Power System Performance with 30% Wind Penetration

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Outline

- Objective
  - To characterize the effect of wind variability on power systems
- Method
  - Wind variability mitigated through geographic diversity, and then other system resources
  - Represent remaining variability with distribution of forecast errors
  - Uncertainty incorporated via Monte Carlo Simulation
  - Power system modeling via OPF
- Results: Quantify system performance

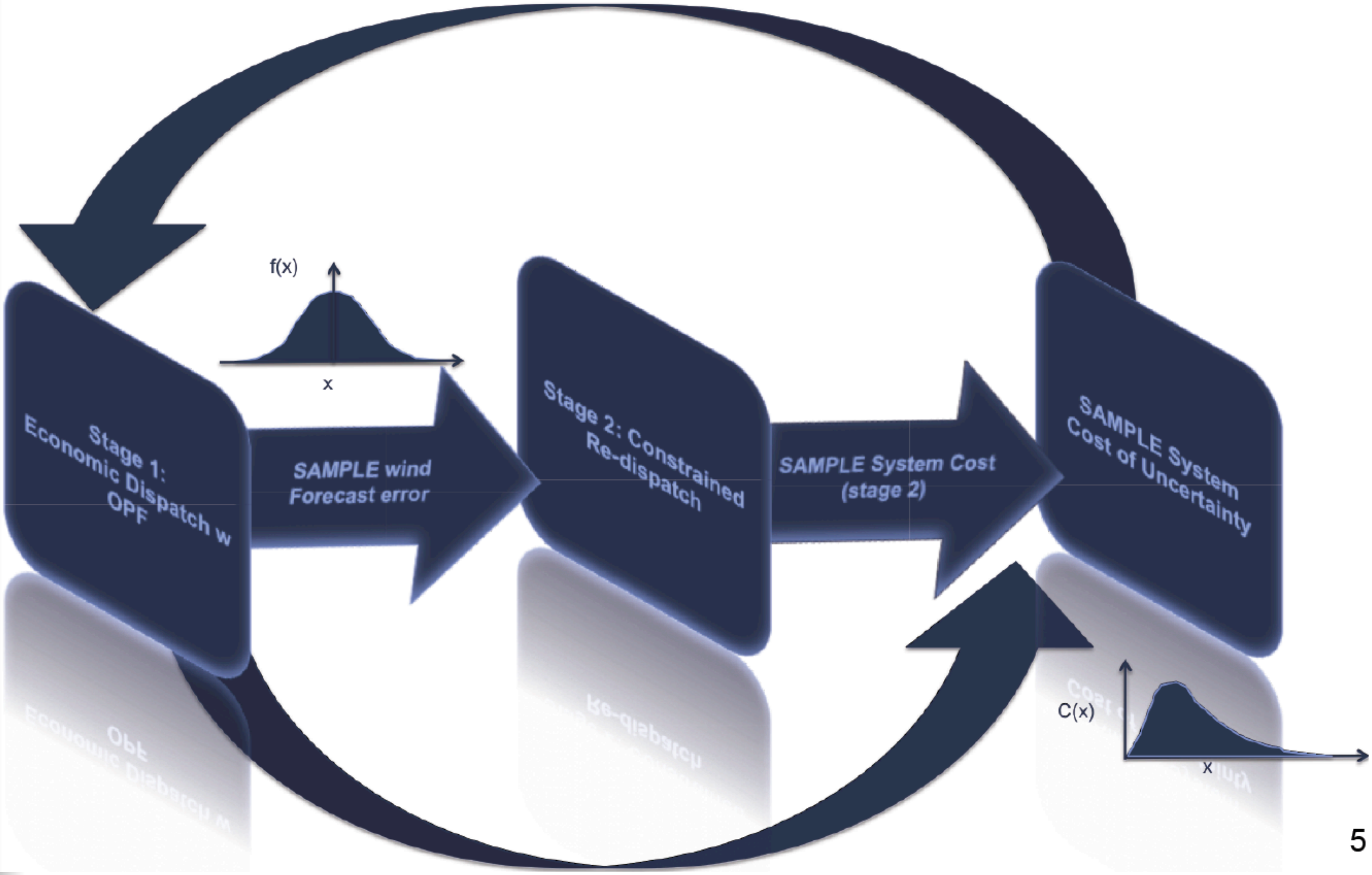
Modeling Objective

- Quantify the effect of wind variability on power system operations
- Monte Carlo + OPF analysis shows impact of uncertainties on system behavior
- System impacts:
  - Costs: Production cost, LMP
  - Other: losses, voltage, flows

Integrating OPF with MCS

- Uncertainty is introduced to the OPF dispatch problem with a MCS approach
- Forecast error is a stochastic variable, impacting the system behavior
- The MCS and OPF are integrated as follows:

OPF & Monte Carlo Simulation Flow Chart



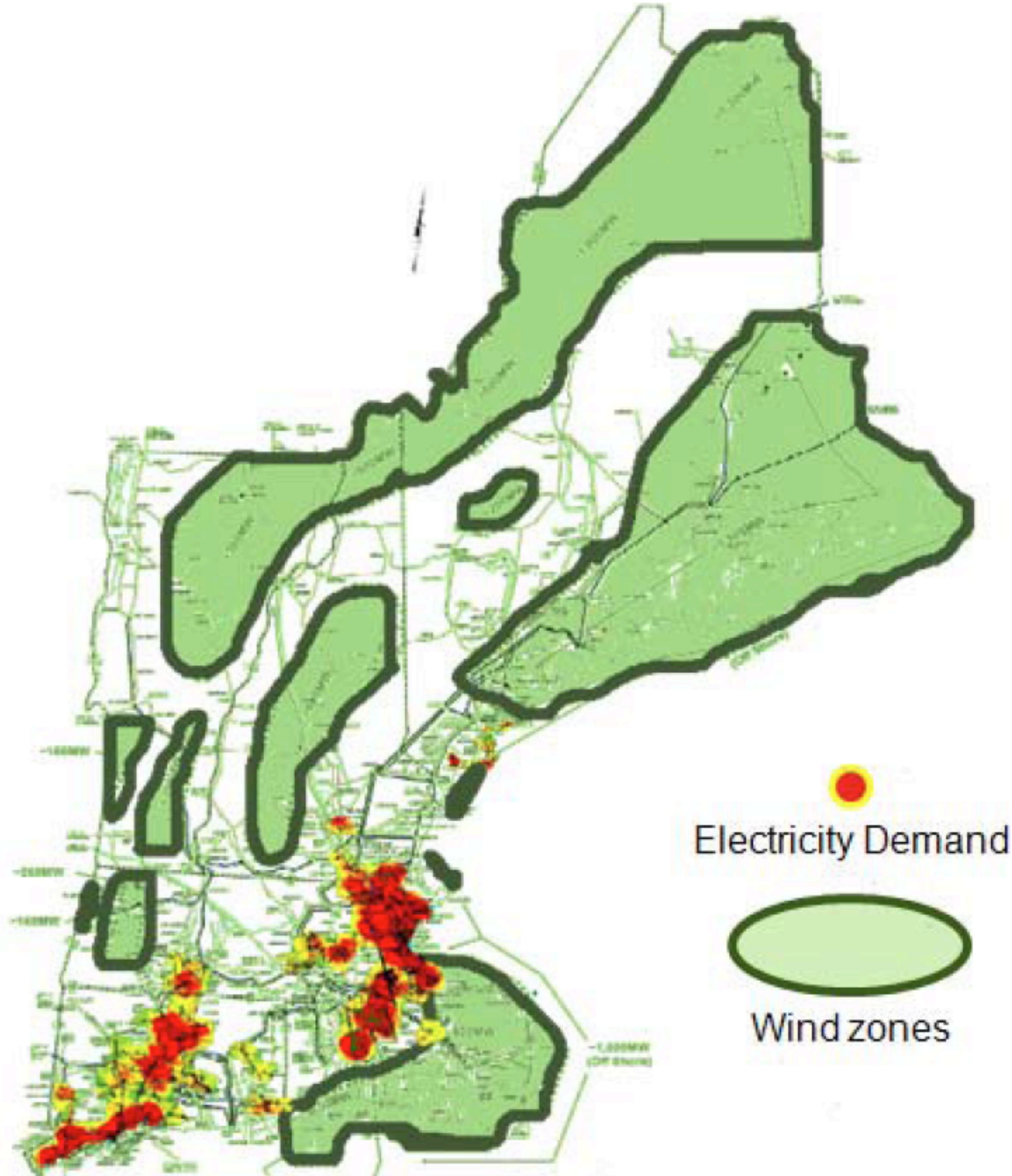
Capturing Forecast Uncertainty

- A key element of is the distribution of forecast errors for MCS
- Requires
  - Forecast
  - Distribution of forecast errors
- Forecast error data is generally proprietary
- Generate distribution of errors via forecasting with observed data

Wind Speed Data & Modeling Wind Farms

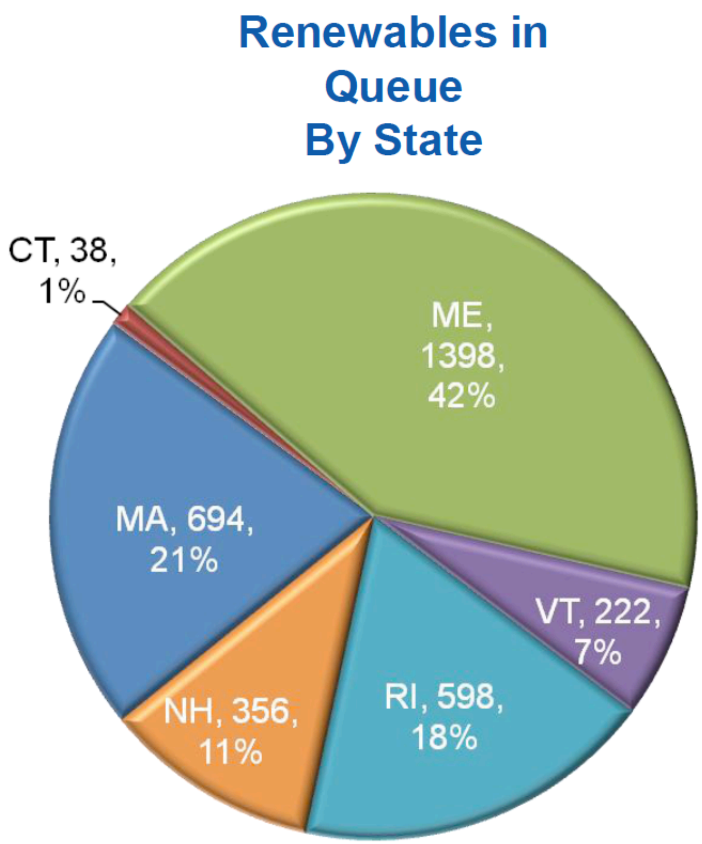
- "*New England Governors' Renewable Energy Blueprint*," Sept. 15, 2009
- NREL Eastern Wind Dataset provides the wind speed and location data
- Data set provides
  - "Feasible" wind farm locations
  - Hourly (simulated) wind speeds
  - Hourly (simulated) wind outputs
  - correlations between sites
  - Wind output forecast at various time periods

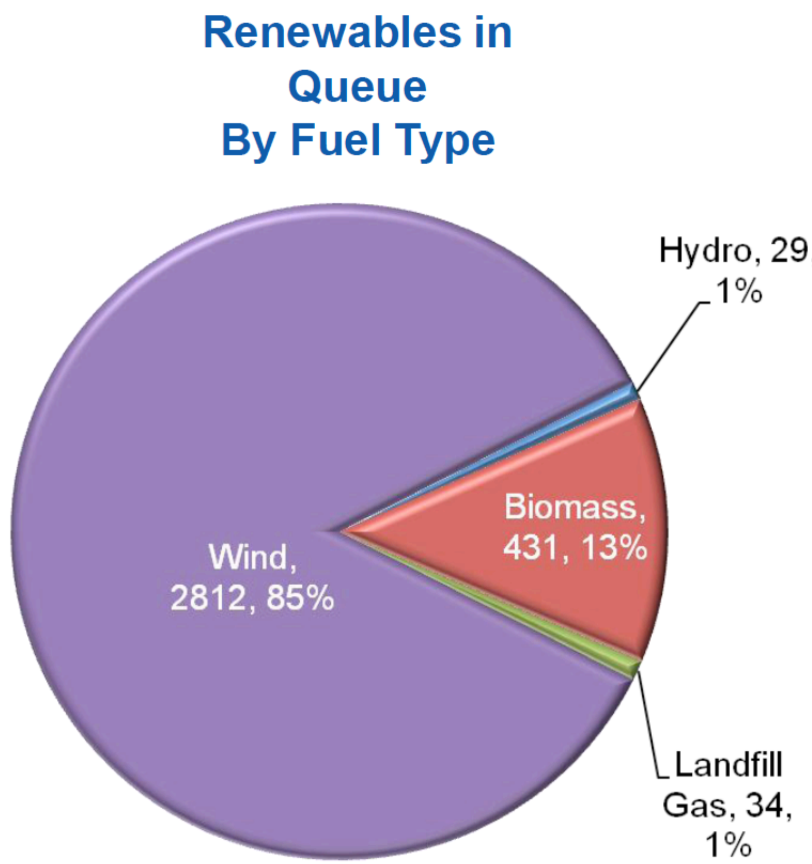
New England: Potential Wind Zones & Load Centers



Gordon van Welie, *ISO on Background – New England Wind Integration Study,* Dec. 15, 2010

Renewables Queue in N.E.





