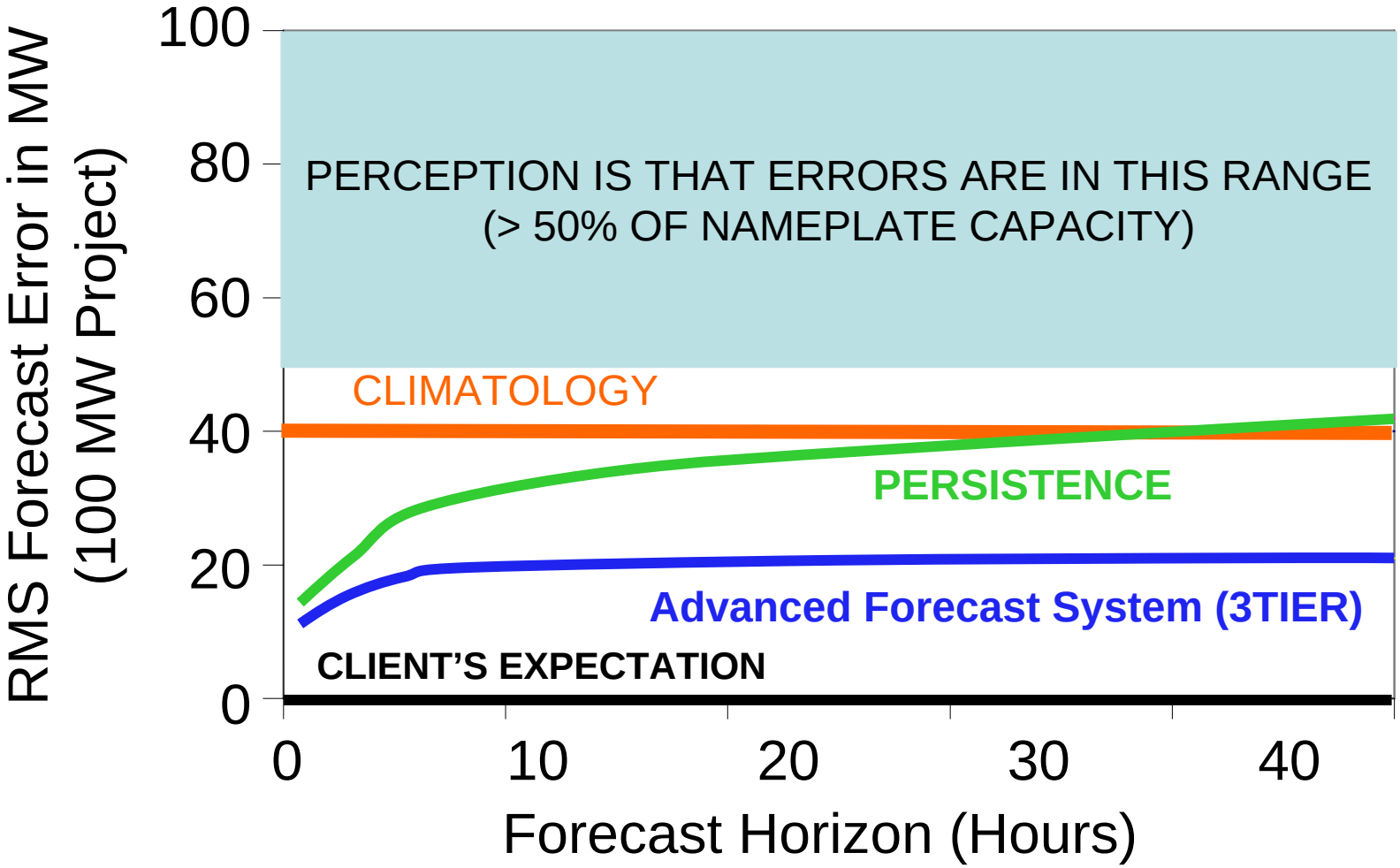
PERCEPTION AND REALITY



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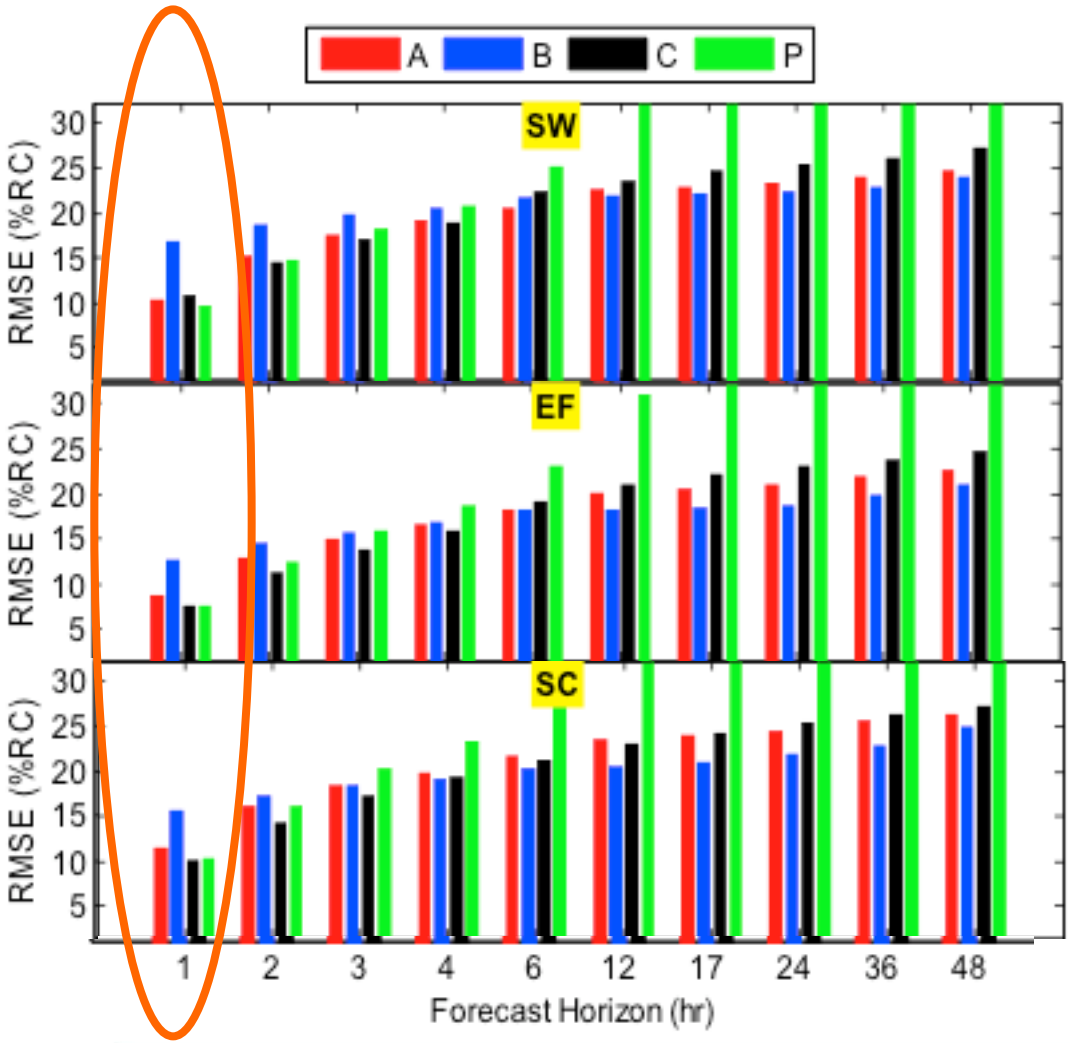
Hour-ahead forecasting is difficult



- Hour-ahead forecasting is complex and the simple benchmark of persistence can be difficult to beat.
- In the AESO study none of the forecast providers outperformed persistence according to Ortech's analysis shown to the left.

Source: Ortech Power, AESO Wind Power Forecasting Pilot Project – The Quantitative Analysis, AESO Wind Power Forecasting Pilot Project Final Workshop, 2008

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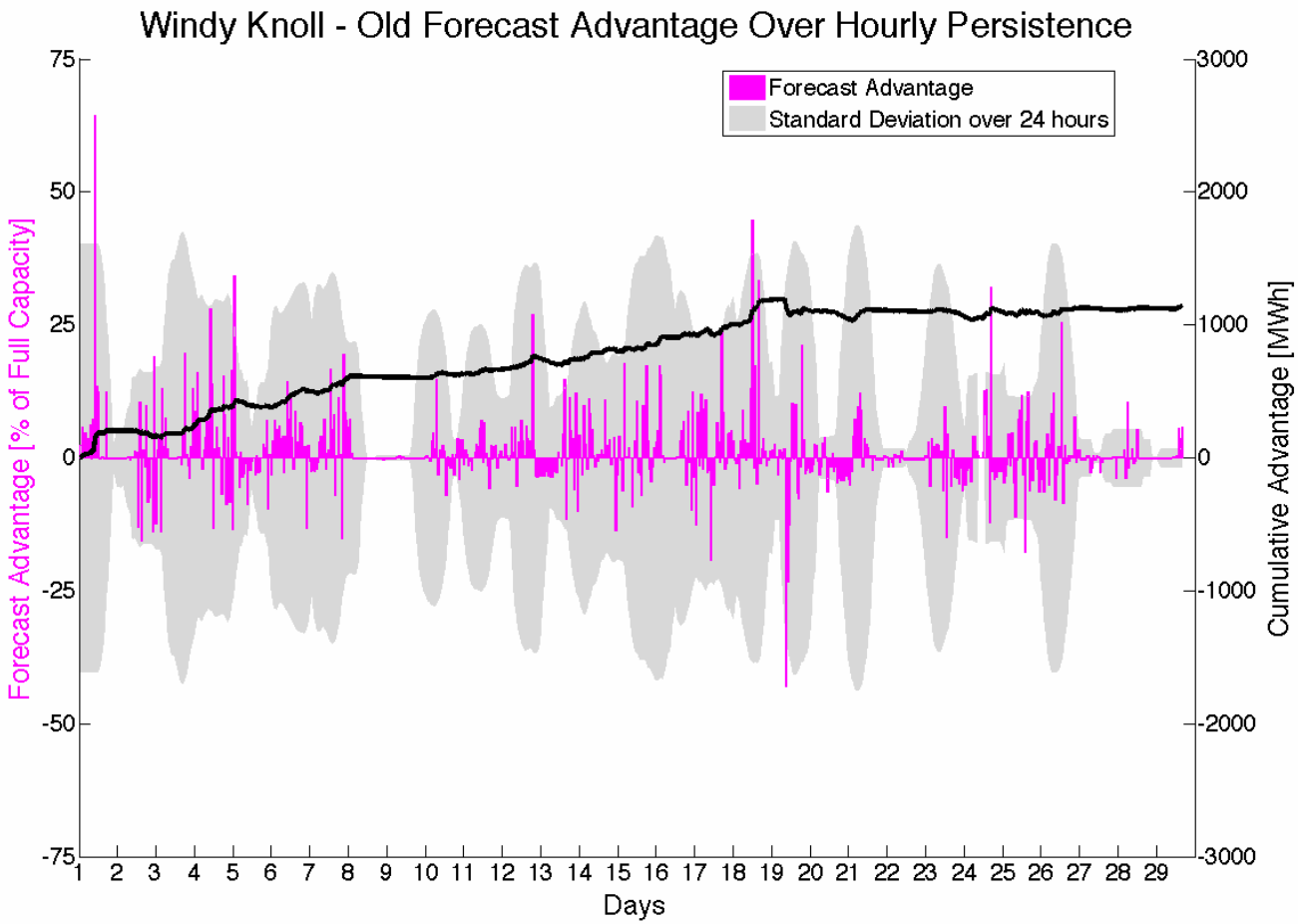
3TIER consistently beats persistence



