Modeling Wind Energy Resources in Generation Expansion Models

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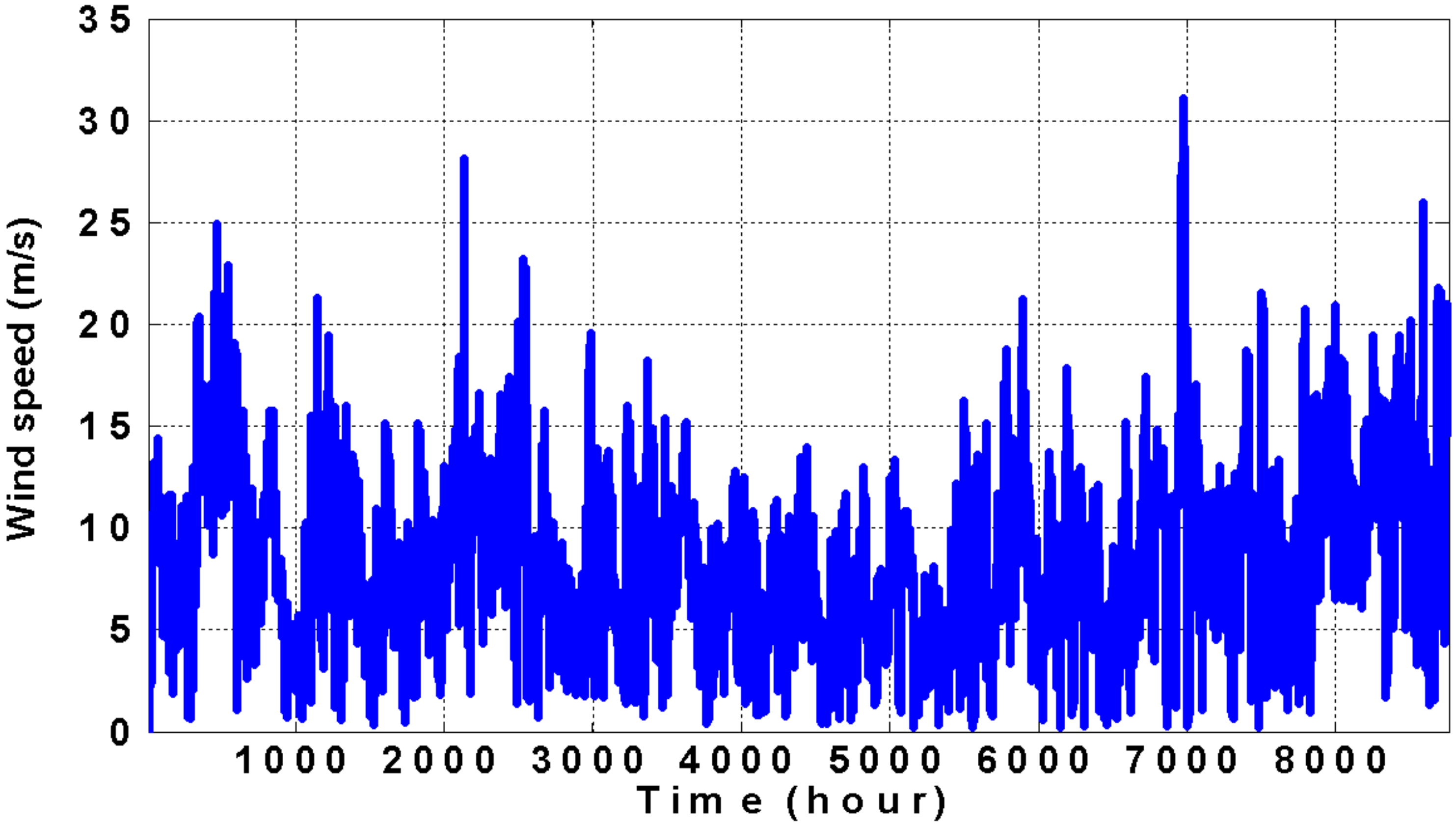
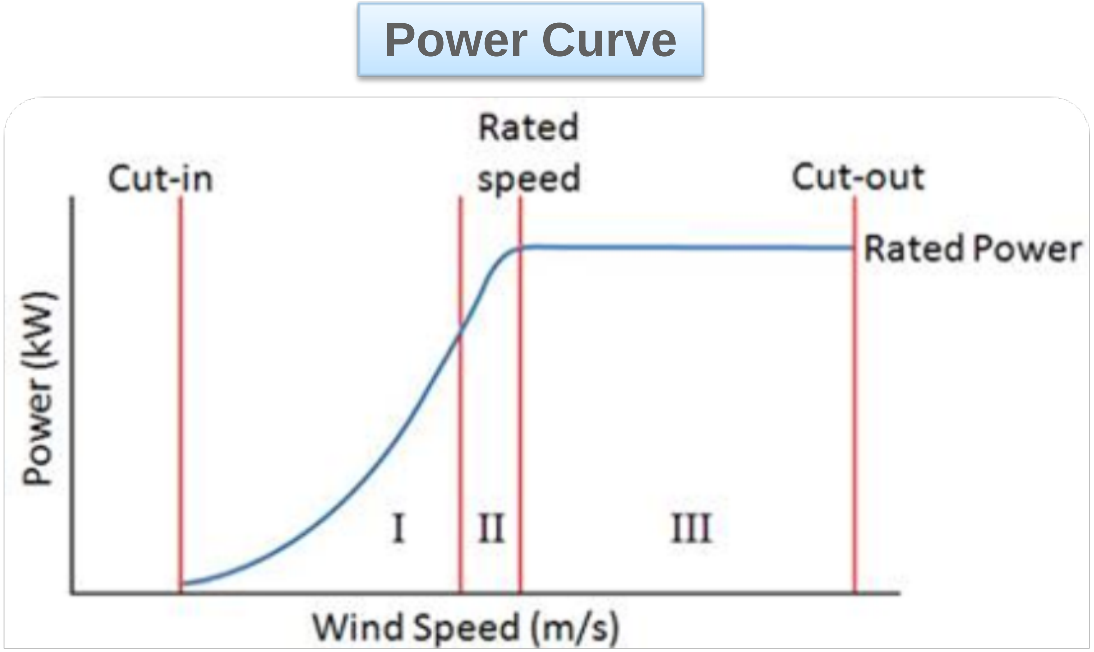
Key Challenges in Modeling Wind and Other Variable Sources in Expansion Planning