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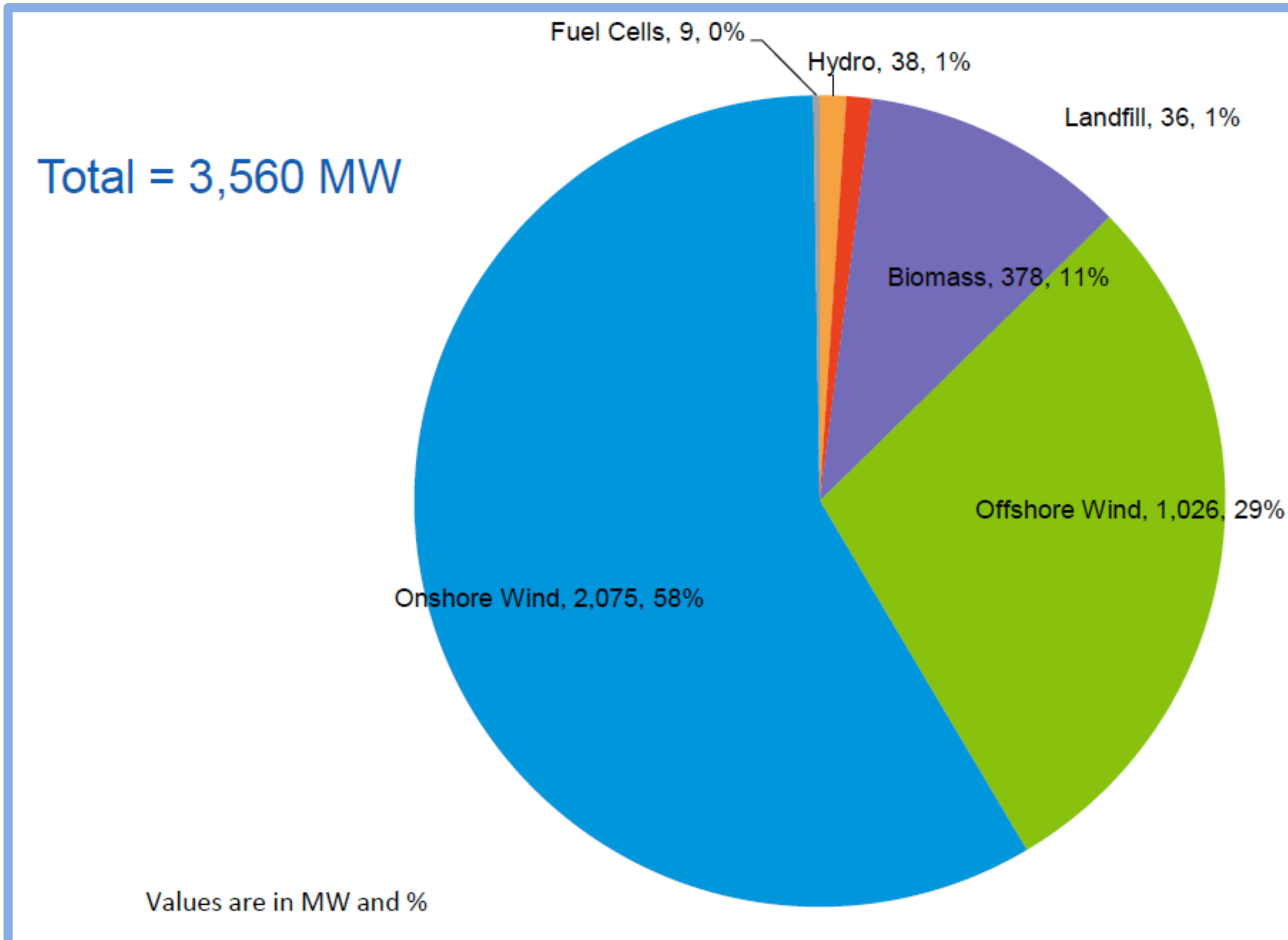
ISOne Queue: Renewables



Matt Garber, isonewengland.net/committees/comm_wkgrps/prtcpnts_comm/pac/mtrls/2010/may252010/rps.pdf

Wind Projects in N.E. Queue
(ISO Best Site Selection)
8.8GW, 20% annual energy
Requires 4 GW Tx expansion

	Onshore			**Offshore**			**Total**			**Capacity Factor (%)**		
State	# of sites	Name Plate (GW)	Energy (GWh)	# of sites	Name Plate (GW)	Energy (GWh)	# of sites	Name Plate (GW)	Energy (GWh)	On shore	Off shore	Total
CT	-	-	-	-	-	-	-	-	-	-	-	-
ME	33	3.372	9,571	4	1.5	5,169	37	4.872	14,740	32%	39%	35%
MA	3	0.059	183	2	1.498	5,800	5	1.557	5,983	35%	44%	44%
NH	8	0.647	2,096	-	-	-	8	0.647	2,096	37%	-	37%
RI	-	-	-	7	1.513	5,657	7	1.513	5,657	-	43%	43%
VT	5	0.209	584	-	-	-	5	0.209	584	32%	-	32%
Tot.	49	4.287	12434	13	4.511	16,626	62	**8.8**	**29,060**	34%	42%	38%

www.windpoweringamerica.gov/newengland/pdfs/2010/webinar_neweep_wind_impacts_henson_presentation.pdf

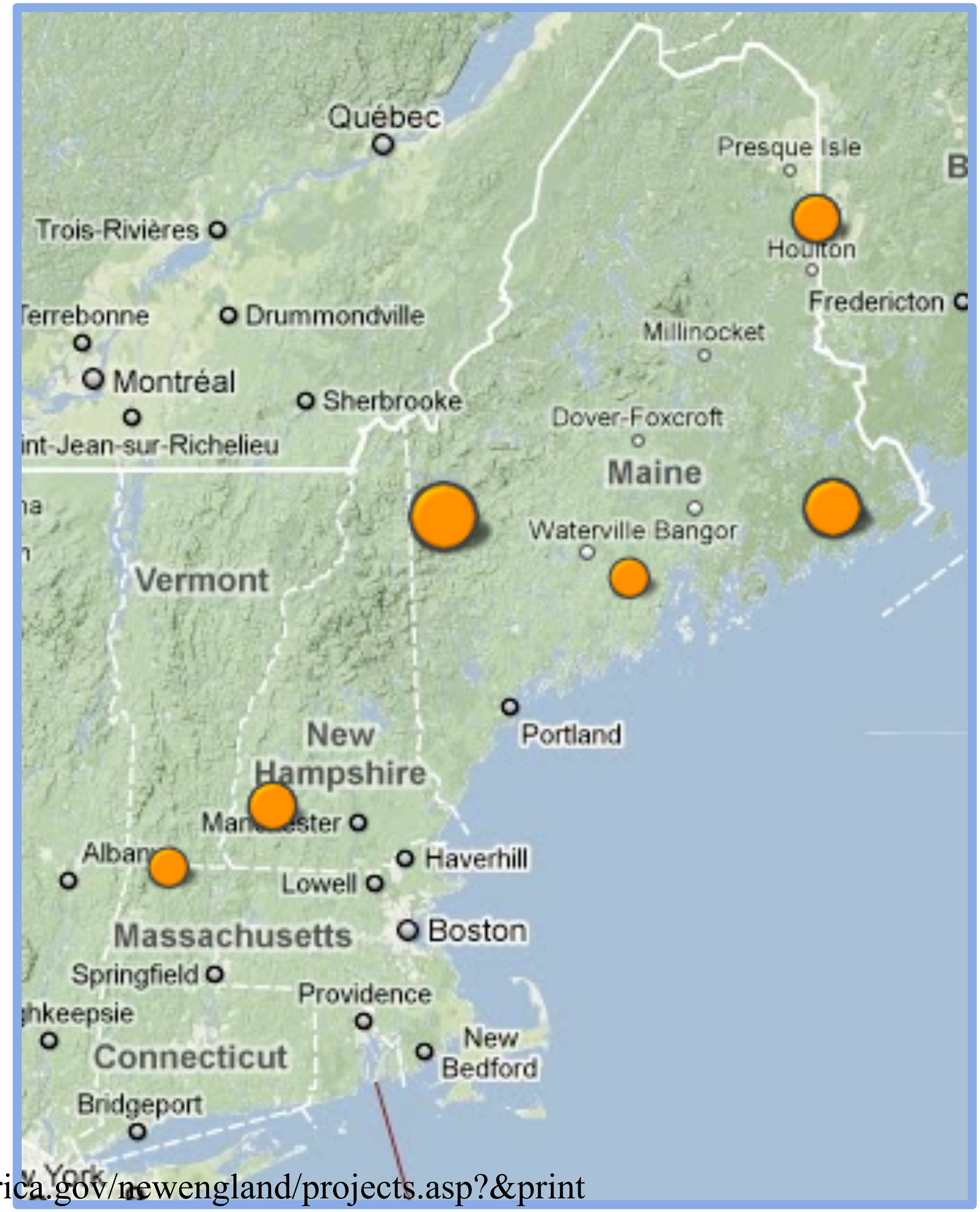
Wind Projects in New England

Project Name	City	Stat	Size	Status
Beaver Ridge Wind Project	Freedom	ME	4,500	Operating
Kibby Wind Power Project	Kibby Mountain	ME	132,000	Operating
Lempster Wind Project	Lempster	NH	24,000	Operating
Mars Hill Wind Farm	Mars Hill	ME	42,000	Operating
Owl and Jimmy Mountain	Unorganized terr	ME	25,500	Operating
Searsburg Wind Power Project	Searsburg	VT	6,600	Operating
Stetson Ridge Wind Project	Unorganized terr	ME	57,000	Operating

Total = 291.6 MW

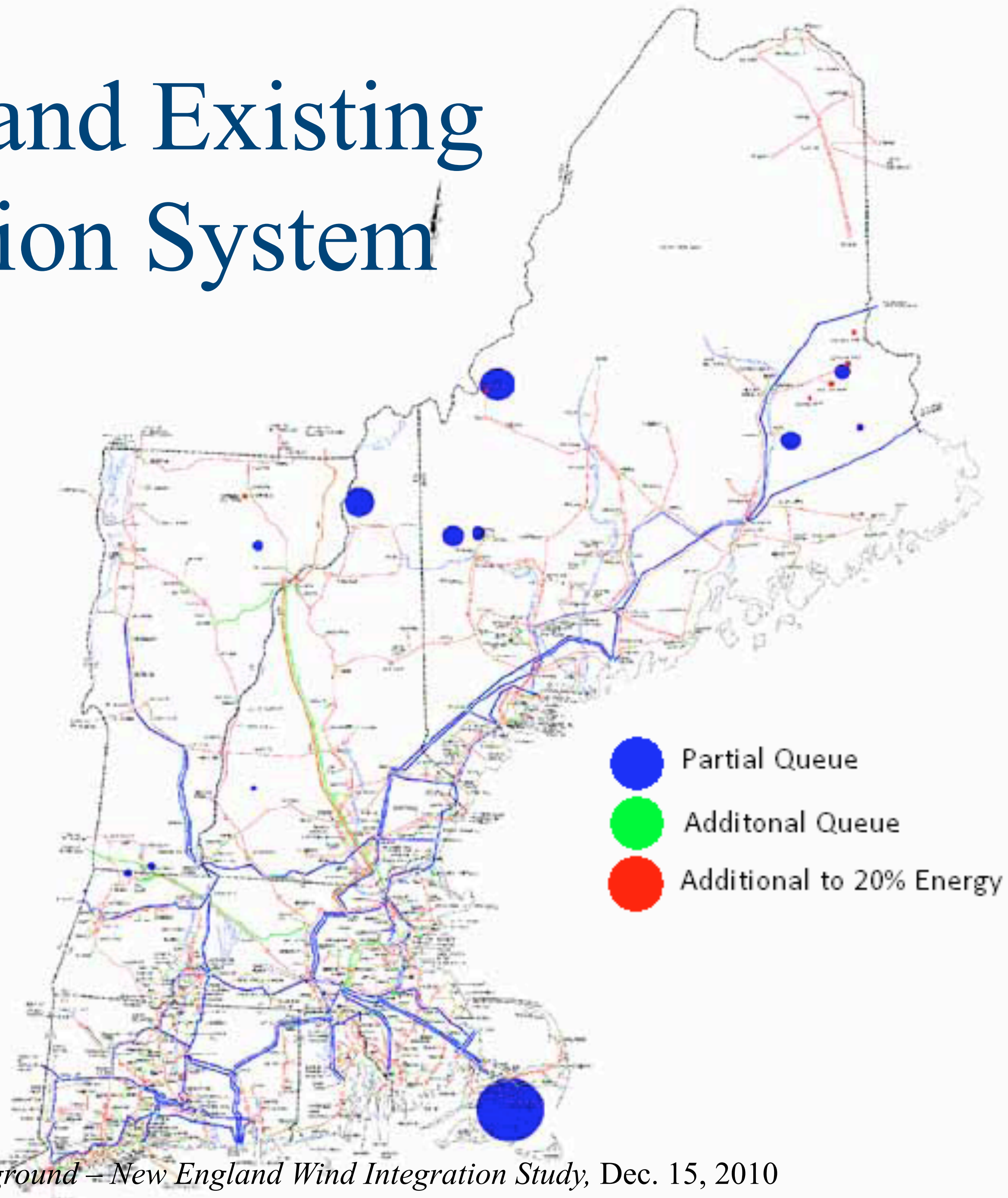
http://www.windpoweringamerica.gov/newengland/projects.asp?&print