3TIER beats persistence

Persistence beats 3TIER

The cumulative advantage is in 3TIER's favor

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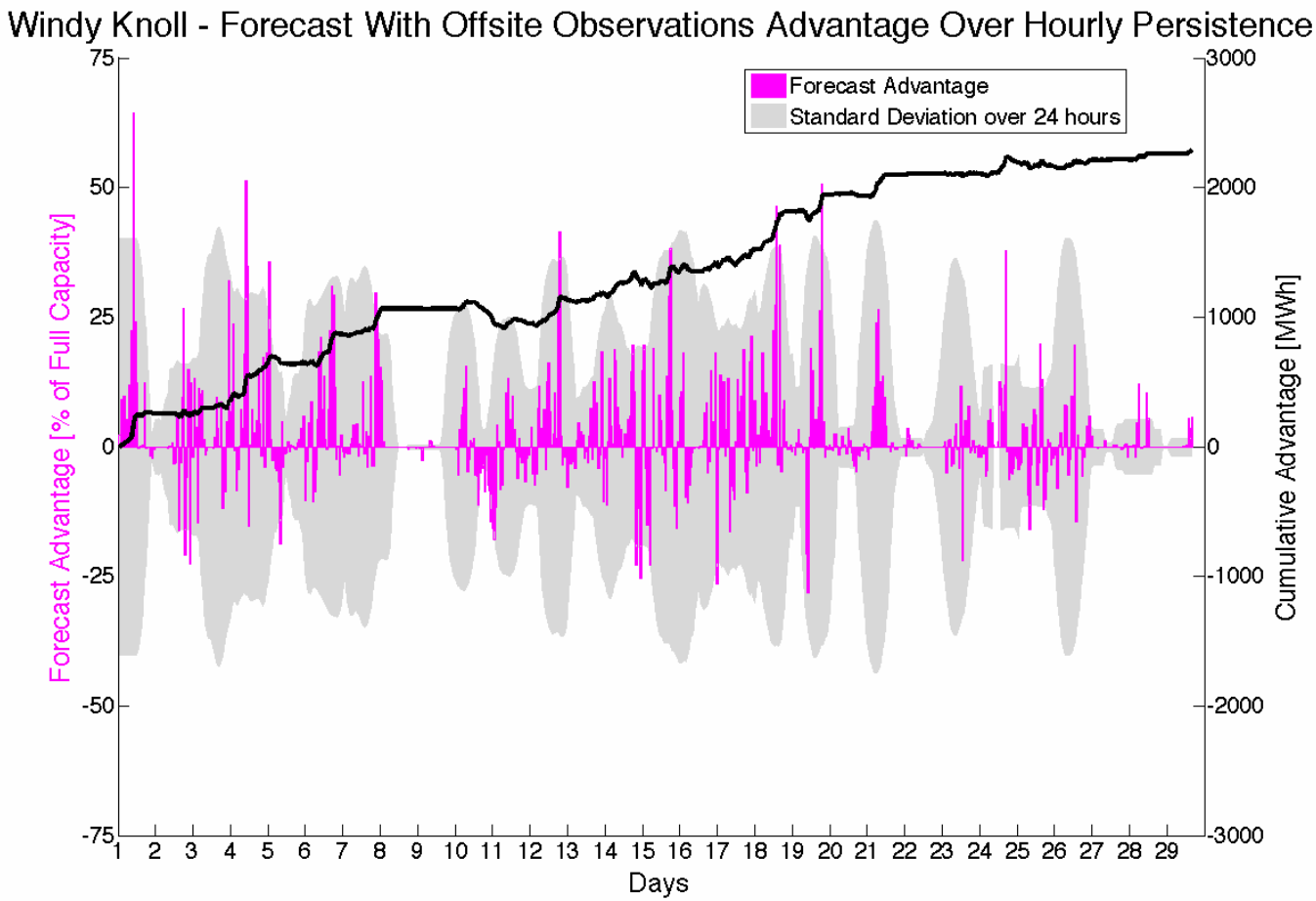
… and improves with additional data



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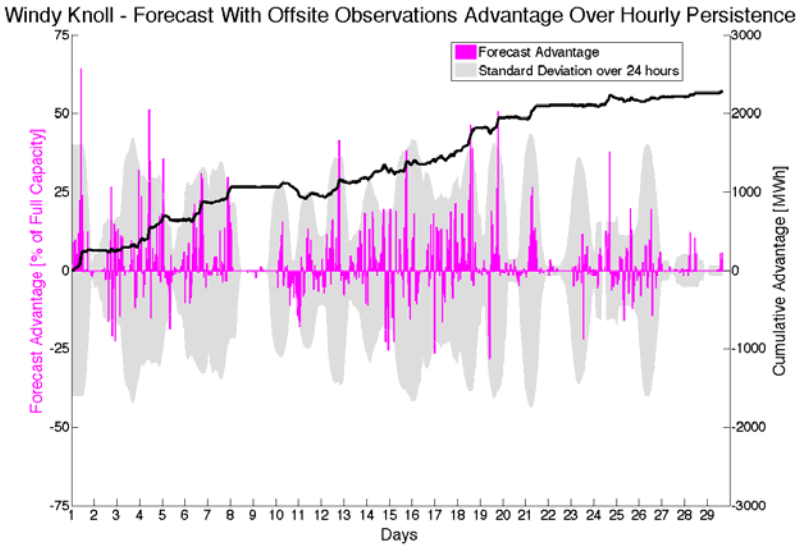
TYPICAL ACCURACY SUMMARY

- Hour-Ahead:
  - Bias: < 2% installed capacity
  - MAE: 6-9% installed capacity
  - RMSE: 7-11% installed capacity
  - Skill: 5-25% improvement over persistence
  - Cumulative Advantage: 5 1500 MWh over persisten for a 100MW facility (factor of 5x-15x)



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LIVE DEMONSTRATION
(large BPA ramp event)

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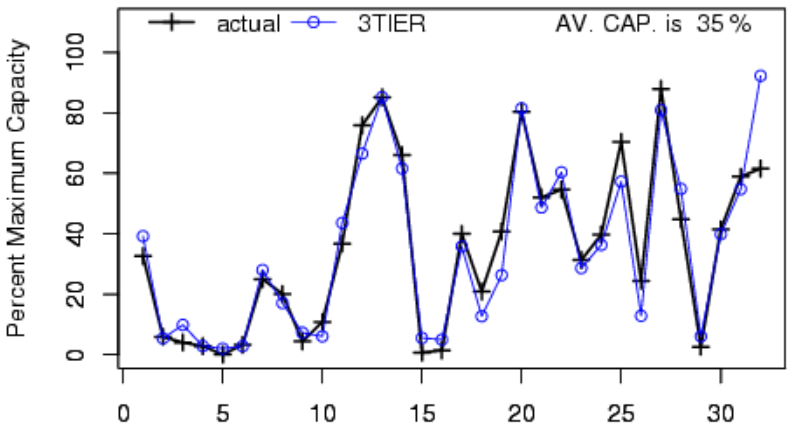
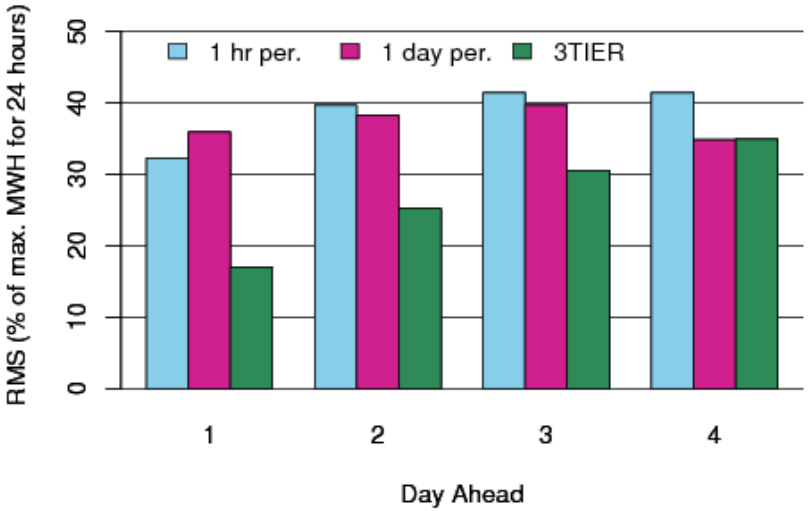
TYPICAL ACCURACY SUMMARY