- How to properly represent and model their:
  - Uncertainty
  - Variability



Wind Plant Characterization

Example: Wind Turbine Vensys 77 (1.5 MW)



Wind speed (m/s)	Power (kW)
0	0
3	21.9
4	75.1
5	155.8
6	274.3
7	439.3
8	668
9	932.1
10	1215.4
11	1418.2
12	1473.7
13	1496.5
14	1500
15	1500
16	1500
17	1500
18	1500
19	1500
20	1500
21	1500
22	1500

Cut-in wind speed: 3.0 m/s
Cut-out wind speed: 22 m/s

Wind Speed Characterization

Historical Wind Speed:

Date	Hour	70m Wind speed mph
1-Sep-06	0	7.10
	1	8.10
	2	6.78
	3	7.37
	4	6.47
	5	6.83
	6	8.82
	7	9.12
	8	8.40
	9	7.75
	10	9.90
	11	8.12
	12	10.63
	13	10.92
	14	11.32
	15	10.42
	16	13.27
	17	11.48
	18	12.12
	19	11.55
	20	12.48
	21	11.82
	22	11.05
	23	9.22

Wind Speed Models:

Weibull Distribution

$$f(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} & x \geq 0 \\ 0 & x < 0 \end{cases}$$

Time Series

$$X_t = c + \sum_{i=1}^{p} \varphi_i X_{t-i} + \varepsilon_t$$

Markov Chains, etc.

From Wind Speed to Wind Power

Historical hourly wind speed

or

Wind speed model

→

Power Curve

Wind speed (m/s)	Power (kW)
0	0
3	21.9
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20	1500
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22	1500

→

Estimated hourly power output

or

Power output model

What is the Capacity Value of a Wind Plant?