Wind Projects in New England



http://www.windpoweringamerica.gov/newengland/projects.asp?&print

New England Existing Transmission System



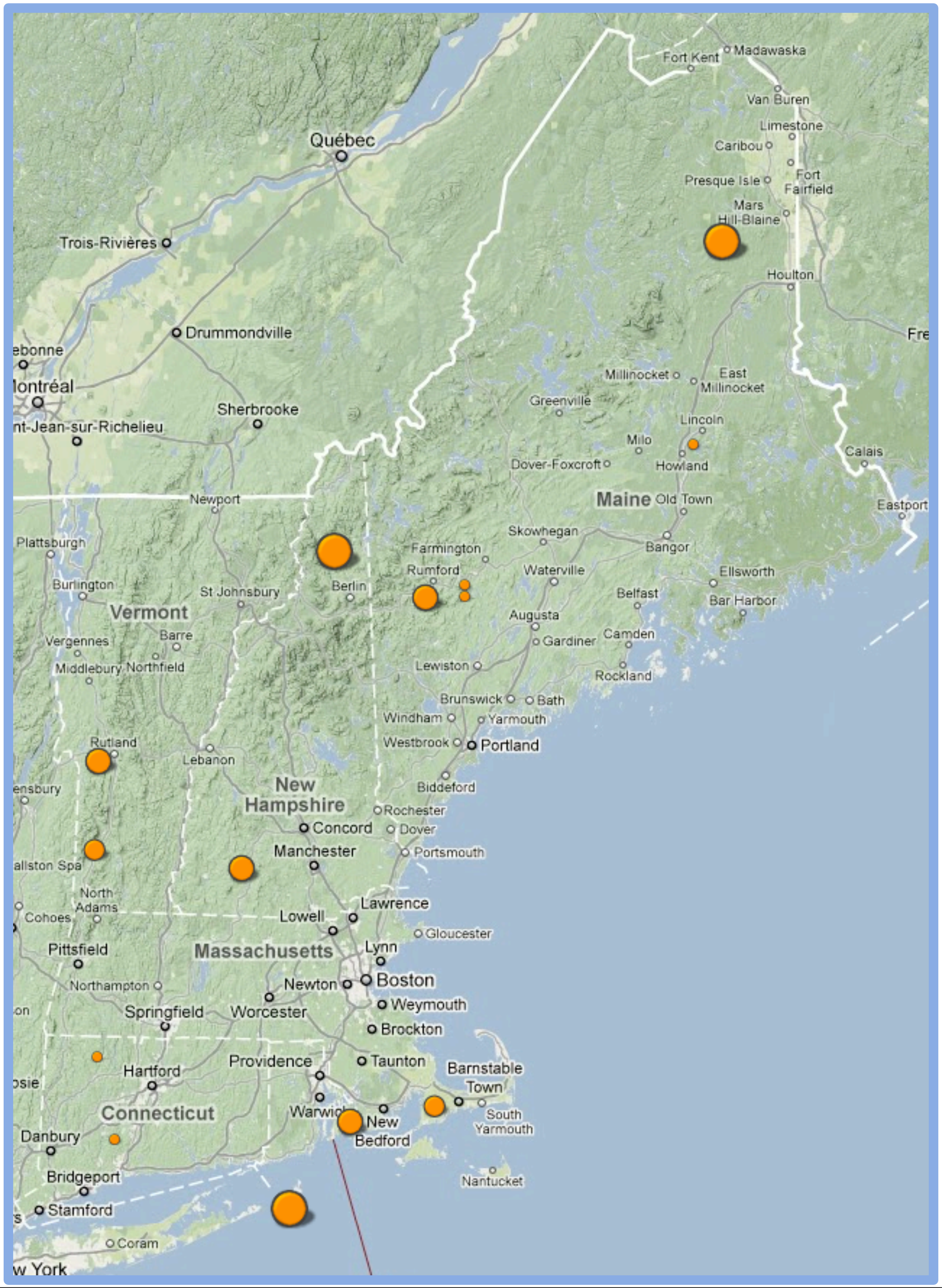
Gordon van Welie, *ISO on Background – New England Wind Integration Study,* Dec. 15, 2010

Projects under Development

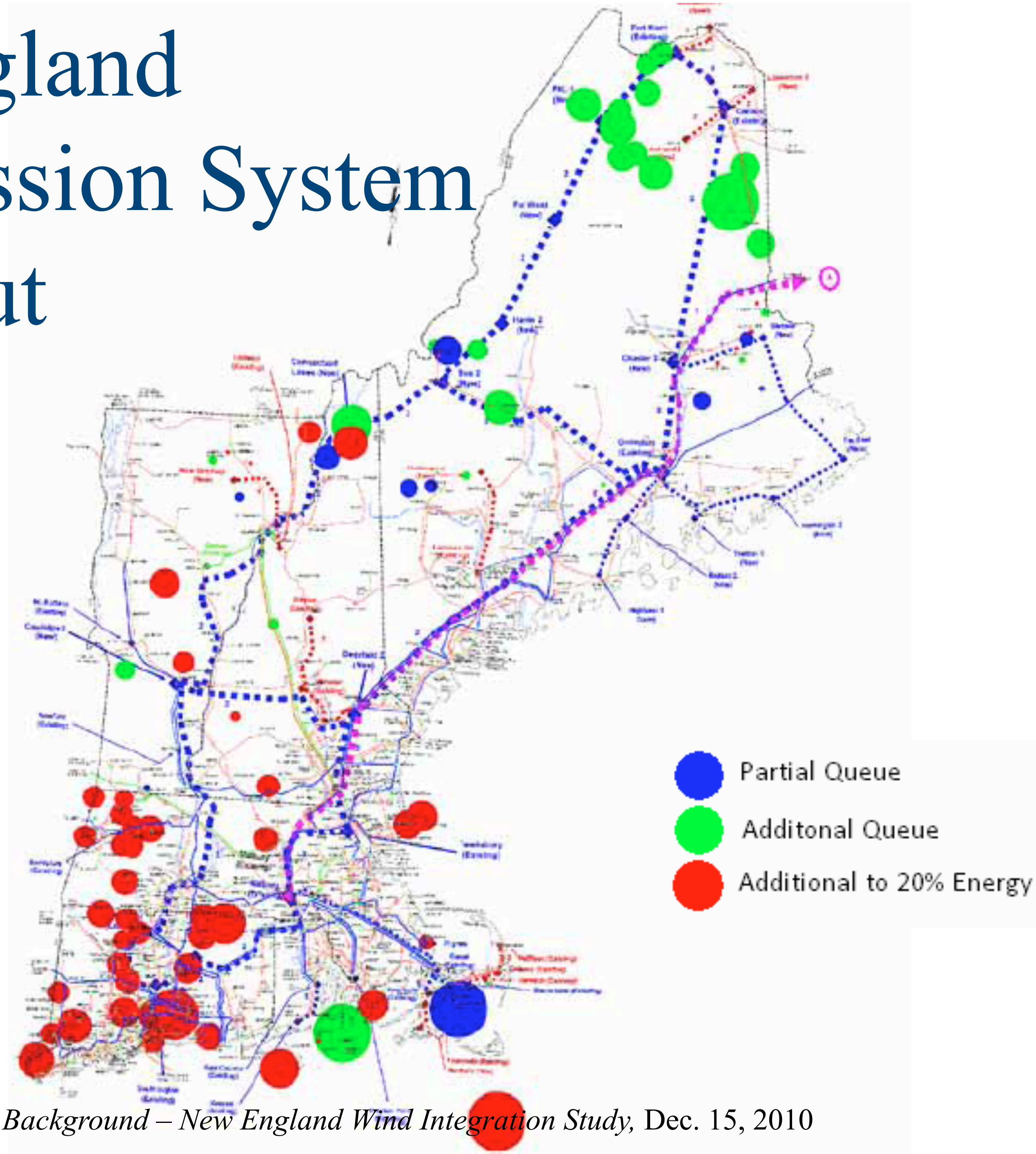
Project Name	City	Sta	Size (kW)
Deep Water Phase II	Offshore	RI	380,000
Eco-Industrial Park of RI	Tiverton	RI	24,000
Equinox Wind Farm	Little Equinox, M	VT	9,000
Grandpa's Knob Windpark	West Rutland an	VT	50,000
Longfellow Windpark	Rumford	ME	50,000
Massachusetts Military Reservation Phase	Bourne	MA	7,500
North Country Wind	Coos County	NH	180,000
Number 9	Aroostook Count	ME	350,000
Passadumkeag Mountain	Penobscot Count	ME	
Timber Wind - Canton	Canton	ME	
Timber Wind - Dixfield	Dixfield	ME	
Tuttle Hill - Antrim	Antrim	NH	18,000
Wind Colebrook	Colebrook	CT	
Wind Prospect	Prospect	CT	

Total = 1,068.5+ MW

Wind Projects under Develop-ment



New England Transmission System Build-Out



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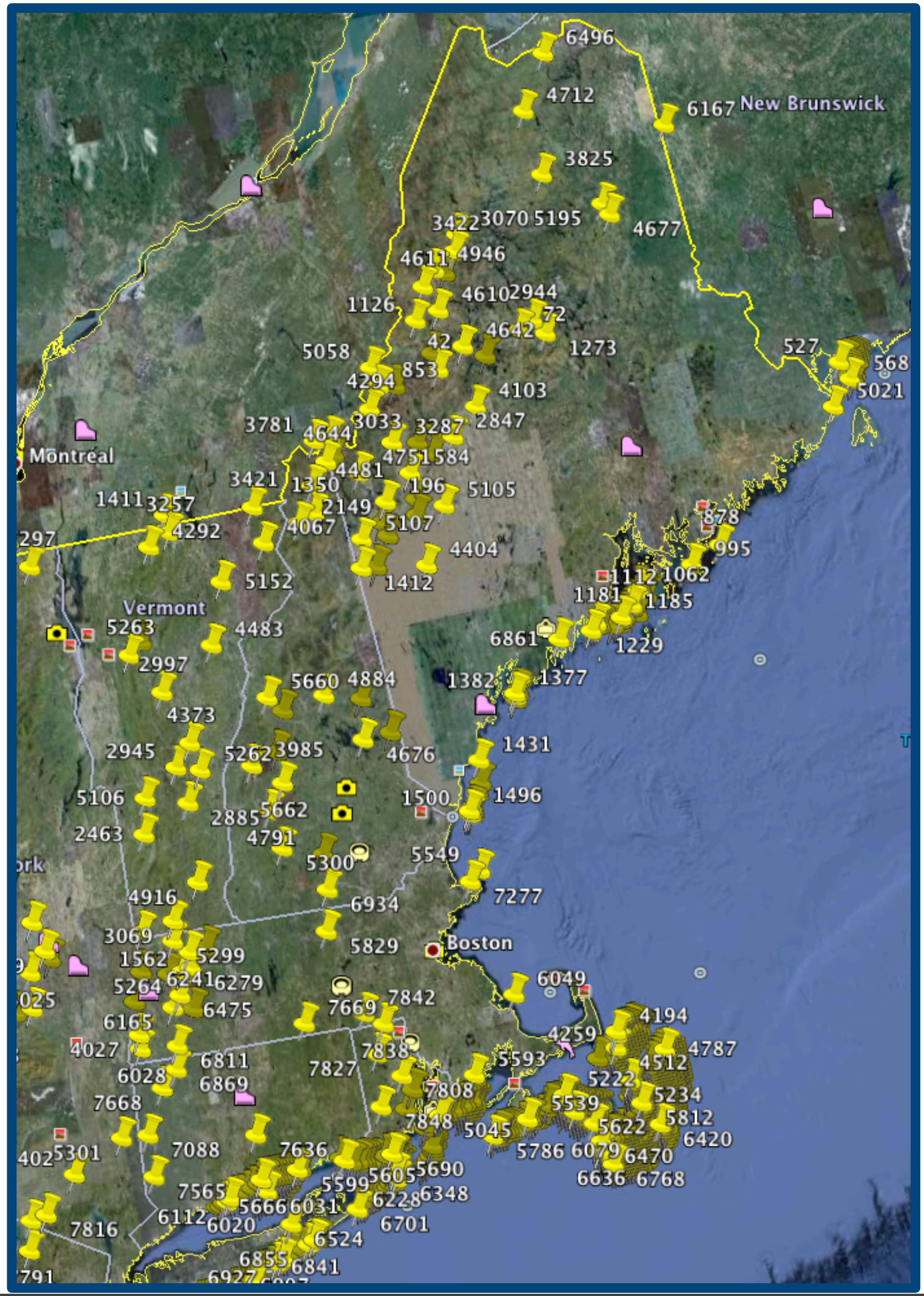
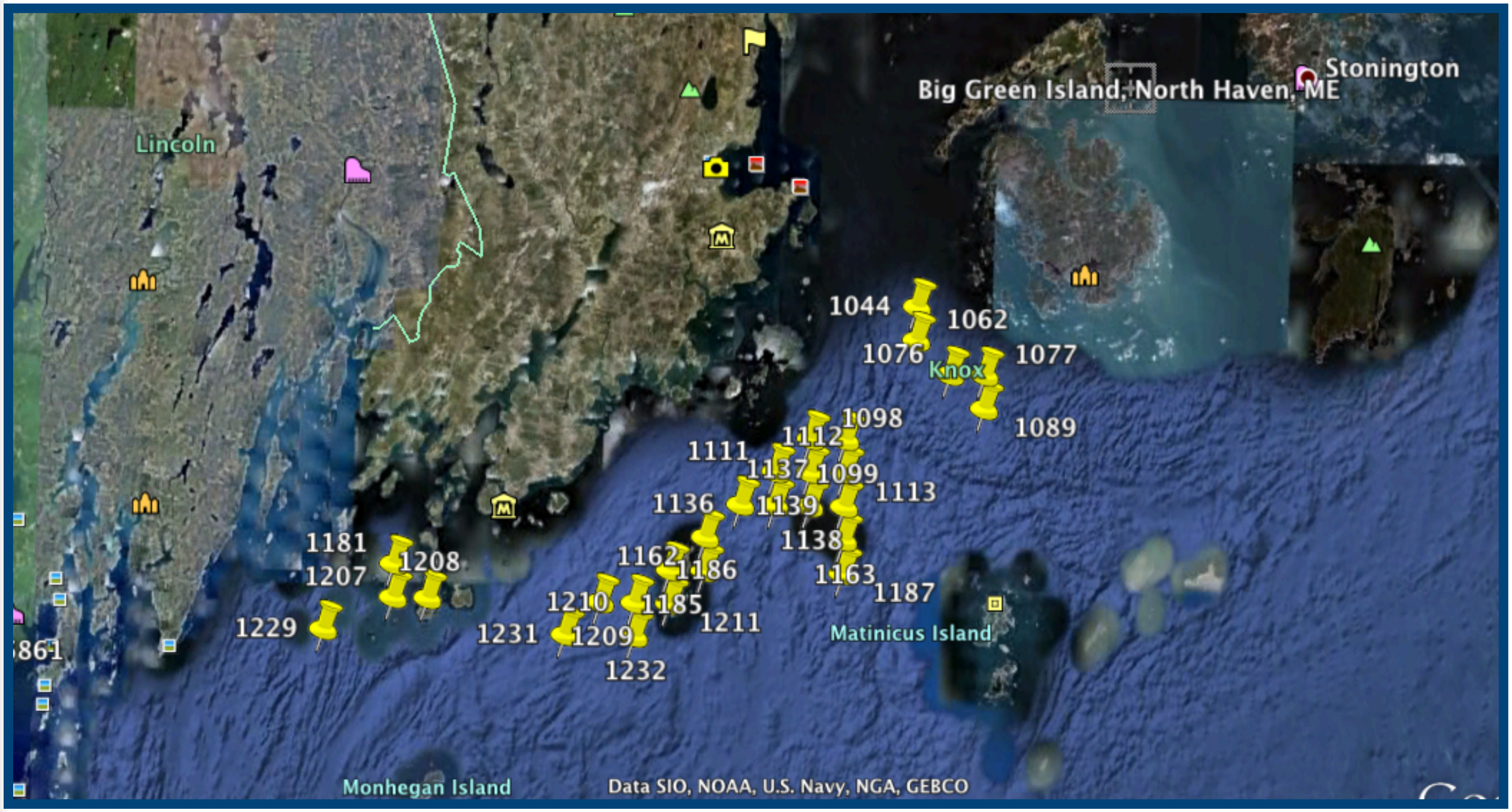
New England: NREL Wind Sites