- Day-Ahead:
  - Bias: < 5% installed capacity
  - MAE: 11-14% installed capacity
  - RMSE: 15-20% installed capacity
  - Skill: 40-60% improvement over climatology





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EMERGING APPROACHES

- New metrics are needed
  - Standard metrics (MAE, RMSE) do not assess performance during high impact events, e.g. ramps
  - Forecast systems optimized based on these standard metrics tend to be conservative – they hedge toward the mean
  - Yields smooth forecasts and therefore results in serious under-prediction of ramps
- Interest in ramp-event verification is growing

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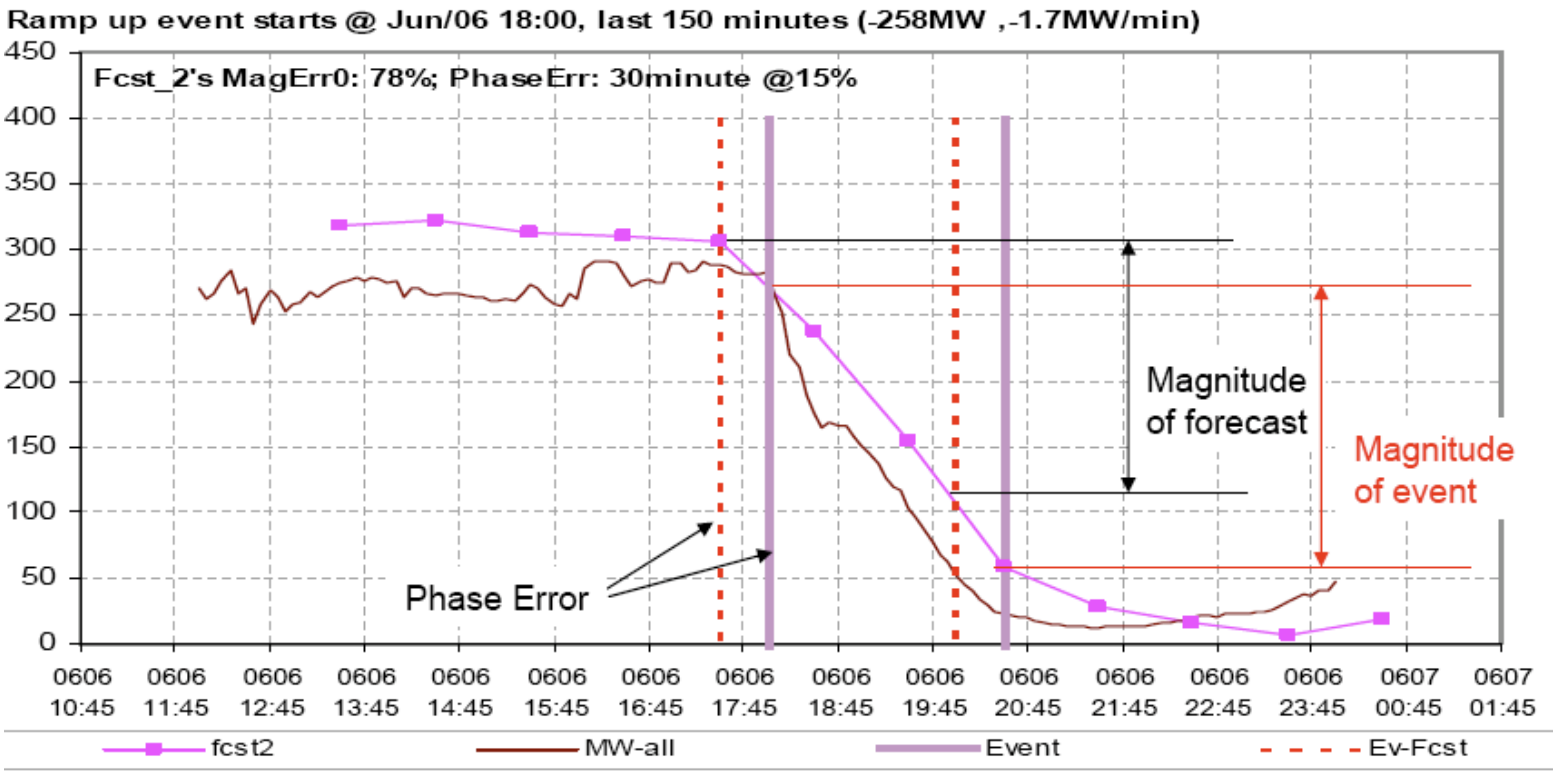
EMERGING APPROACHES

- Ramp size and timing error measures…



Source: AESO, Darren McCrank

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EMERGING APPROACHES

- With categorical (yes/no) forecasts of a binary event, there are four possible outcomes.

		Ramp Observed	
		Yes	No
Ramp Forecast	No	Miss	Correct Negative
	Yes	Hit	False

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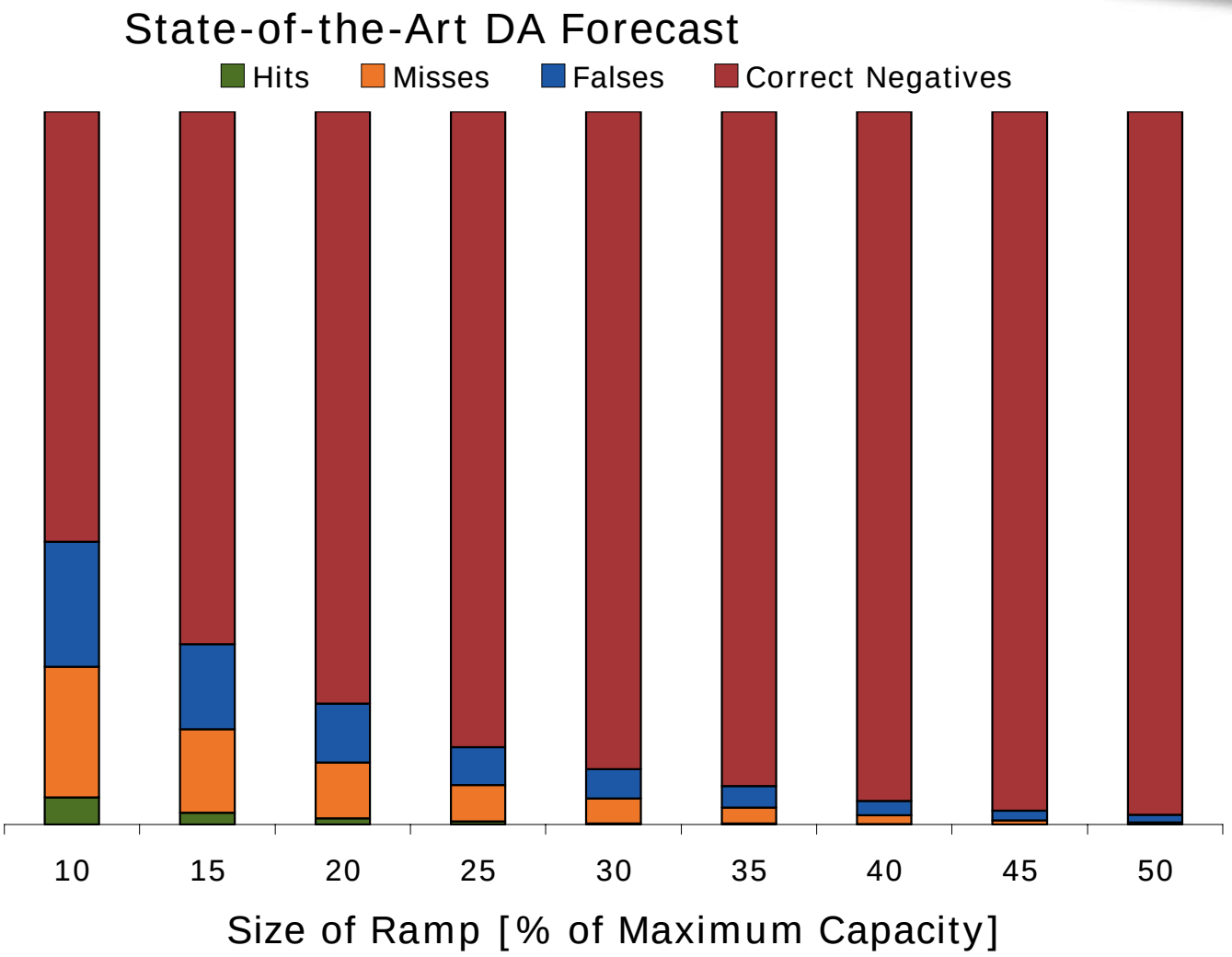
RAMP VERIFICATION EXAMPLE