- Utilities use different approaches to estimate the capacity value (capacity credit or firm power) of wind plants
- First we need to distinguish whether capacity credit is determined for planning or operation purposes:

Long-Term Expansion Planning:

- The long-term capacity credit is usually linked to how much of new conventional generating capacity additions can be replaced by the wind plant
- The overall availability of wind plant (e.g., capacity factor) is one of the key factors influencing the capacity value of wind plant in the long term

Operations Planning:

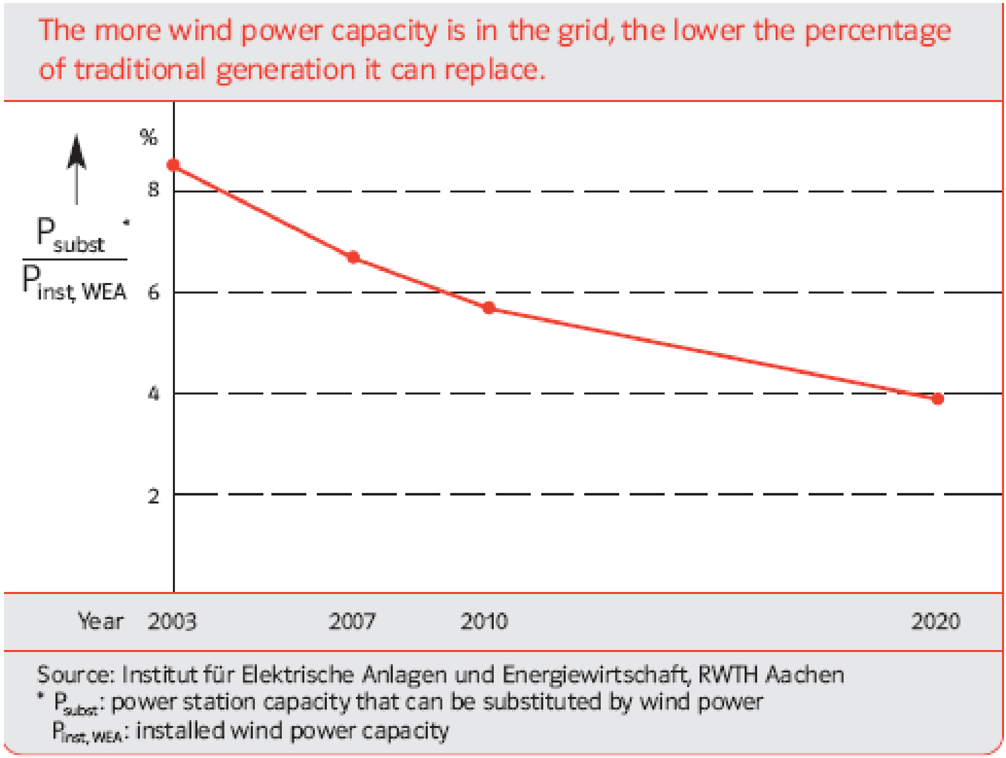
- In operations planning, the capacity credit is related to how much wind capacity will be available for meeting the load next day, especially during the peak hours
- Good wind forecasting plays a key role in determining the wind capacity credit in the short term

Wind Capacity Credit and System Reliability

- Reliability of system operation is one of important aspects for determining both short- and long-term capacity credits
- Although the operational availability of a wind turbine may be very high, it will not operate when there is no wind, which makes it a relatively unreliable generation source
- The concept of Equivalent Load-Carrying Capacity (ELCC) is often used to determine the capacity credit of wind farms in the long term
- The ELCC method is based on the LOLP measure of system reliability so that a wind farm is benchmarked against an ideal, perfectly reliable unit with 100% availability
- The amount of perfectly reliable capacity that achieves the same system reliability as in the case with wind plant determines the ELCC of a wind plant
- A related "equivalent capacity" approach is to use an alternative conventional unit (e.g., gas turbine) instead of the ideal unit
- The equivalent unit is sized so that the system LOLP is the same if calculated with a wind plant instead of the gas plant

ELCC Decreases with Higher Penetration of Wind Capacity in the System

- German utility E.ON: “The more wind power capacity is on the grid, the lower the percentage of traditional generation it can replace.”
  - Firm capacity from wind in 2007: about 7% of installed capacity
  - Firm capacity in 2020 is expected to drop to 4%.