NREL Data Set



Distribution of forecast errors

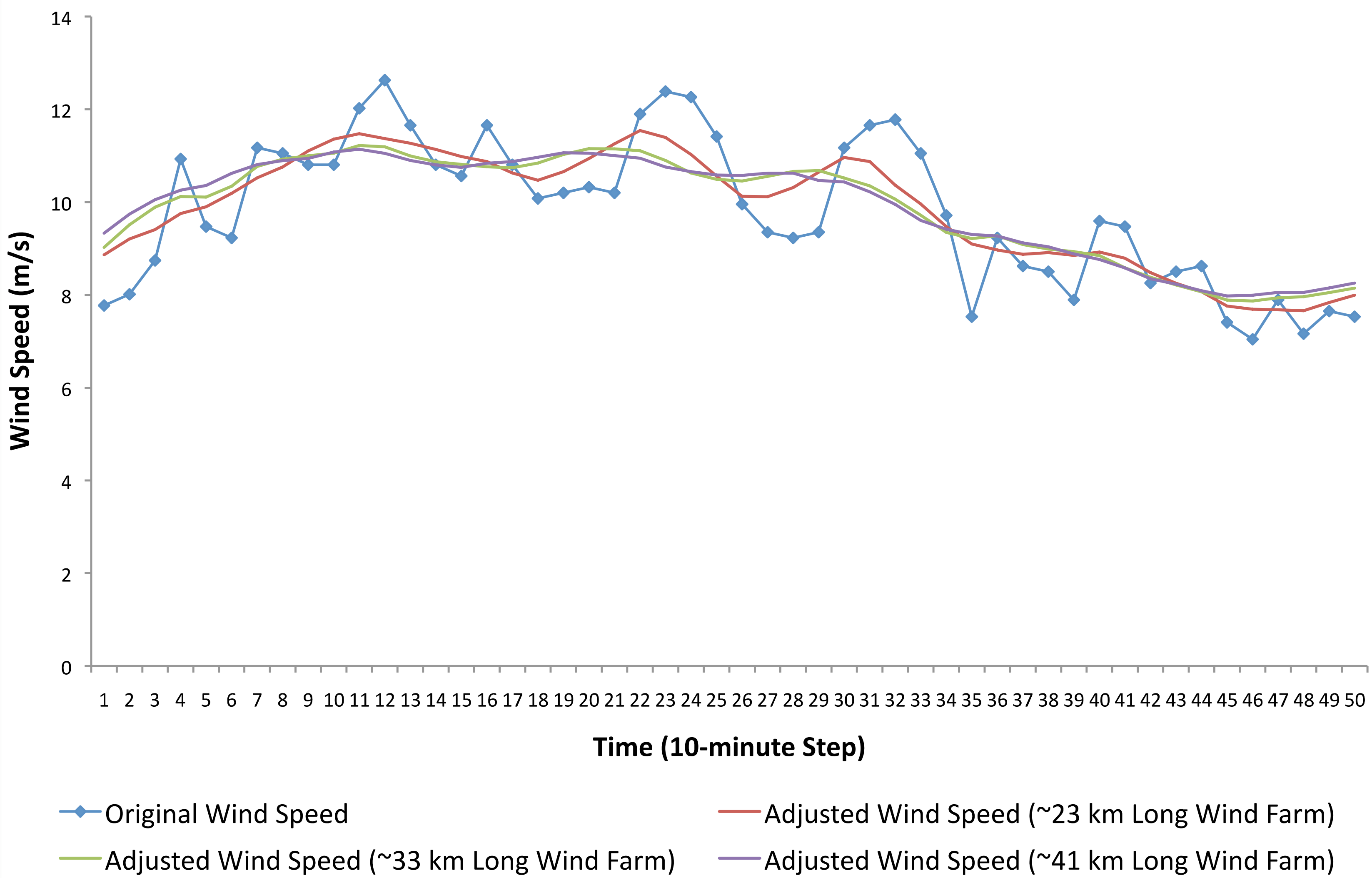
- NREL sites are selected in New England,
  - 2 offshore
  - 3 onshore
- Wind speed data sets are used for each site to
  - Develop hour ahead forecasts
  - Generate wind generation data sets

Wind Speed to Generation

- Wind speeds are converted to generation using the algorithm in [1]
- a two-step process to address wind speed and aggregation of power curves
  - Smoothing wind speeds to represent larger area
  - Development of aggregated power curve to represent large number of turbines

[1] Norgaard and Holttinen. A Multi-Turbine Power Curve Approach. Nordic Wind Power Conference (2004) pp. 1-5