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PREDICTION INTERVALS

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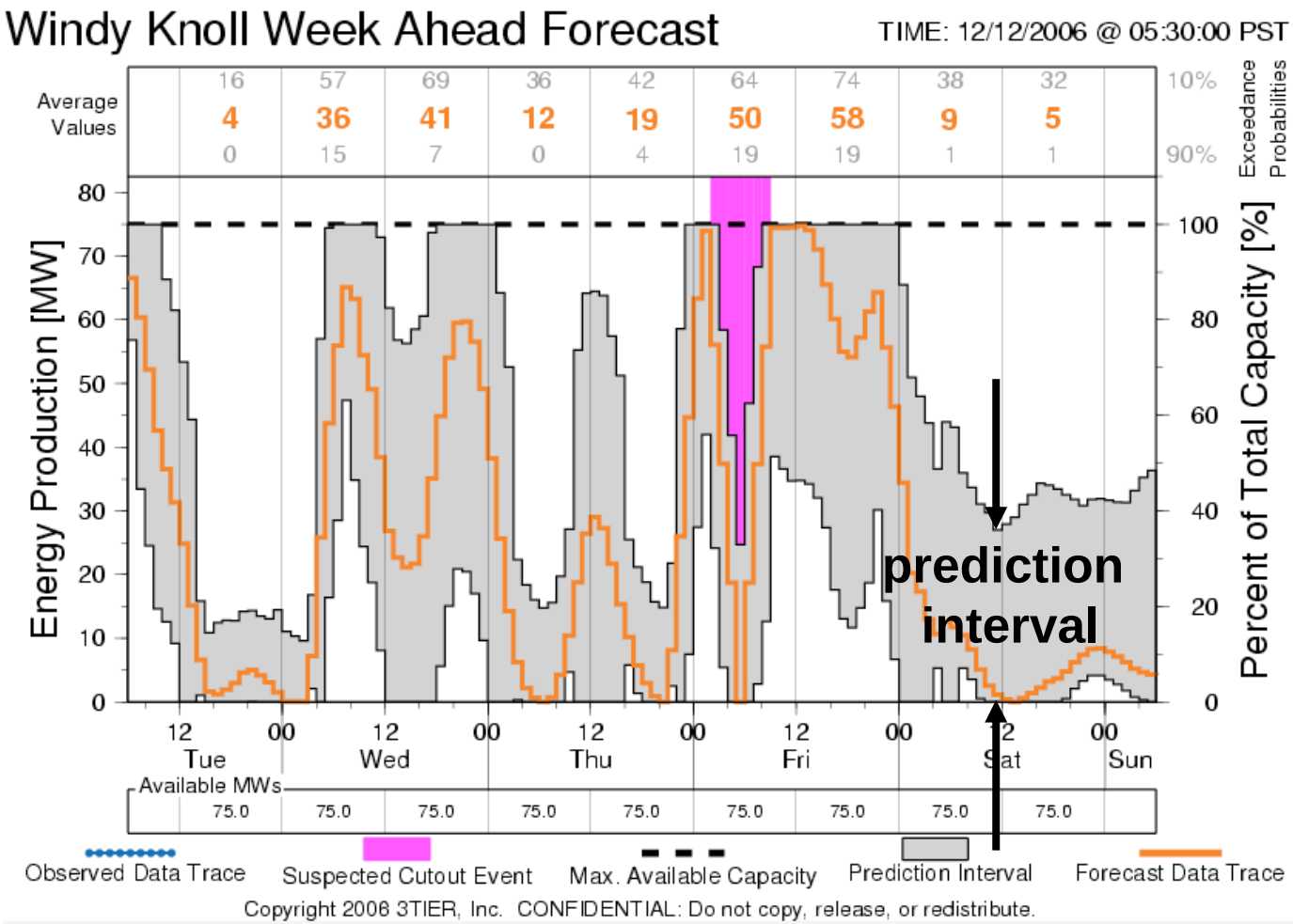
Even a great forecast has uncertainty



Sources of uncertainty:

- Weather forecast
- Power conversion

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ESTIMATION TECHNIQUES

- Power Forecast Error Analysis
  - Quantile Regression
  - Conditional on Power Curve Location

  [operational since 2004]

- Dynamic Estimation of
  - Weather Forecast Uncertainty
  - Power Conversion Error

  [offline studies, beta version since 2007]

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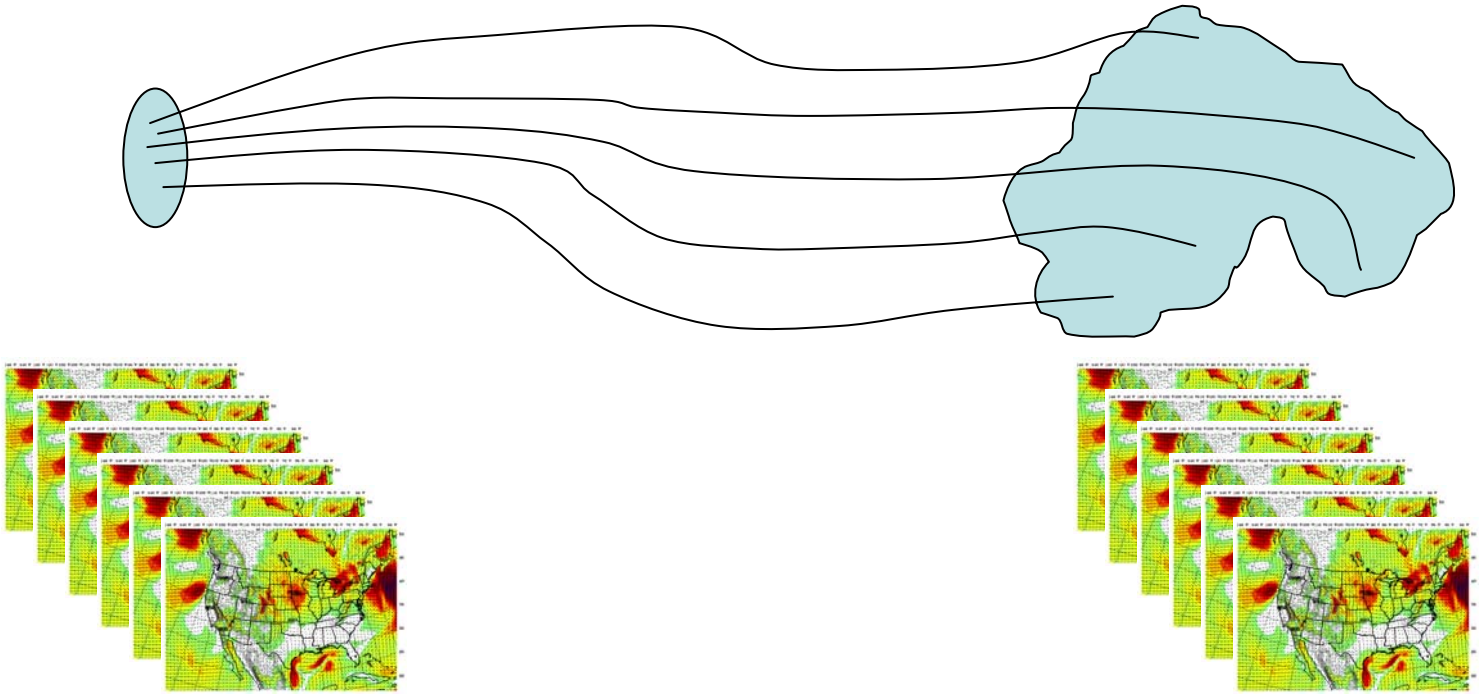
ESTIMATING WEATHER UNCERTAINTY

- Weather Forecast Ensemble
  - A series of NWP simulations, each obtained from unique initial conditions and/or NWP models
  - A sample of the uncertainty related to the current weather forecast



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Statistical calibration

Forecast ensembles are not perfect

- Limited sample of the weather uncertainty
- Members are not always equally likely

Bayesian Model Averaging

- Determine the relative skill of each ensemble member
- Provide a weighted ensemble-mean forecast
- Calibrate the original ensemble and to provide prediction intervals that are both:
  - Dependable
  - Skillful

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STATISTICAL CALIBRATION

- The prediction intervals must be:
  - Dependable (reliable / calibrated)
  - Skillful (sharp)
- With dependable confidence intervals…
  - The expected forecast accuracy is communicated
  - Users can make better decisions based on their tolerance for risk

	Forecast A	Forecast B
P10	90 MW	80 MW
P50	70 MW	70 MW
P90	20 MW	50 MW

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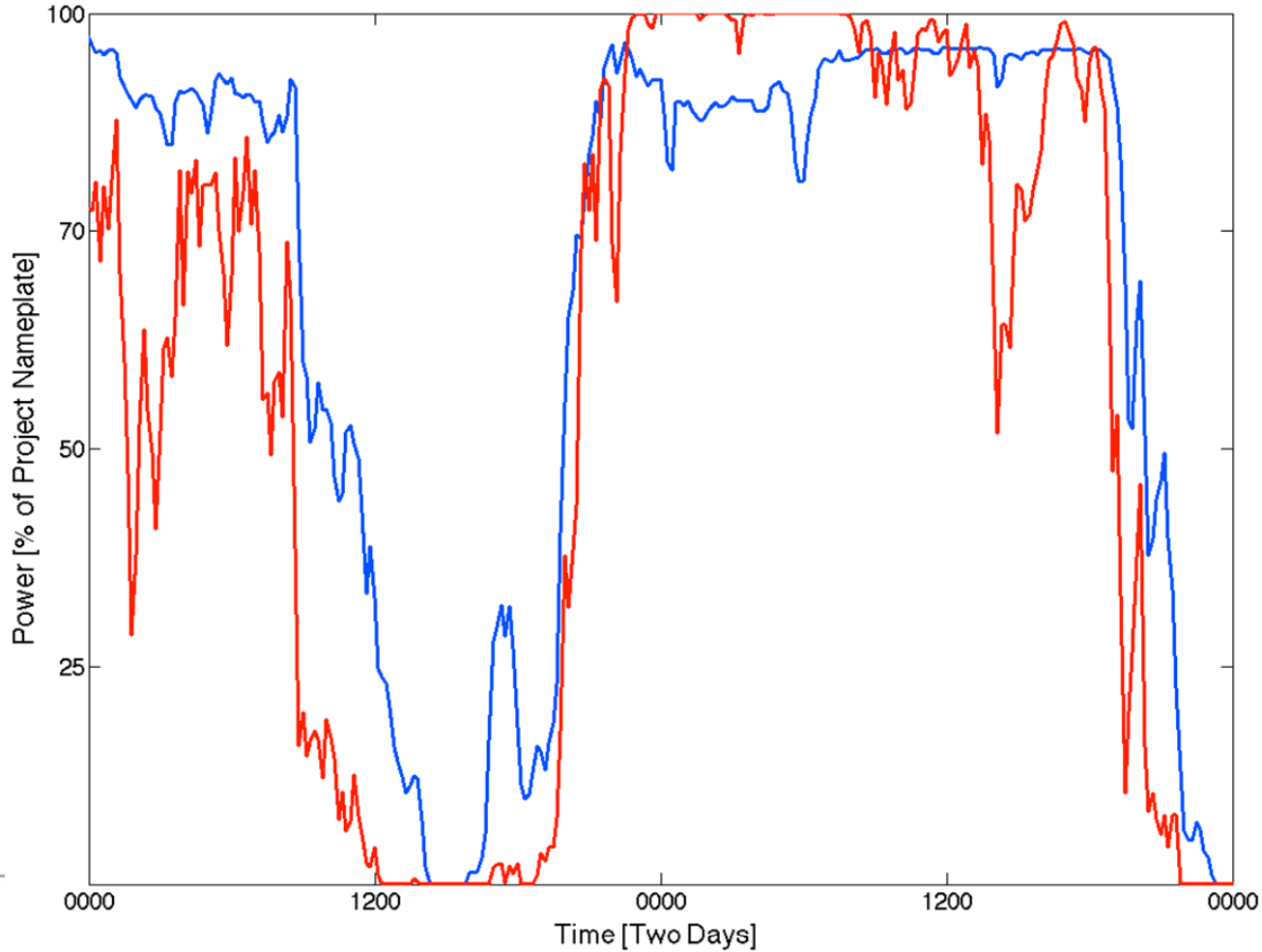
POWER CONVERSION UNCERTAINTY

Even with a perfect wind speed forecast, uncertainty still exists.