Source: E.ON Wind Report 2005

Benefits of Wind Power

- Energy Credits
  - Energy generation + fuel savings
- Capacity Credits
  - Capacity value or ELCC
- Emission Credits
  - Reduced overall pollutant emissions in the system

Calculation of Wind Power Benefits in the Long Term

- Economic cost/benefit analysis
- Usually performed over the lifetime of a wind farm
- Calculations performed in terms of net present value

Long-Term Benefits of Wind Power Can Be Calculated using Capacity Expansion Models

- The objective of models for optimal capacity expansion, such as WASP-IV, is to determine the least-cost system expansion plan that would meet the demand over the study period, while satisfying all reliability and other constraints specified by user

- The operating and investment costs, determined by the model, can be used to calculate energy and capacity credits of wind plants

- The emissions of various pollutants calculated by the model can be used to determine the emission credits

Calculation of Long-Term Benefits of Wind Power using a Capacity Expansion Model

- Typically, the analysis is performed for two scenarios:
  – Case without wind power (Reference Case)
  – Case with the wind power capacity

- System reliability (e.g., LOLP and ENS) should be kept at approximately the same level in both scenarios

- The analysis can be performed either for a specific wind farm or for a given penetration of wind farm capacity over the study period

Comparison of Results for Two Scenarios

- Energy credits can be calculated from the differences in operating costs
- Capacity credits can be calculated from the differences in expansion schedules:
  - The amount of conventional capacity (MW) displaced or deferred by wind farms
  - Savings in the investment costs ($) for new generating capacity can also be calculated
- Emission credits can be calculated from the differences in air emissions

Representation of Wind Power in Capacity Expansion Models

- There are several approaches for modeling wind power in expansion planning models:

1. Load Modification Approach (“Negative Load” approach)

2. Supply-Side Approach (wind is treated as conventional power plant)
   i. Run-of-river hydro capacity
   ii. Unreliable thermal capacity

3. Multi-Block Probabilistic Simulation Approach

Representation of Wind Power as Negative Load


Modified Load(t) = Load(t) – W(t)

Advantages:
a) Chronological information of wind speed is maintained
b) The approach captures variability of wind power
c) Appropriate for short-term studies (for best results, the wind generation pattern should be “typical”)

Disadvantages:
a) Does not capture uncertainty (assumes the same chronological wind pattern in the future)
b) When simulated wind speed is used, zero wind power is averaged out
c) Could provide inaccurate results for long-term studies

Supply-Side Approach

Available plant generation = Wind generation

Advantages:

a) Wind power is treated as conventional run-of-river hydro or unreliable thermal power plant

b) The wind plant is used in dispatch simulations and reliability calculations

c) The approach captures some variability and some uncertainty

d) Appropriate for long-term studies

Disadvantages:

a) Stochastic nature of wind power (zero-rated capacity) is misrepresented

b) Chronological hourly wind information is not captured (not a concern for long-term studies)

Supply-Side Approach: Representation of Wind Power as Run-of-River Hydro Plant

- Wind generation has some similarities with run-of-river hydro generation:
  - Both are non-dispatchable (power has to be used when produced)
  - Both can have seasonal variations
  - Both are characterized by a level of uncertainty (wind conditions or hydrological conditions)
  - There is practically no energy storage available

- If a capacity expansion model allows for multiple hydrological conditions, these can also be used to express the probabilities of expected wind generation

- Using the modeling of run-of-river hydro, specify the expected wind generation and available capacity by period, according to their probabilities of occurrence

- Both existing and candidate wind plants can be represented

Supply-Side Approach: Representation of Wind Power as Unreliable Thermal Generating Capacity

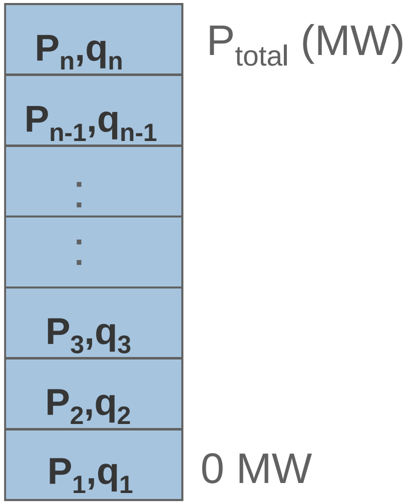
- Simple and easy approach, both existing and candidate wind farms can be represented
- Wind farm is represented as very unreliable thermal generating unit
- The forced outage rate of the thermal unit should be specified high (thermal unit generation should match the expected generation from the wind farm)
- Since wind farms operate throughout the year, there should be no maintenance requirements for the fictitious thermal unit
- Fuel costs can be specified as zero, while O&M costs should correspond to the real O&M costs of the wind farm
- Since the running costs of this unit are very low or zero, the wind farm will always be loaded when available