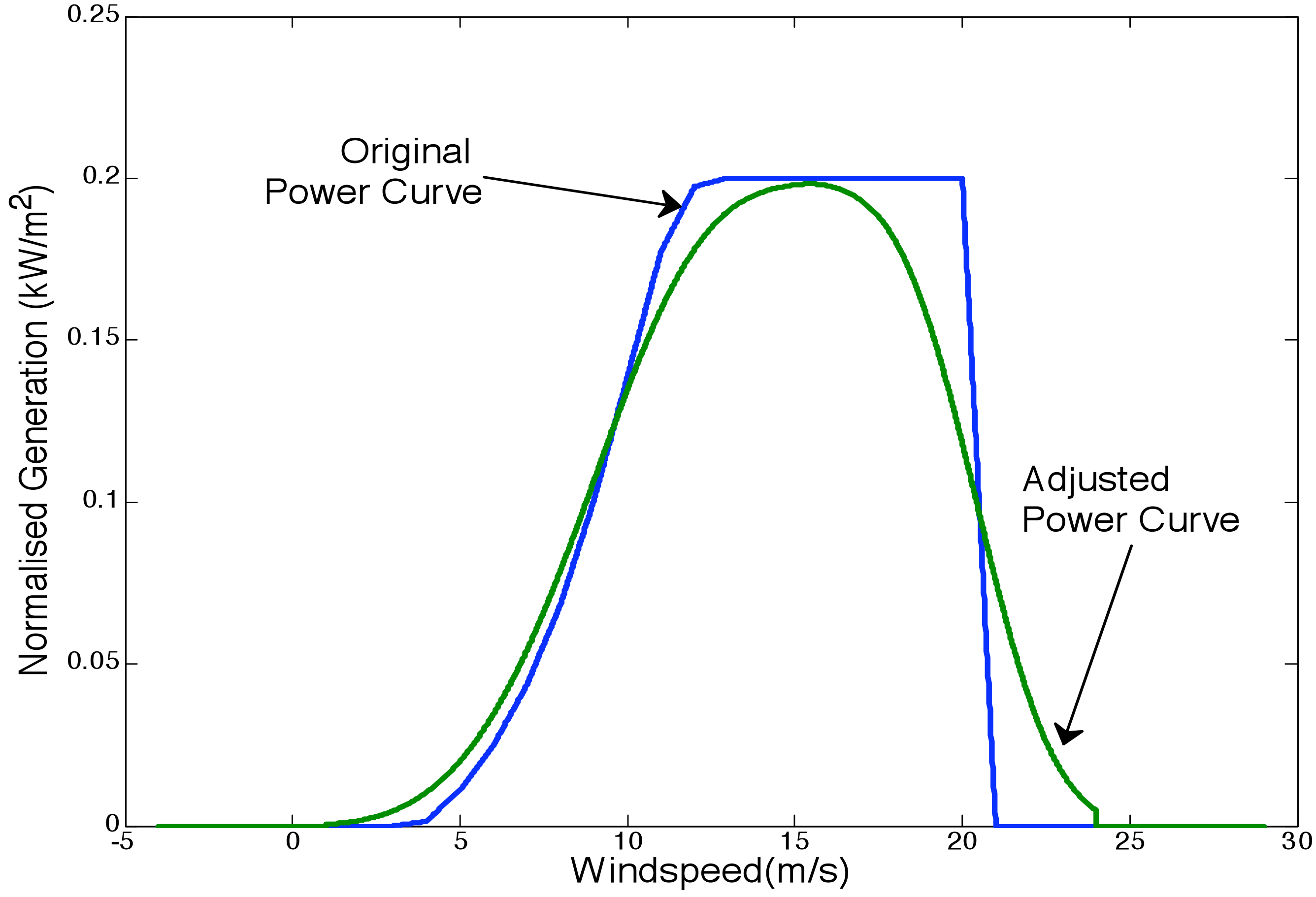
Spatial Smoothing Sample



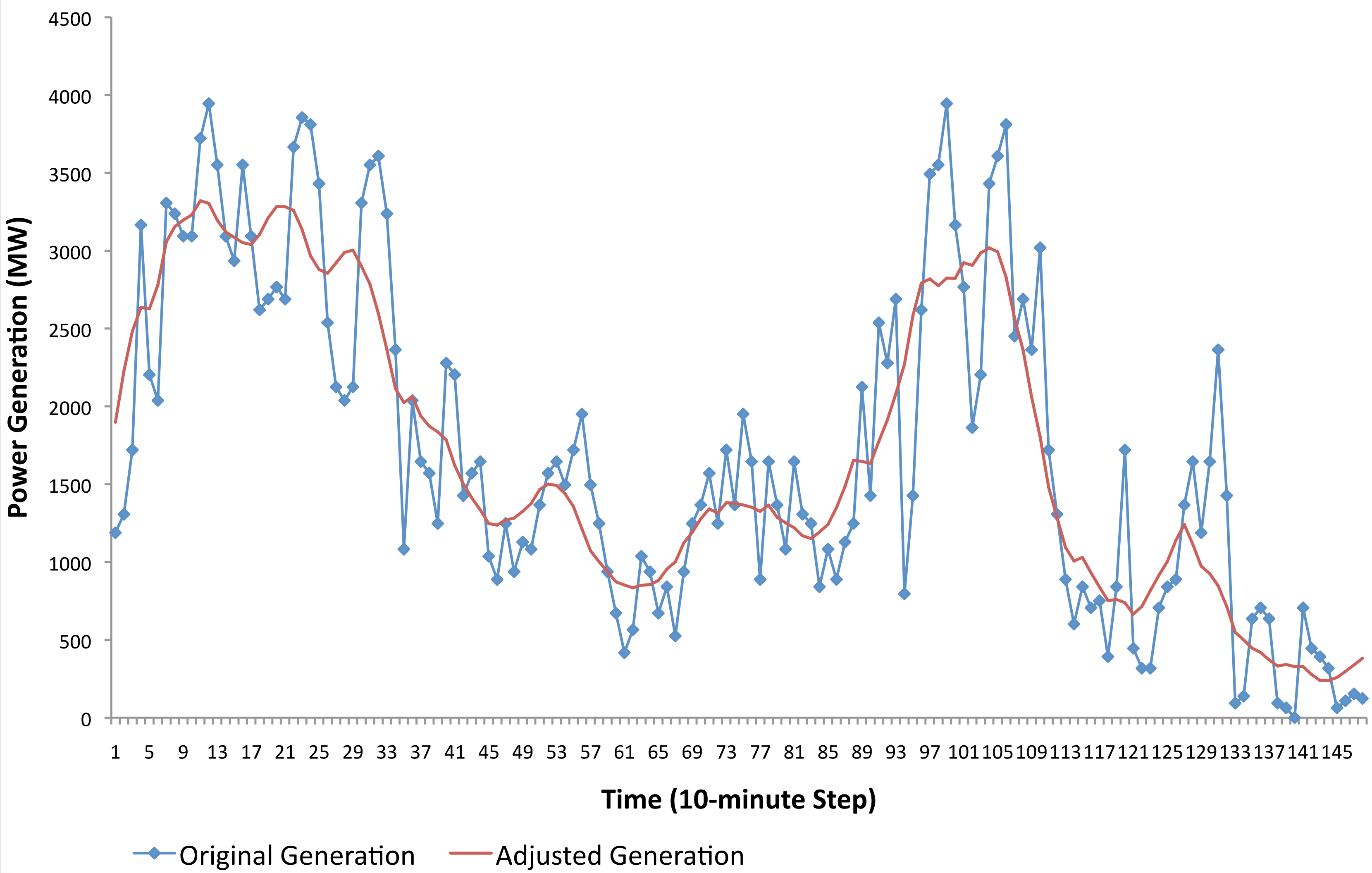
Aggregating Multiple Turbines

- Adjust power curve to represent multiple wind turbines (~convolution with Normal distribution)
- Adjust aggregate power curve for total energy capture to equal original power curve
- *Final Calculation:* Determine wind farm power generation by using adjusted wind speed data with adjusted turbine power curve

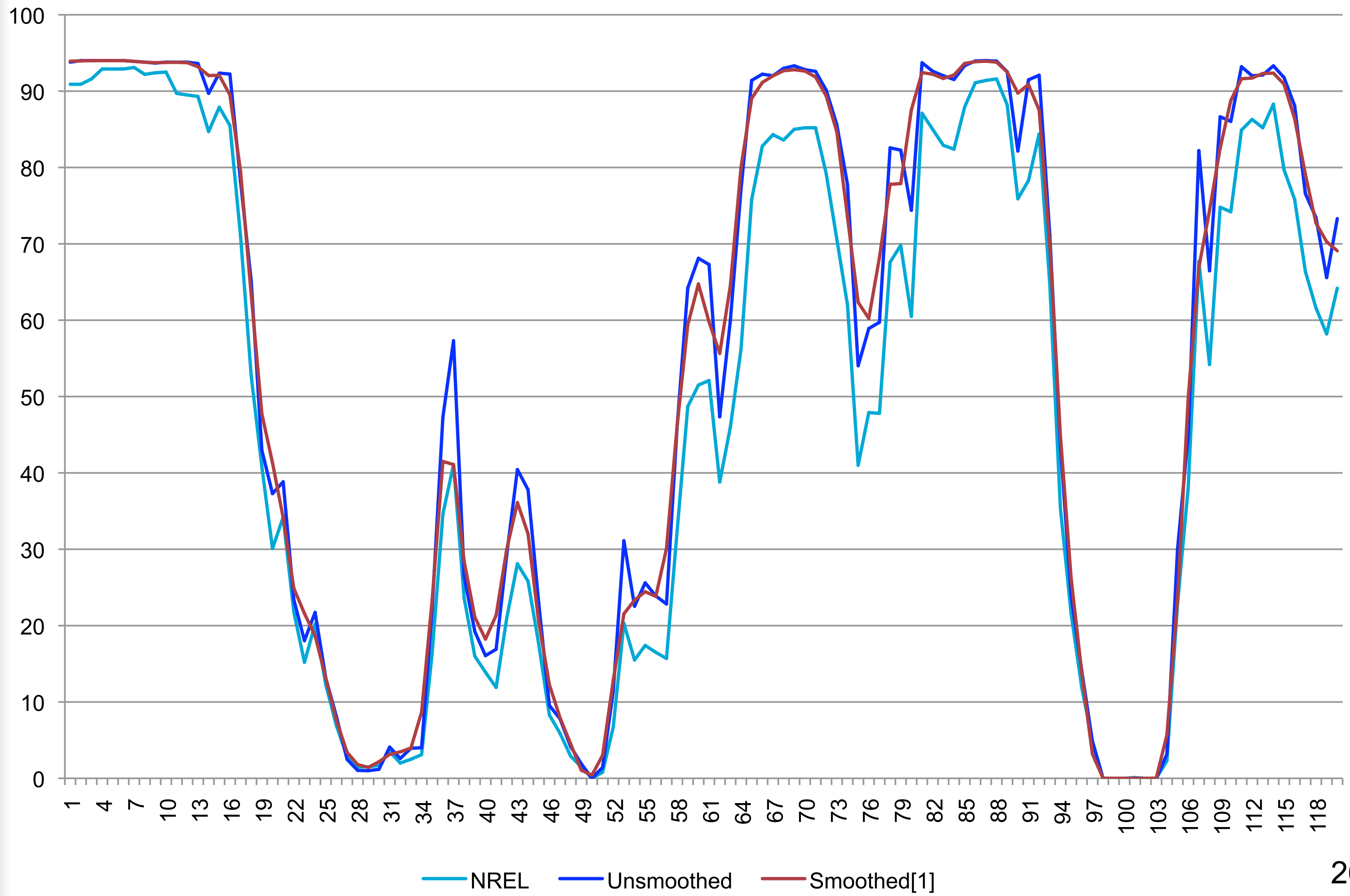
Modeling Wind Power Generation: Power Output Geographic Diversity



Modeling Wind Power Generation: Power Output Geographic Diversity



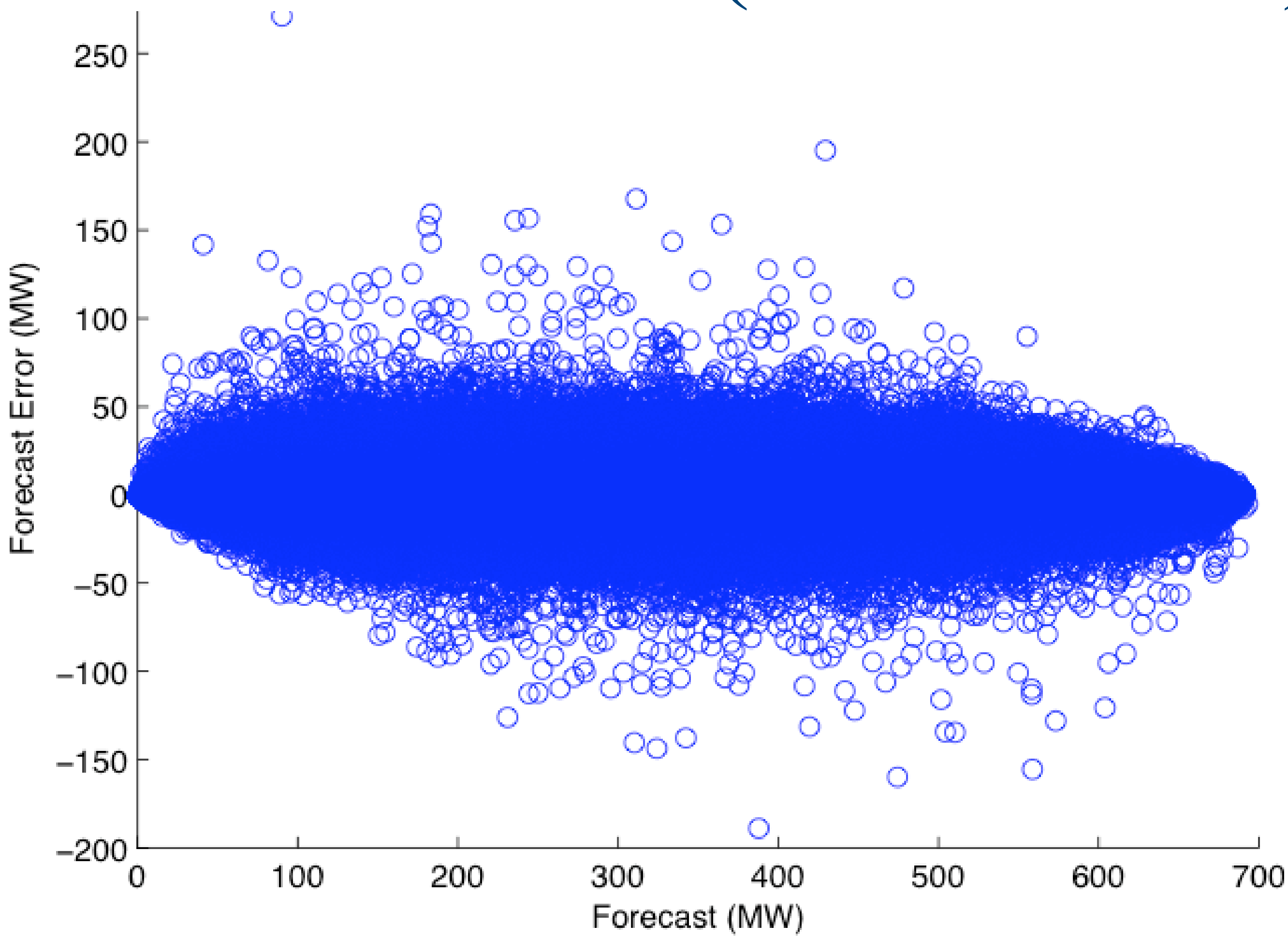
Modeling Wind Power Generation: Power Output Geographic Diversity



Distribution of Forecast Errors

- Wind generation forecasts are required to generate the distribution of errors
- NREL data set includes output forecasts, but not at the correct timescale
- Wind speed forecasts are developed from the NREL simulated data, and then processed to provide forecasted generation
- Forecast errors are calculated from forecasted and observed (simulated) outputs

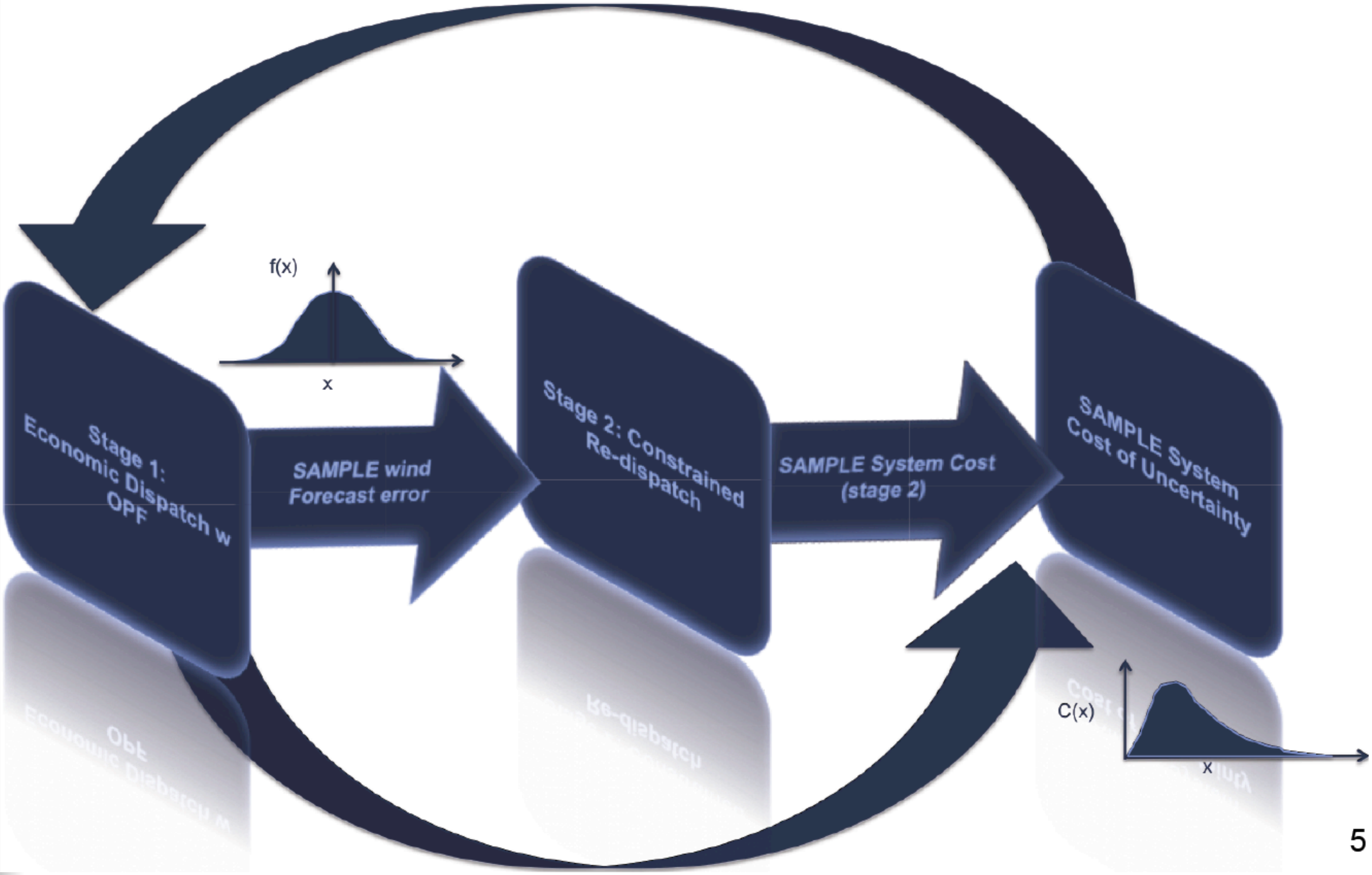
Forecast v. Error (AR1 Model)