Wind speed at a single location does not adequately describe the wind affecting a project.

In fact, due to non-linearities in the power curve, the relationship between wind speed and power has inherent uncertainty in both space and time.

Rated energy based on observed wind speed at a single met tower, compared to actual



POWER CONVERSION EXAMPLE

A simple example:

Two V90 turbines experiencing an average wind speed of 13m/s (separated by space OR time).

Case1: T1 @ 13m/s, T2 @ 13m/s > Power = 5.674MW

Case2: T1 @ 12m/s, T2 @ 14m/s > Power = 5.509MW

Case3: T1 @ 11m/s, T2 @ 15m/s > Power = 5.140MW

Case4: T1 @ 10m/s, T2 @ 16m/s > Power = 4.710MW

~10% error with a difference of 4m/s between turbines – and this kind of wind speed variance is not even unusual.

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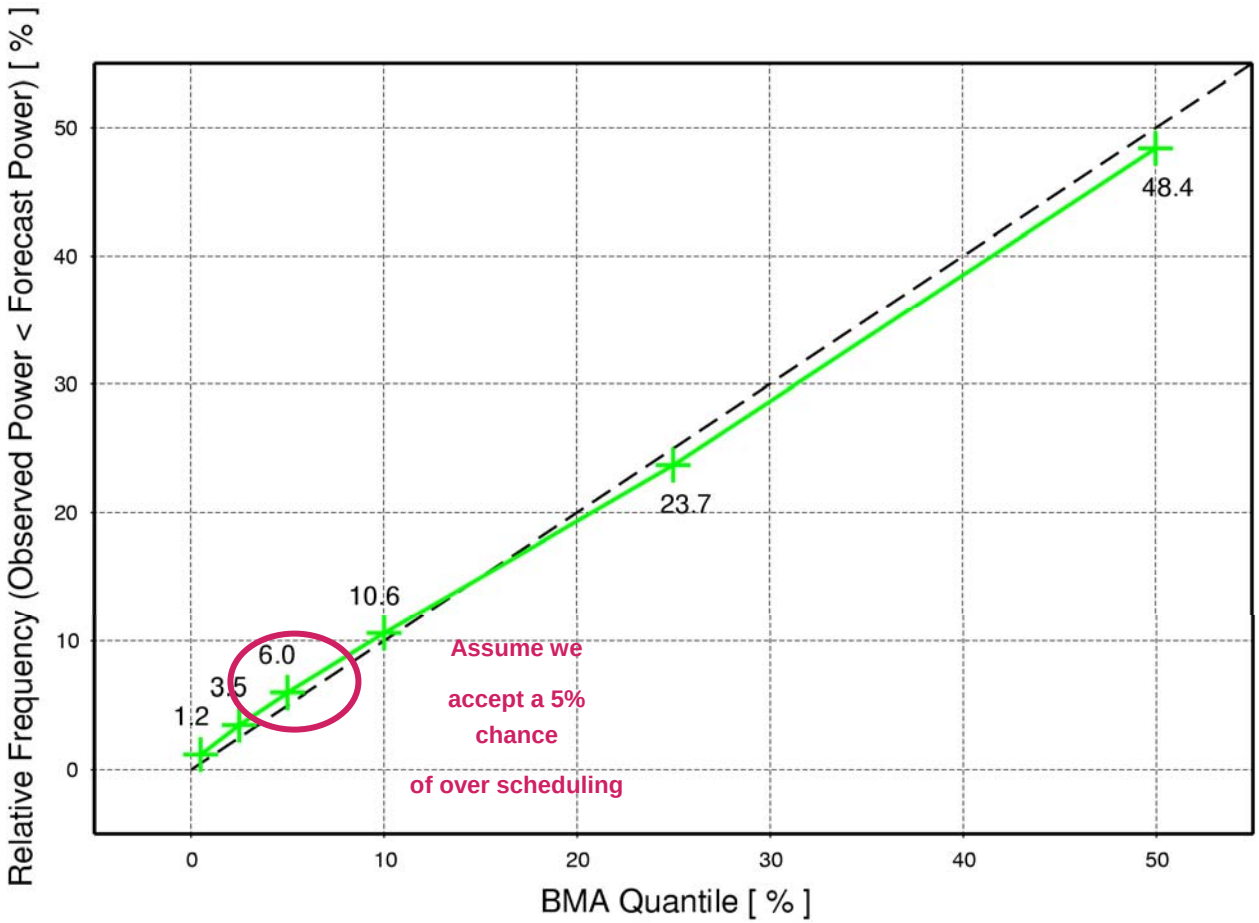
INTERVAL EVALUATION - RELIABILITY



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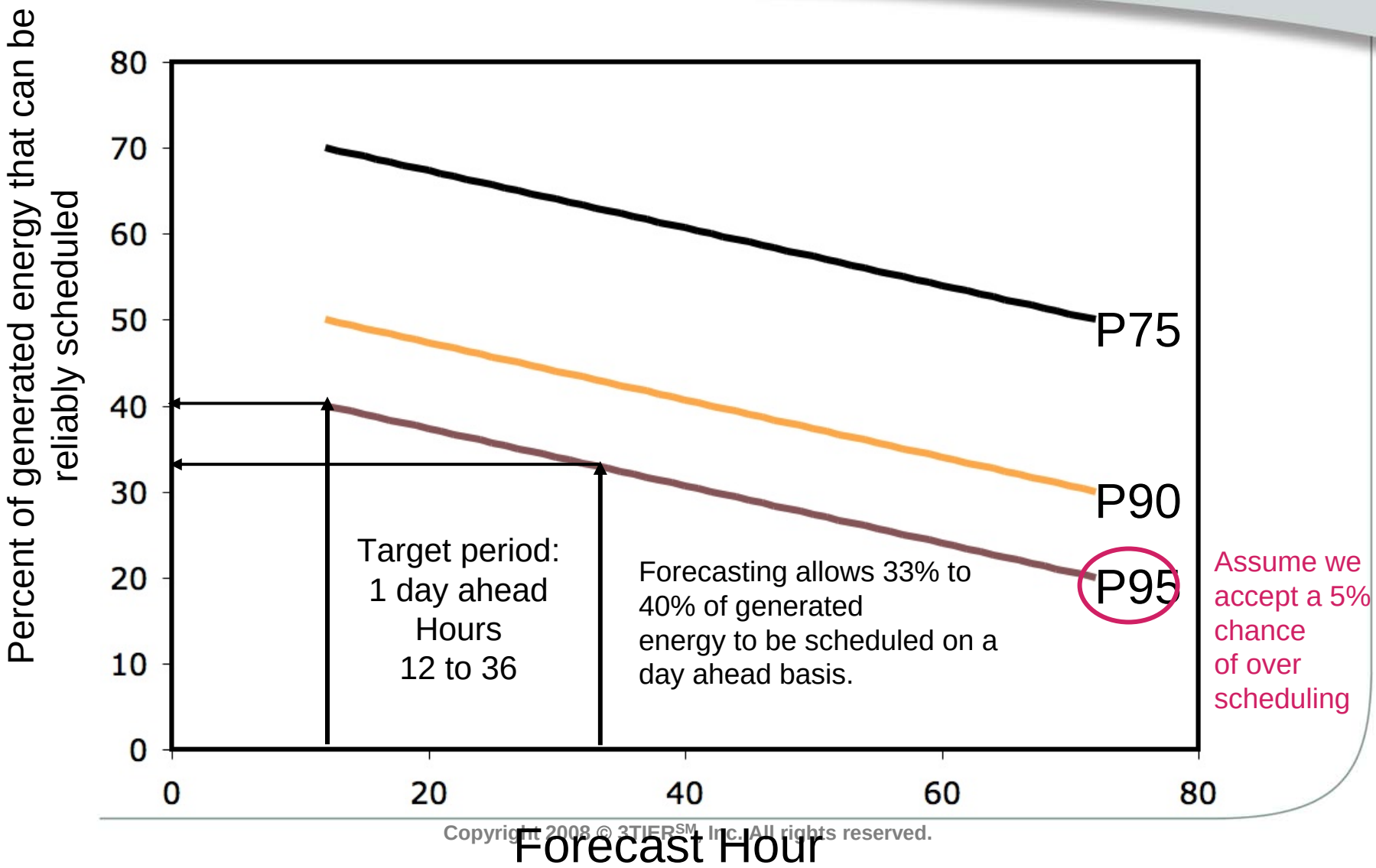
INTERVAL EVALUATION - SHARPNESS



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3TIER'S COMMITMENT TO SCIENCE IS THE SOURCE OF OUR SUCCESS

Science doesn't stand still at 3TIER.

Our people constantly push the boundaries of science and technology to consistently deliver innovative solutions.

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THE FUTURE OF FORECASTING

- Improvements in wind energy forecasting are valuable to the renewable energy industry.
- 3TIER has identified three major areas for improvement:
  - Day-ahead ramp forecasting
  - Intra-hour forecasting
  - Hour-ahead ramp forecasting
- 3TIER is actively researching these topics to provide more accurate and more relevant forecasts for our clients.

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DAY-AHEAD RAMP WARNING SYSTEM

- Last year BPA funded 3TIER to develop a prototype system for early warning of ramp events.
- A ramp in wind energy production has three attributes: time, magnitude, and direction
  - We defined the **duration** of a ramp to be **1 hour**, since that is the natural temporal resolution of day-ahead wind energy forecasts
  - The **magnitude** of a ramp is the **absolute change** in hourly-average wind energy
  - The **direction** of the change can be **positive or negative**

*We defined a "rapid ramp event" **(RRE)** as a ramp rate exceeding 10% of nameplate per hour, which is consistent with prior work performed for BPA*[1]

1. "Wind Power Modeling and Analysis of Output for Existing and Planned Wind Farms in the Klondike/Dalles Region [BPA, 2006]"

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WHY A NEW TOOL IS NEEDED

- Normal goal for forecasting is to minimize large deviations from the observations
  - “Best” forecast is often chosen so that the root mean square error (RMSE) is minimized
  - Tends to be conservative – hedges toward the mean
  - Yields smooth forecasts and therefore results in serious under-prediction of ramps
- Need a forecast system that is tuned to optimize prediction of ramp events

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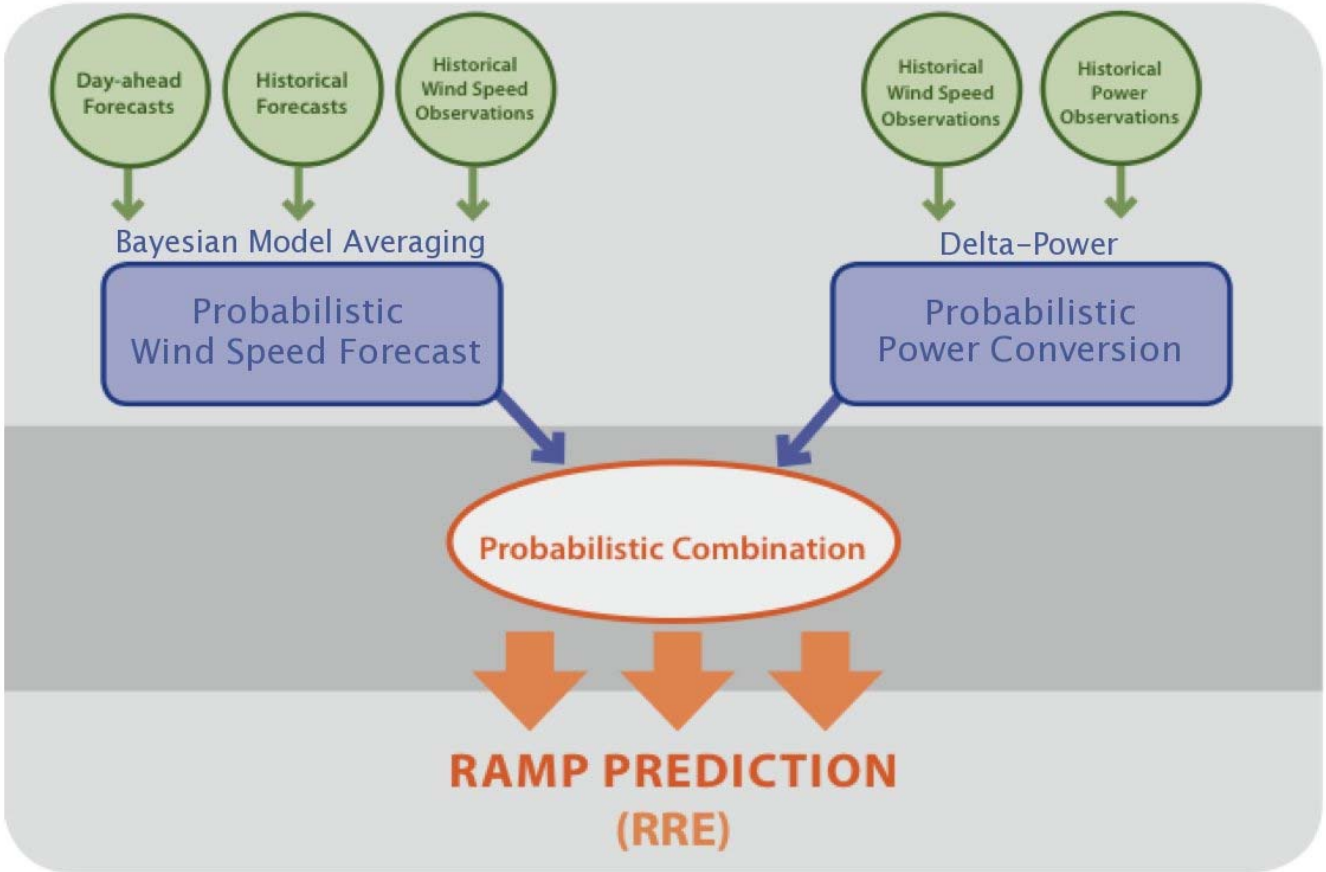
CHALLENGES FOR PREDICTION

- Timing
  - Example: Day-ahead forecasts of winter-time frontal passage on the west coast can be off by 6 h or more
- Intensity/Strength
  - Example: Small errors in offshore-onshore pressure gradients can result in poor land/sea breeze intensity
- Location
  - Example: Thunderstorm locations are difficult to forecast due to poor simulation of their initiation, development and decay processes

SOLUTION: ACCOUNT FOR THESE POTENTIAL ERRORS WITH A FULLY PROBABILISTIC SYSTEM

RRE PREDICTION METHODOLOGY

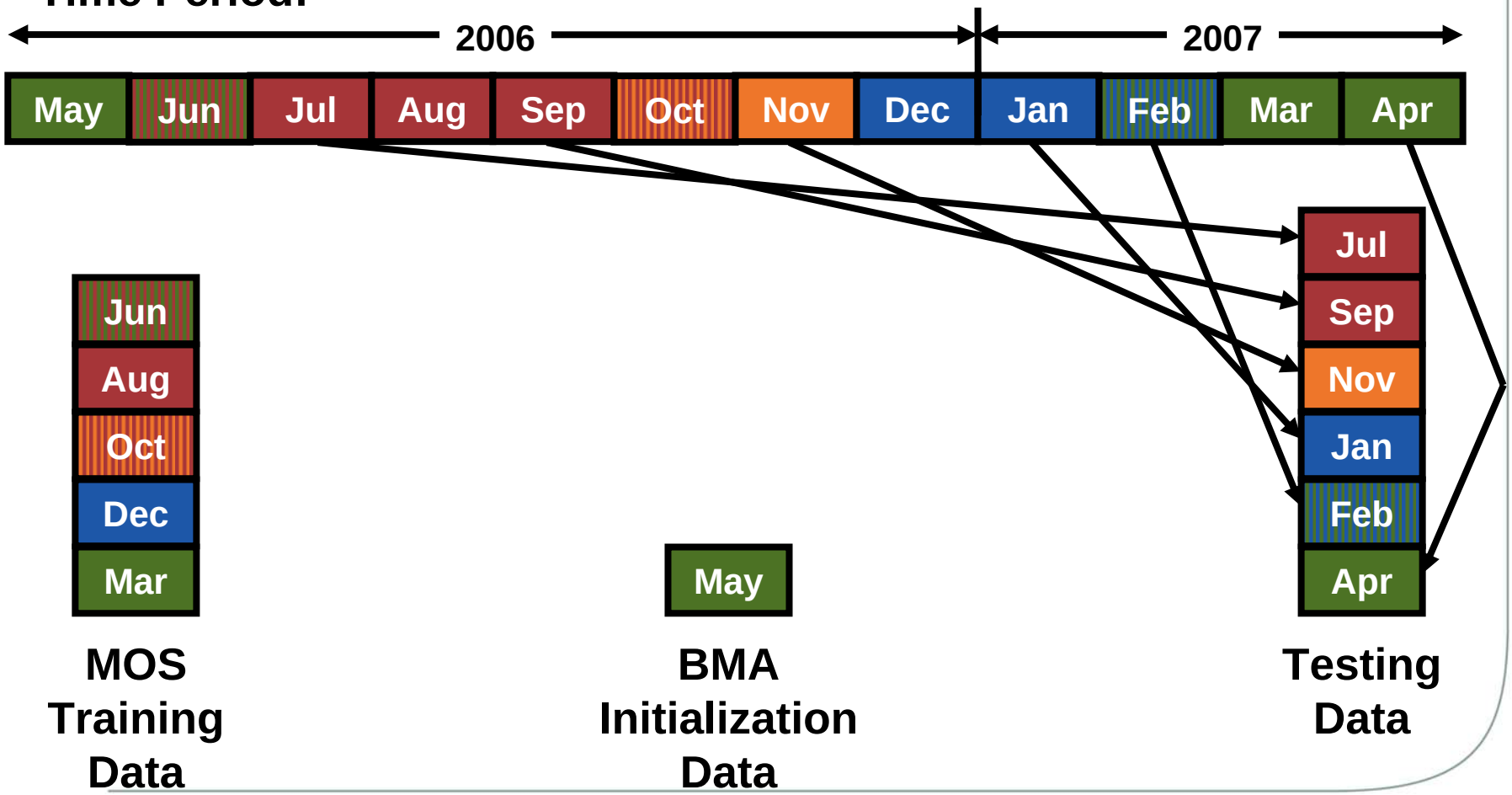


Combine probabilistic wind speed forecasts obtained via BMA at adjacent hours (times t and t-1) and the probabilistic power conversion for each hour using the appropriate Delta-Power curves to get a predictive PDF of the one-hour change in wind power.