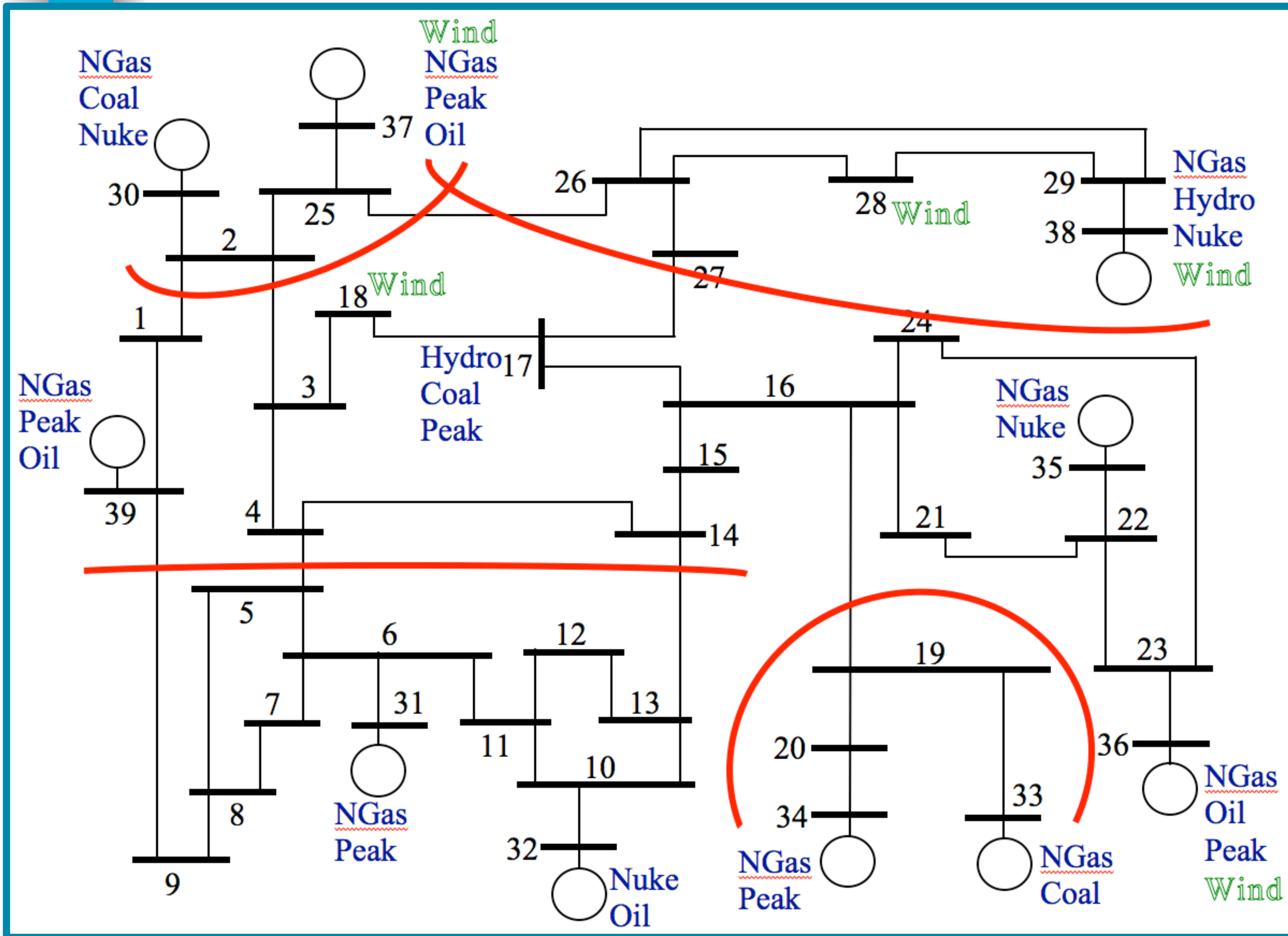


Method	Parameters		MAE*	Max Error		Min Error
	Slope	Intercept				
Linear AR Model	0.9974	0.6268	9.5717	271.1	-189.0	2.33e-04
Persistence	n/a		9.5484	271.5	-189.4	0

Forecast Characteristics: MA Sites, 10% Penetration (7 sites, total capacity 859 MW)

OPF & Monte Carlo Simulation Flow Chart





NGas
Coal
Nuke
30
2
1
Wind
NGas
Peak
Oil
37
25
26
28
Wind
29
NGas
Hydro
Nuke
Wind
38
27
18
Wind
Hydro
Coal
Peak
17
24
16
3
NGas
Peak
Oil
39
4
15
14
NGas
Nuke
35
21
22
5
6
12
19
23
7
31
13
11
10
20
36
NGas
Oil
Peak
Wind
33
34
8
NGas
Peak
32
9
Nuke
Oil
NGas
Peak
NGas
Coal

Differentiating Generators

- Percentage of each generating type
  - Model New England technology mix
  - Prorate generating capacity in test system based on historic regional totals
    - "north," "MA," "south"
- Location
  - Nuclear, hydro and coal based on New England
  - NGas/CC and peaking spread throughout

Differentiate Generating Capacity by State

	Coal	Fuel Oil	Peaker	NGas	Nuke	Hydro	Wood
ME		1057	837	2611		434	801
NH	579	433	39	2465	2303	428	
VT			49	1447	531	113	
MA	1749	4412	1560	11709	4210	1778	
RI		27		2349			
CT	633	3006	2065	4304	2707	102	
	5%	17%	8%	46%	18%	5%	1%

- Databases from EIA / FERC / RDI Powerdat
- ISOne reports

Differentiate Generating Capacity for Test System

- Test system has 13.7% actual NE load
- North = ME, NH, VT
- South = CT, RI
- Drop wood generating type (1%)

	Coal	Fuel Oil	Peaker	N Gas	Nuke	Hydro
North	80	205	125	890	390	135
Mass	245	600	215	1600	575	250
South	90	410	280	910	370	

Generator Cost Data

	Fuel Cost	Ramping Cost
	$/MW	% of MC
Coal	24	15
Nuclear	5	15
Oil	115	10
NGas	61	10
Peaking	102	5
Hydro	3	5
Wind	3	n/a

Scenarios

- 3 wind penetration levels
  - 10% requires 3 windfarms
  - 20% requires 4 windfarms
  - 30% requires 5 windfarms
- 3 forecast levels for each wind farm
  - 25%, 60%, 100%
- 3 load levels / reserve margins
  - 10%, 15%, 30%
- 2 system response characteristics
  - Generator ramping capability

Installed Wind:
GW Capacities with 30% Capacity Factor

Wind Penetration	Required Wind Capacity (GW)	Installed Wind Capacity (GW)	Bus 37 (GW)	Bus 18 (GW)	Bus 38 (GW)	Bus 28 (GW)	Bus 36 (GW)	Total (GW)
10%	0.64	2.13	0.8	0.85	0.5			2.15
20%	1.28	4.27	1.0	1.0	0.5	1.5		4.0
30%	1.92	6.40	1.0	1.0	0.5	1.5	2.4	6.4

Determining Redispatch Costs

- OPF with Monte Carlo Simulation (MCS)
  - Estimate the additional cost of power system operation with uncertainty in wind and load forecasts.
- Base case scenarios
  - MCS is used to identify redispatch costs from wind and load uncertainty.
- Quantify the cost of the uncertainty in wind power forecasts
  - In terms of changes in production cost and system lambda.

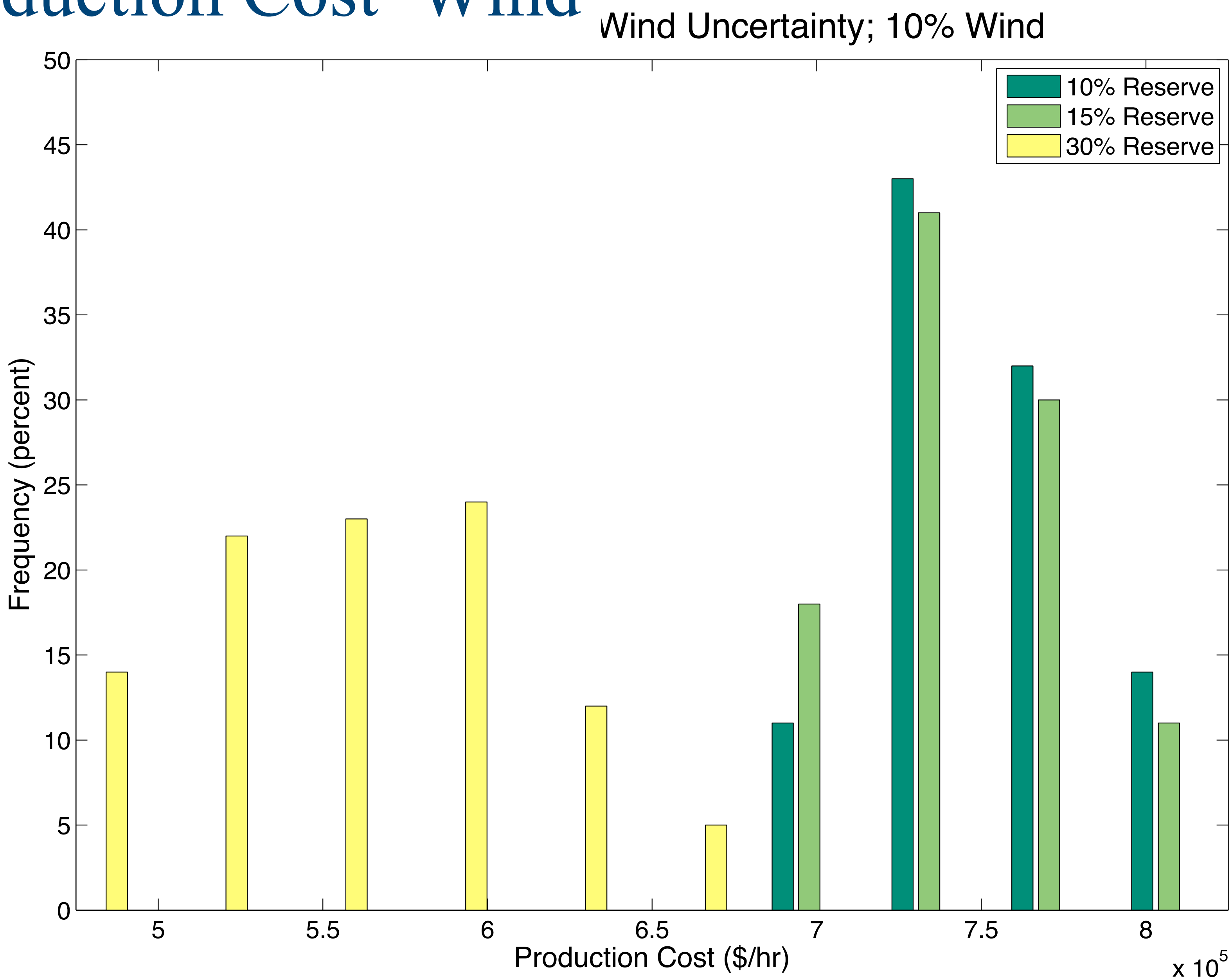
Simulation Results

- Histograms compare 10%, 20% and 30% wind penetration
  - Each chart's bars differ in reserve margin
- 2nd set compares reserve margins
- Results for
  - Production cost, LMP
  - Losses: real and reactive

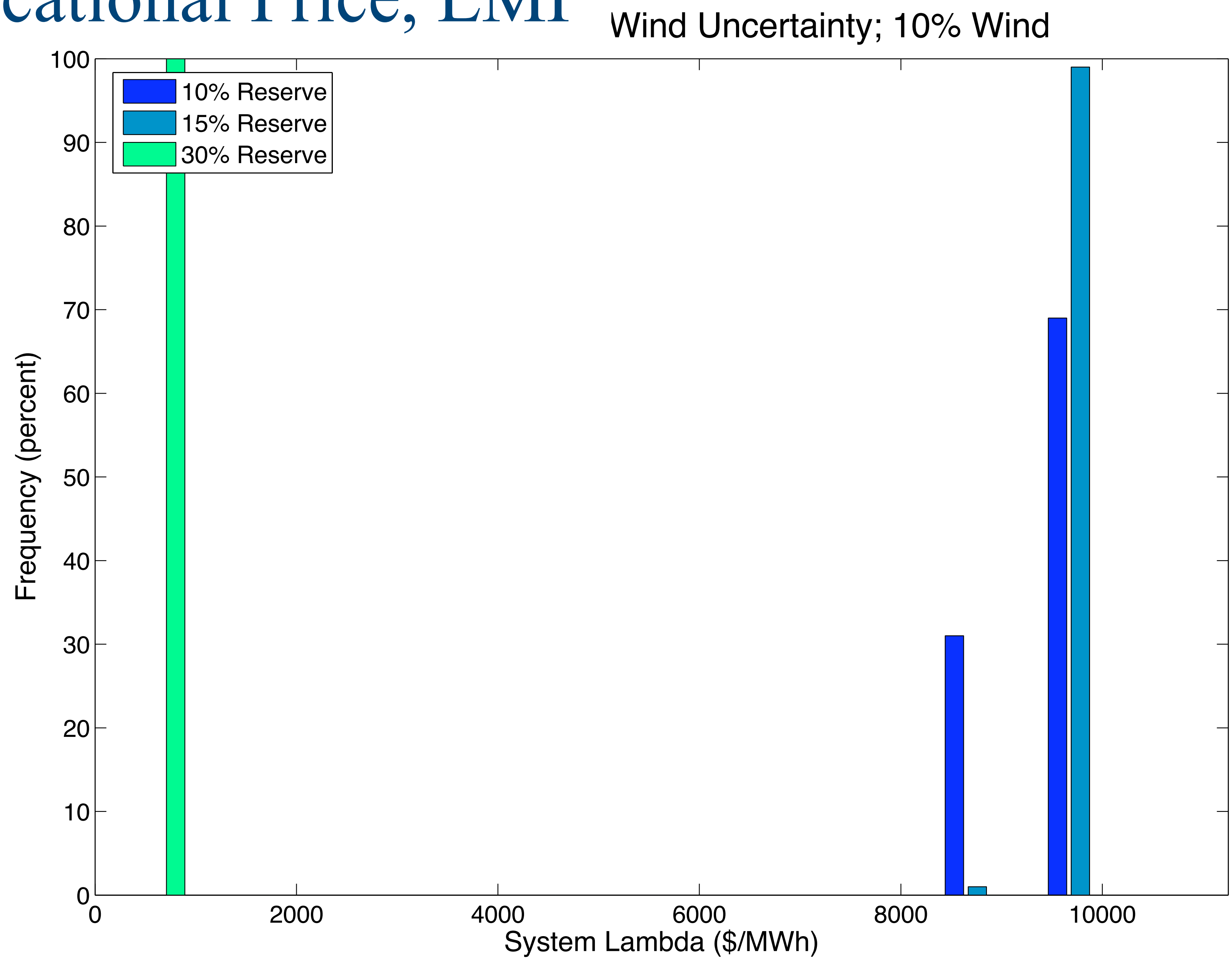
The following charts:

- Each chart has bars comparing different reserve margins, at a given wind penetration level
- Different charts represent the different wind levels: 10%, 20%, 30%