PROTOTYPE DEVELOPMENT

Location: 3 BPA Wind Projects in Columbia Gorge, WA/OR

Time Period:



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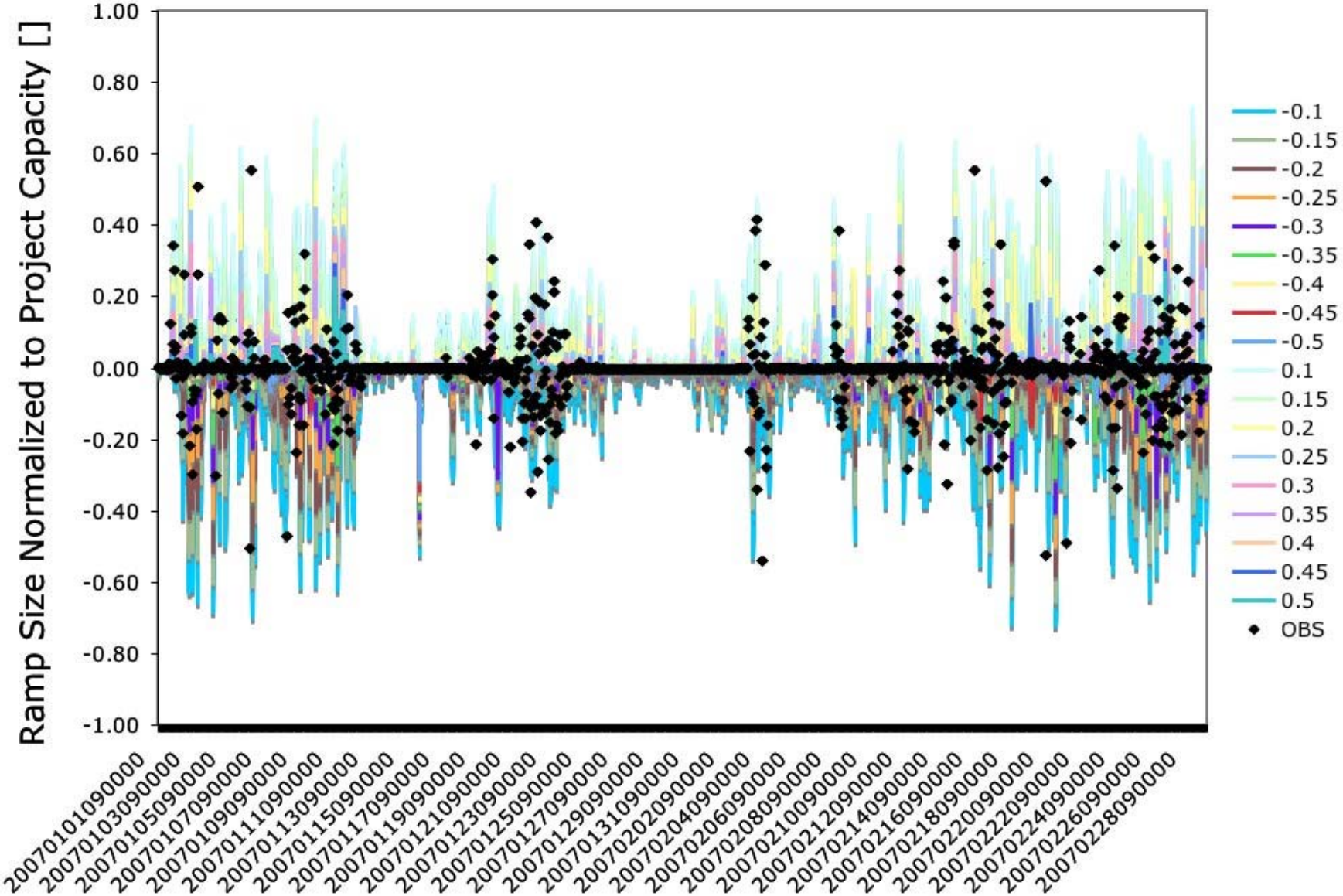
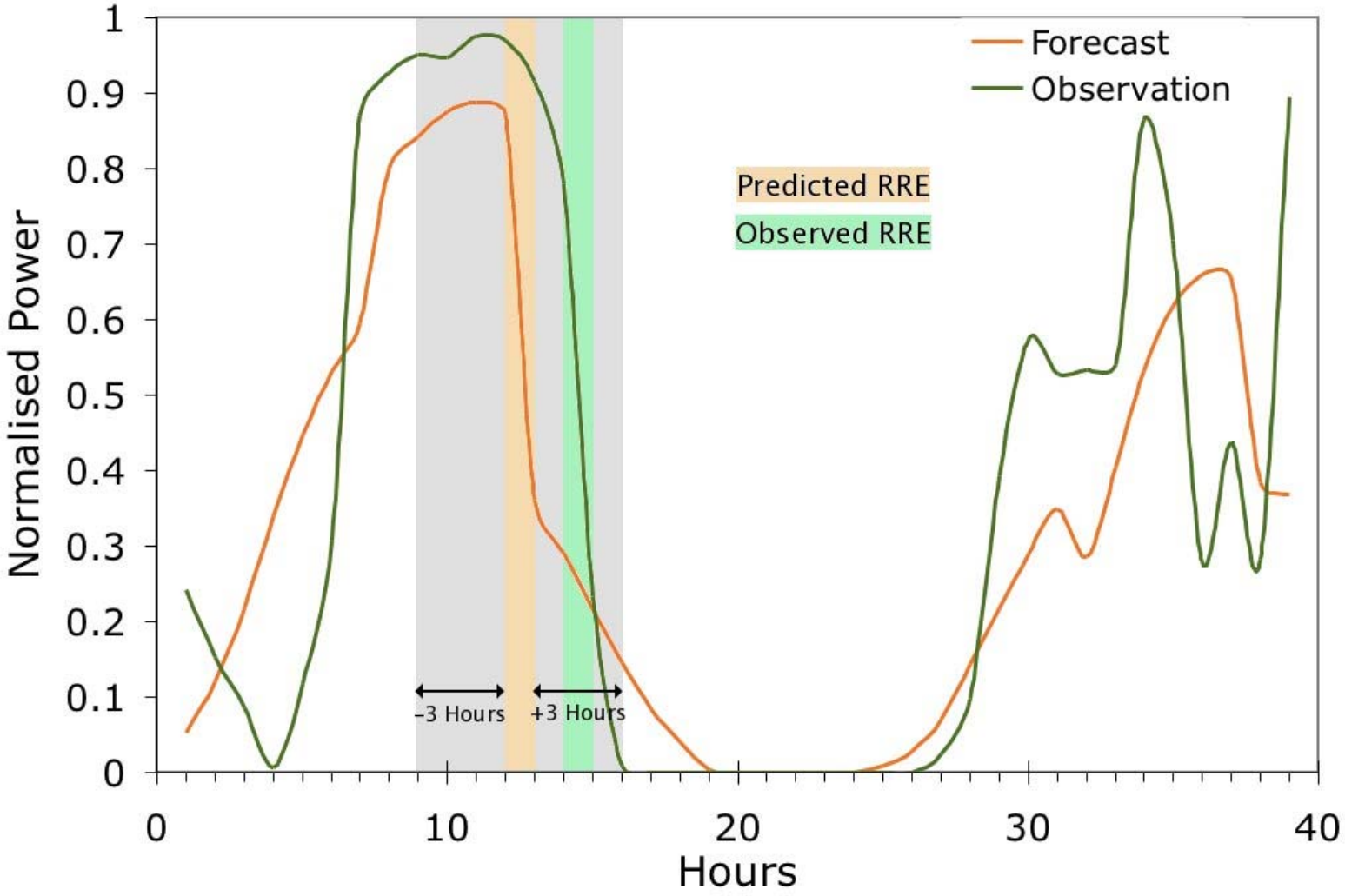
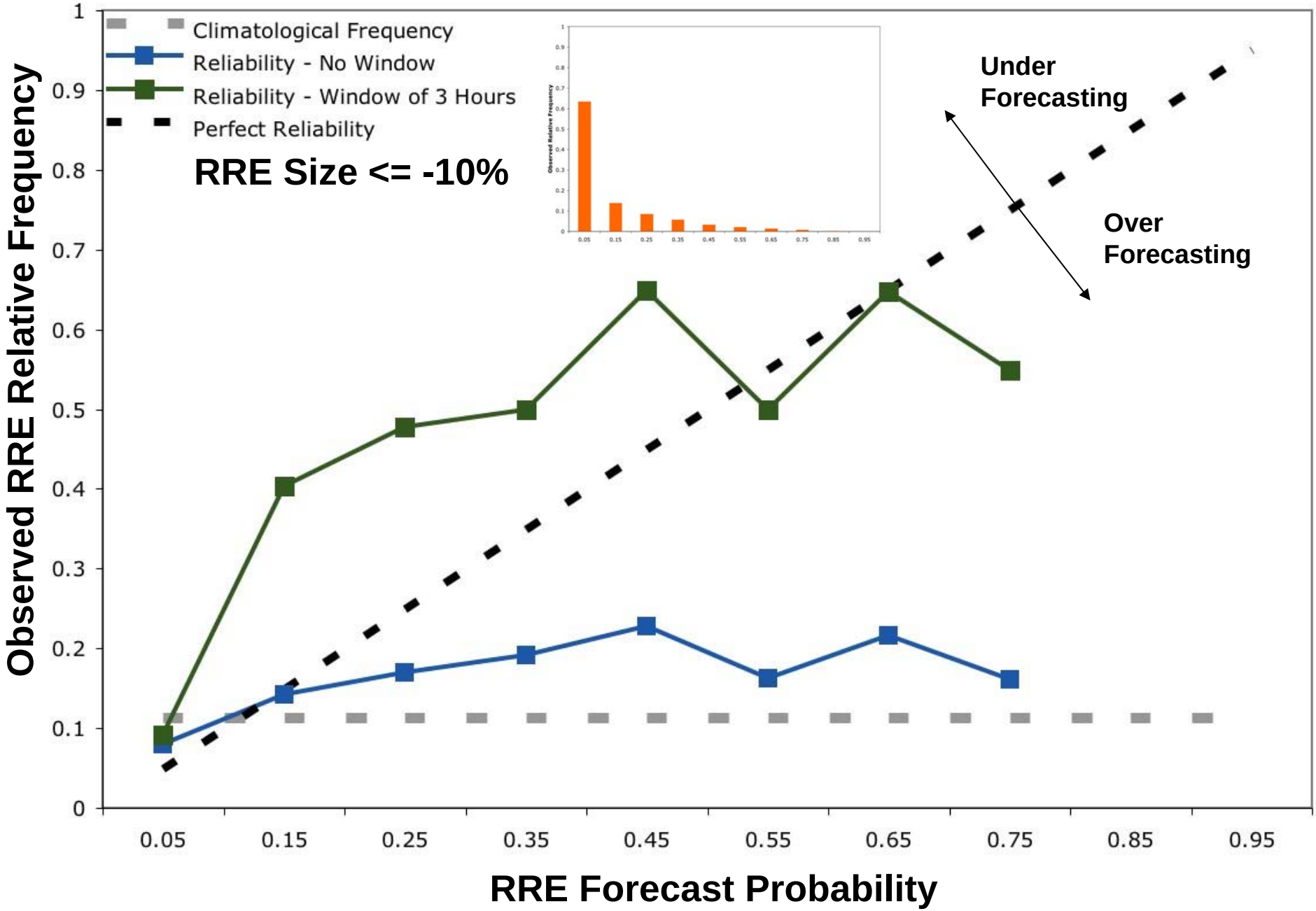
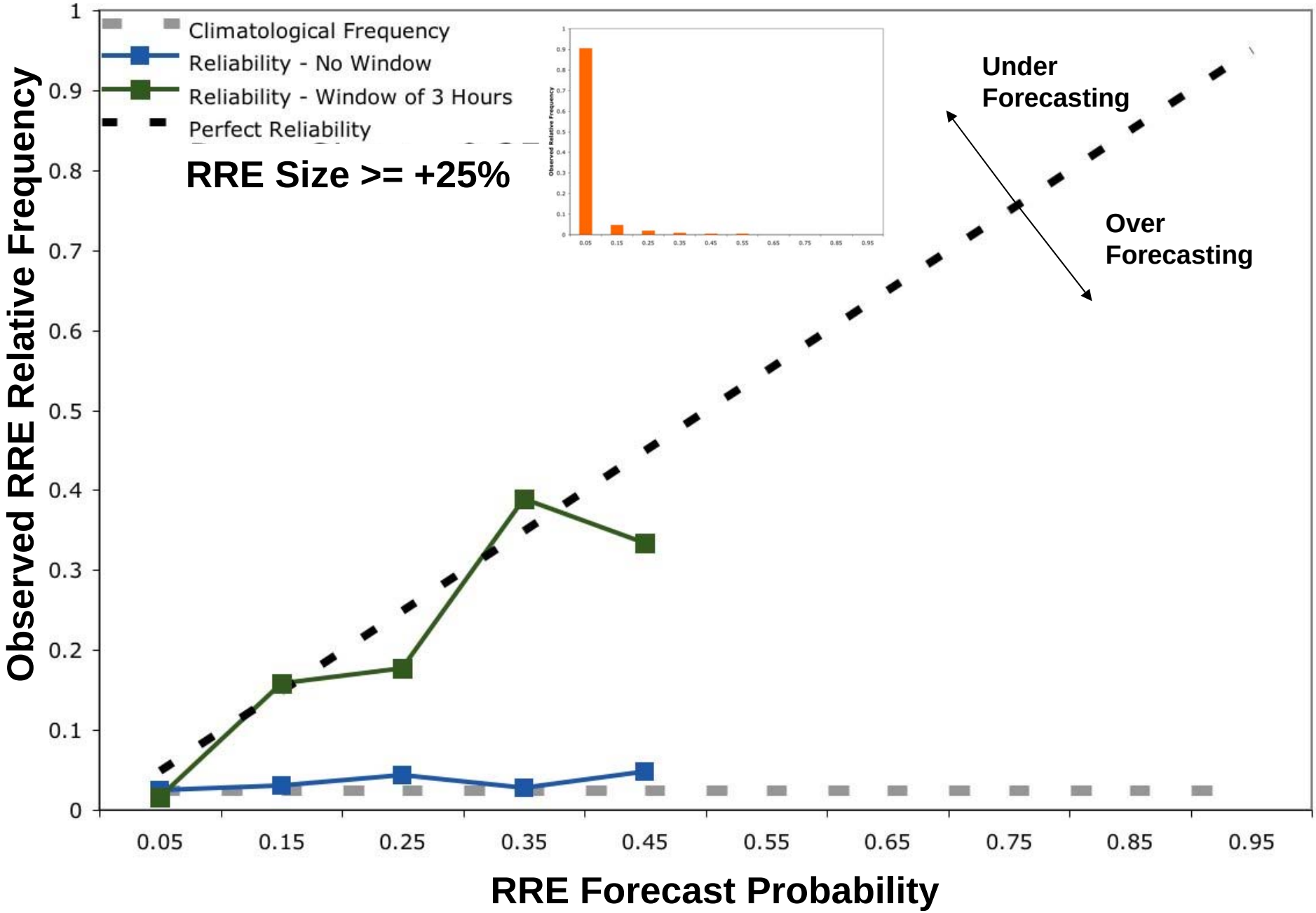
RAMP FORECAST TIME SERIES