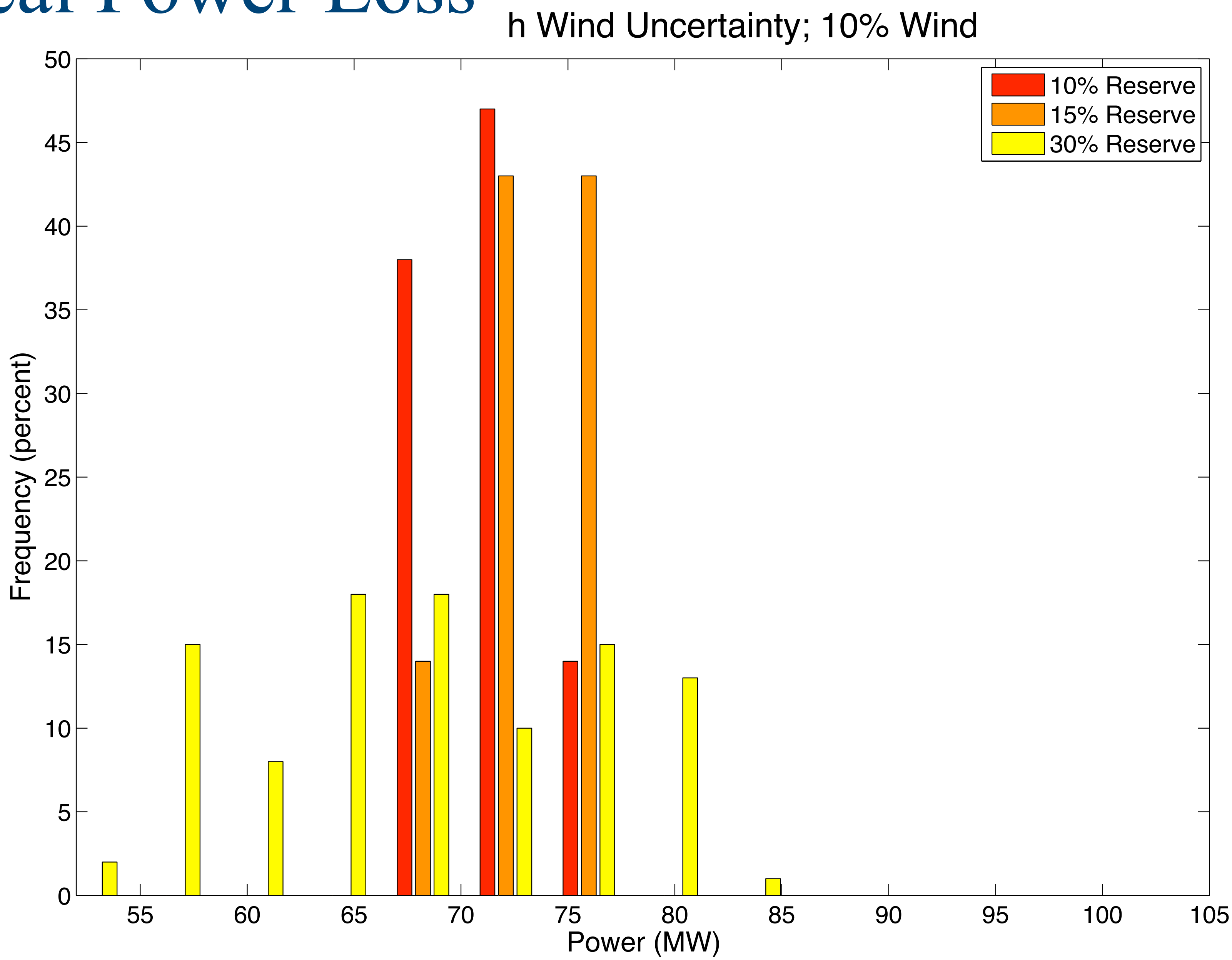
Production Cost–Wind



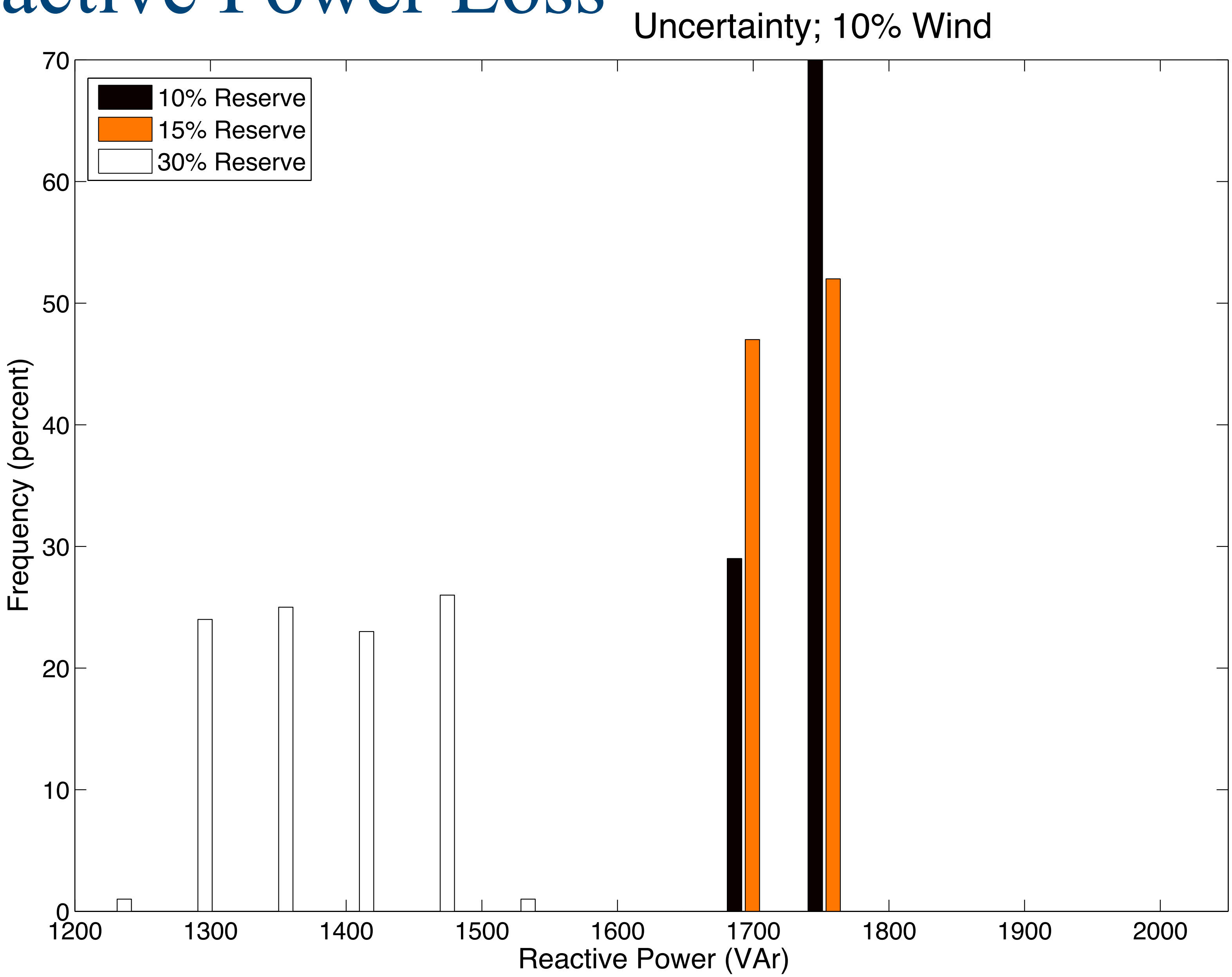
Locational Price, LMP



Real Power Loss



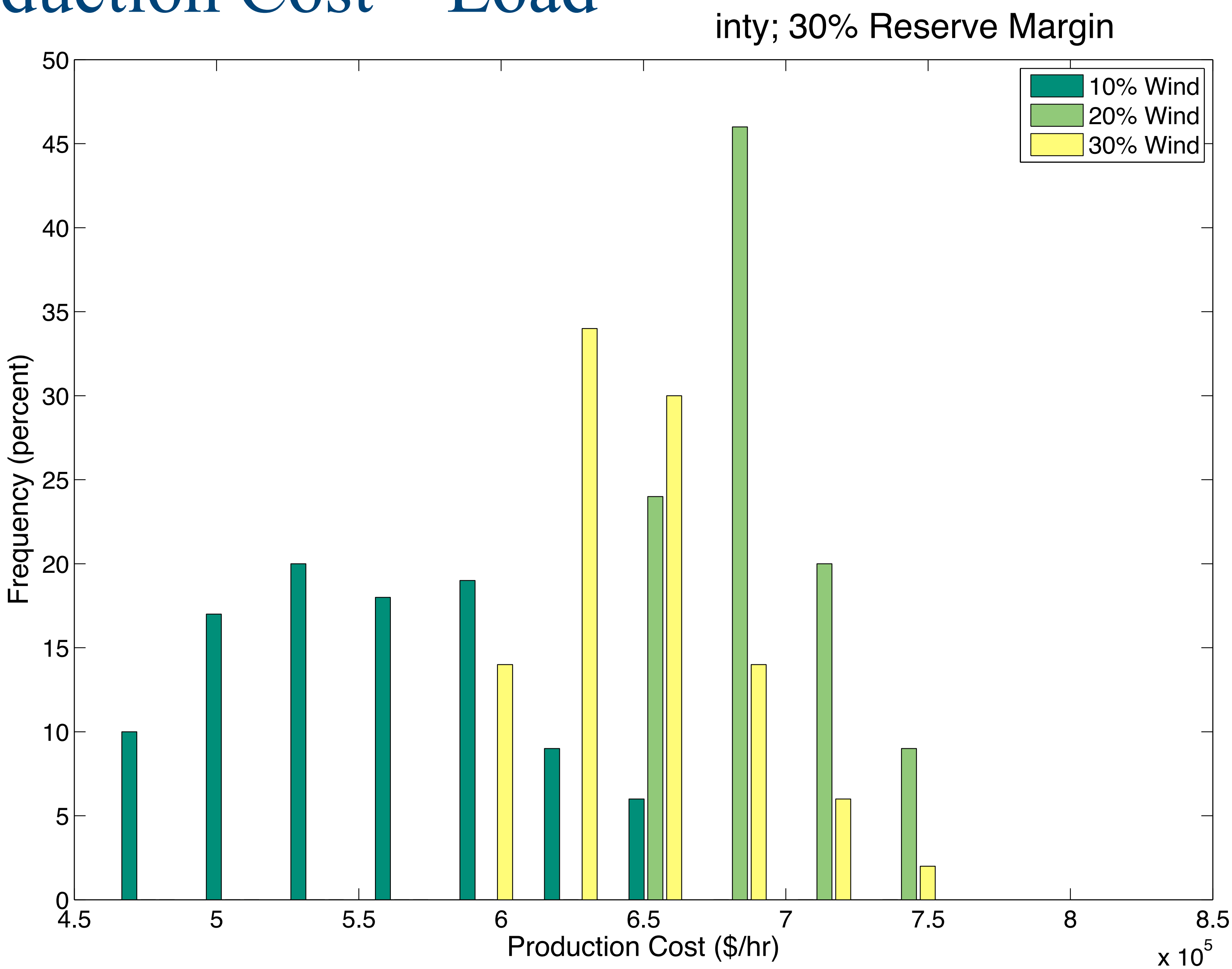
Reactive Power Loss



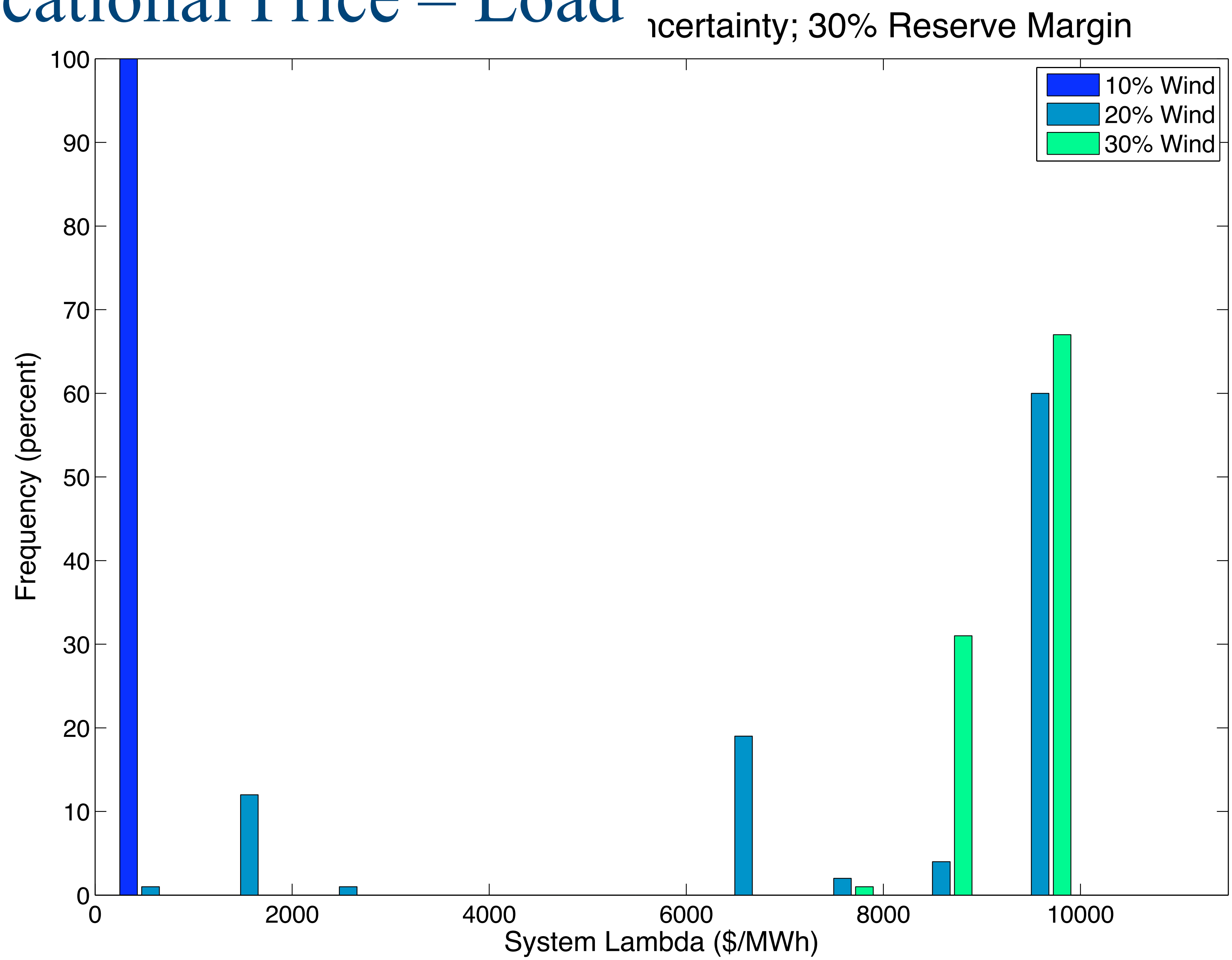
The following charts:

- Each chart has bars comparing different wind levels, at a given reserve margin
- Subsequent charts represent the different reserve margins, for increasing load

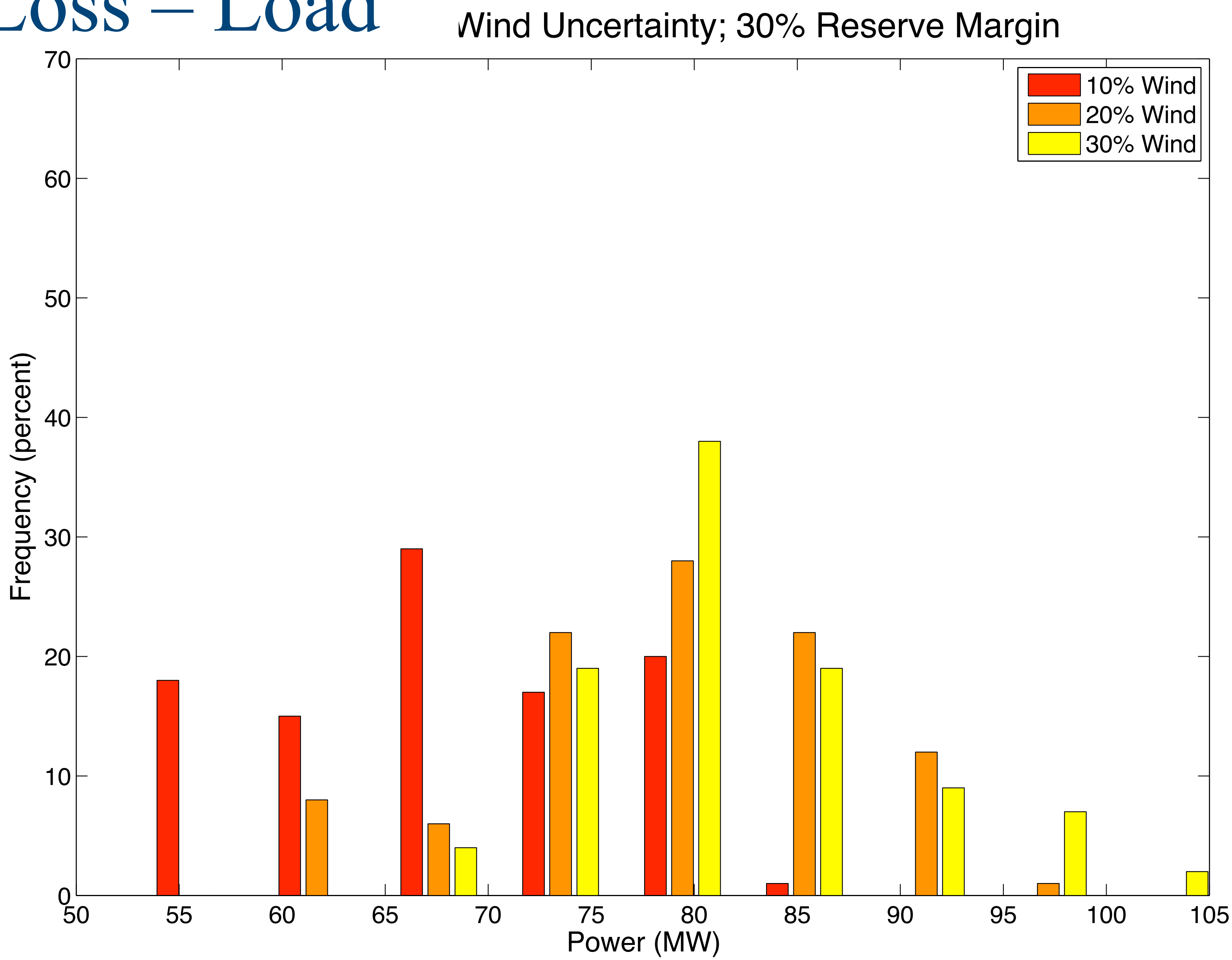
Production Cost – Load



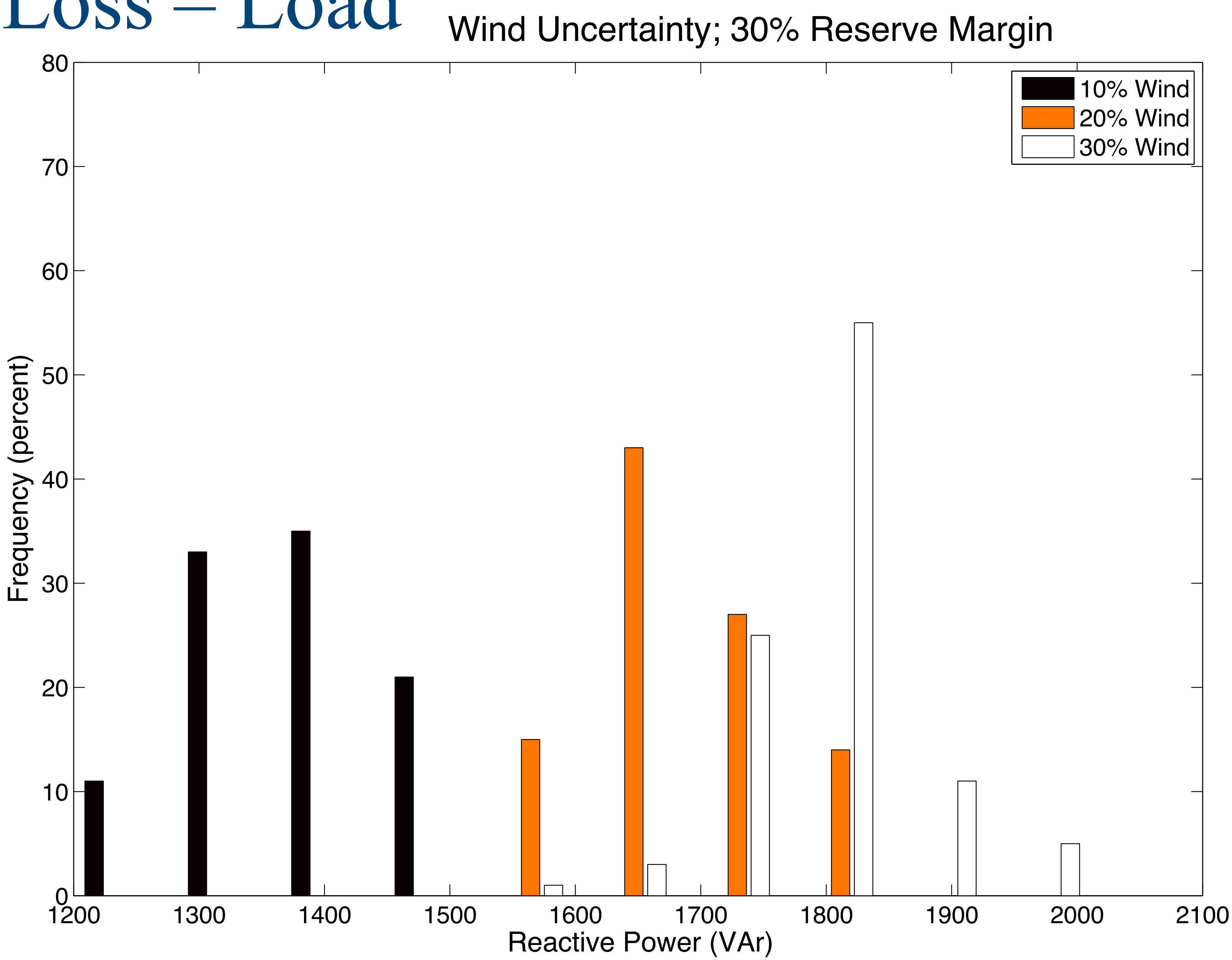
Locational Price – Load



P Loss – Load


Wind Uncertainty; 30% Reserve Margin
10% Wind
20% Wind
30% Wind
Frequency (percent)
Power (MW)
0
10
20
30
40
50
60
70
50
55
60
65
70
75
80
85
90
95
100
105

Q Loss – Load



Wind Uncertainty; 30% Reserve Margin
10% Wind
20% Wind
30% Wind
Frequency (percent)
80
70
60
50
40
30
20
10
0
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Reactive Power (VAr)

Simulations Summary

- Increased wind variability and forecast uncertainty, from increased wind penetration, increases LMP, real and reactive power losses.
- Production cost decreases and wind increases
  - But with lower reserve margin, the benefit decreases
- Responsive load – currently $10k/MWh – is used for almost all scenarios, resulting in dramatic cost increases