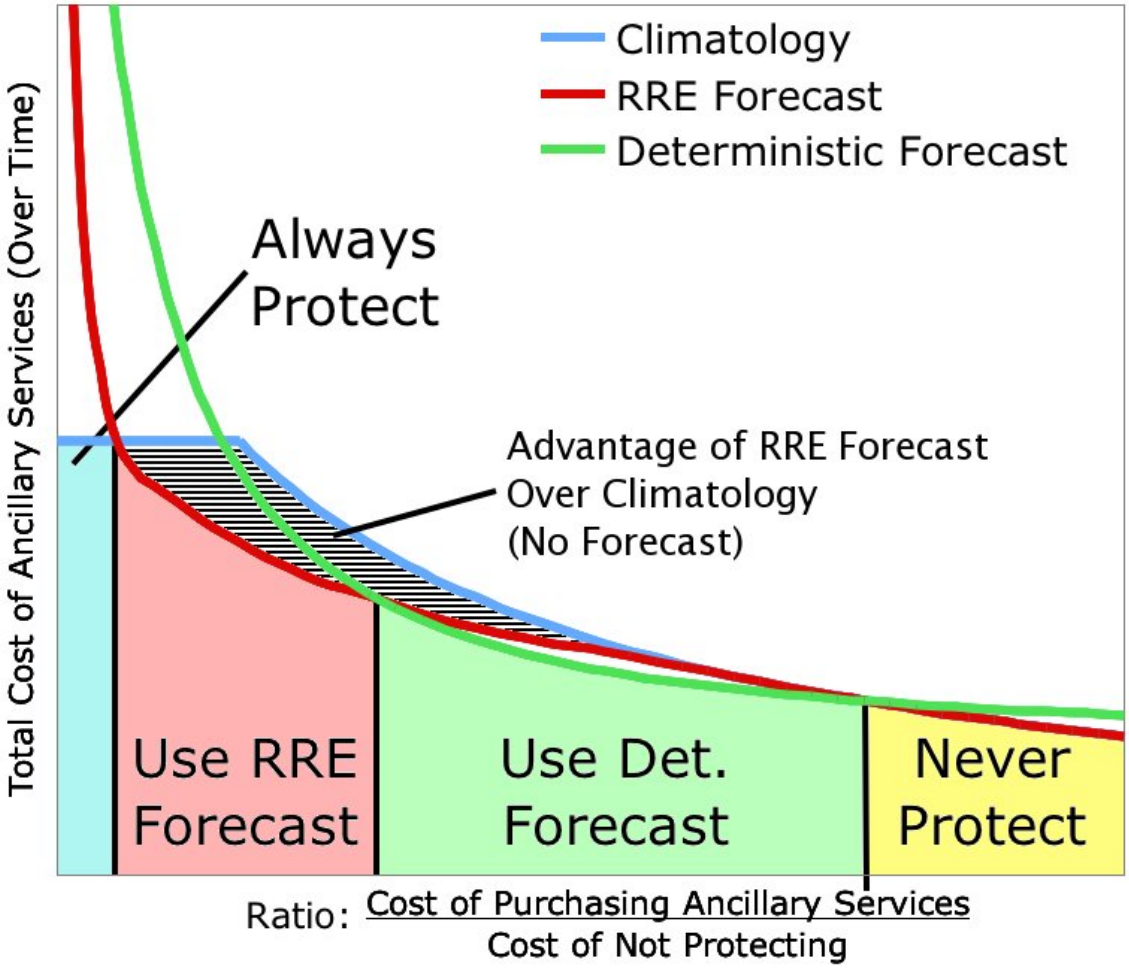
ACCOUNTING FOR TIMING ERRORS




Climatological Frequency
Reliability - No Window
Reliability - Window of 3 Hours
Perfect Reliability
RRE Size <= -10%
Under Forecasting
Over Forecasting
Observed RRE Relative Frequency
RRE Forecast Probability
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.05
0.15
0.25
0.35
0.45
0.55
0.65
0.75
0.85
0.95


Climatological Frequency
Reliability - No Window
Reliability - Window of 3 Hours
Perfect Reliability
RRE Size >= +25%
Under Forecasting
Over Forecasting
Observed RRE Relative Frequency
RRE Forecast Probability
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.05
0.15
0.25
0.35
0.45
0.55
0.65
0.75
0.85
0.95

WHEN TO USE THE RRE FORECAST



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INTRA-HOUR FORECASTS

- 3TIER is presently working on a project funded by BPA to produce intra-hour forecasts.
- BPA proposes to use this short-term forecast as an input to “feed-forward” automatic generation control (FFAGC).
- To be useful in such a system the forecasts have two major requirements: Accuracy & Reliability.
- However, this work is still in its early stages and it is too soon to report our findings.

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HOUR-AHEAD RAMP FORECASTING

- Another BPA project in the pipeline for 3TIER is to produce an accurate ramp tracking system for the hour-ahead timescale.
- Conceptually, this system will refine the RRE probability forecast from the day-ahead, then use local observations to dynamically correct the timing and magnitude of the forecasted ramp events.

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