Multi-Block Probabilistic Simulation Approach

Power blocks and probabilities

Advantages:

a) Wind power is treated as conventional power plant with a number of capacity blocks
b) Stochastic nature of wind power (zero-rated capacity) is represented
c) Probability distribution addresses both the variability and uncertainty of wind power
d) Wind plant is convolved into probabilistic dispatch and reliability calculation
e) Appropriate for long-term studies



Disadvantages:

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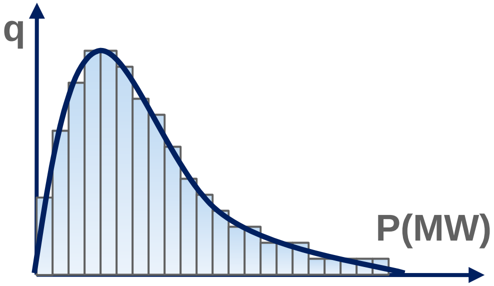
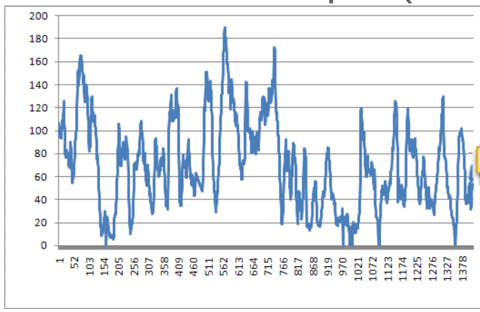
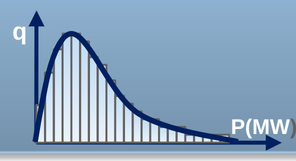


Implementation of Multi-Block Approach

Wind Power Output (MW)



Blocks & Probabilities

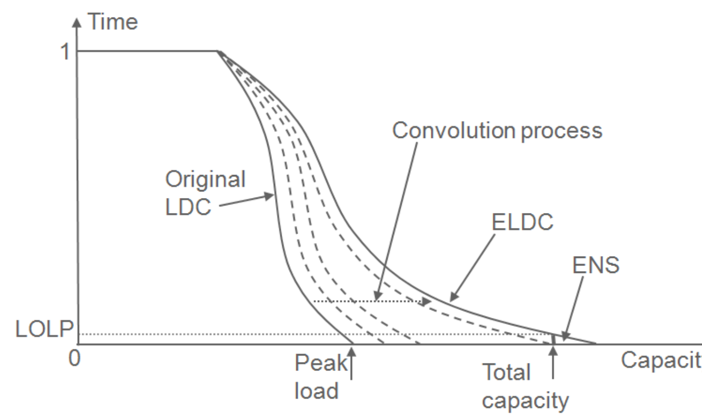


PROBABILISTIC DISPATCH

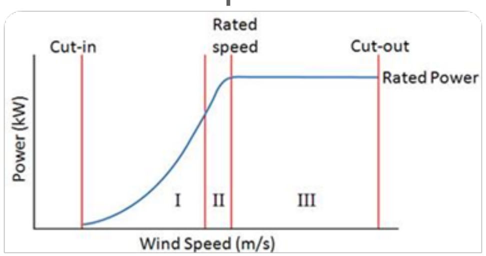
P_n,q_n
P_{n-1},q_{n-1}
:
:
P_3,q_3
P_2,q_2
P_1,q_1

P_{total} (MW)

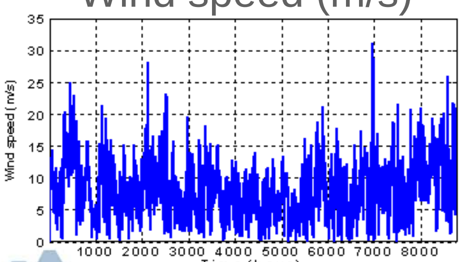
0 MW



Power Output Curve

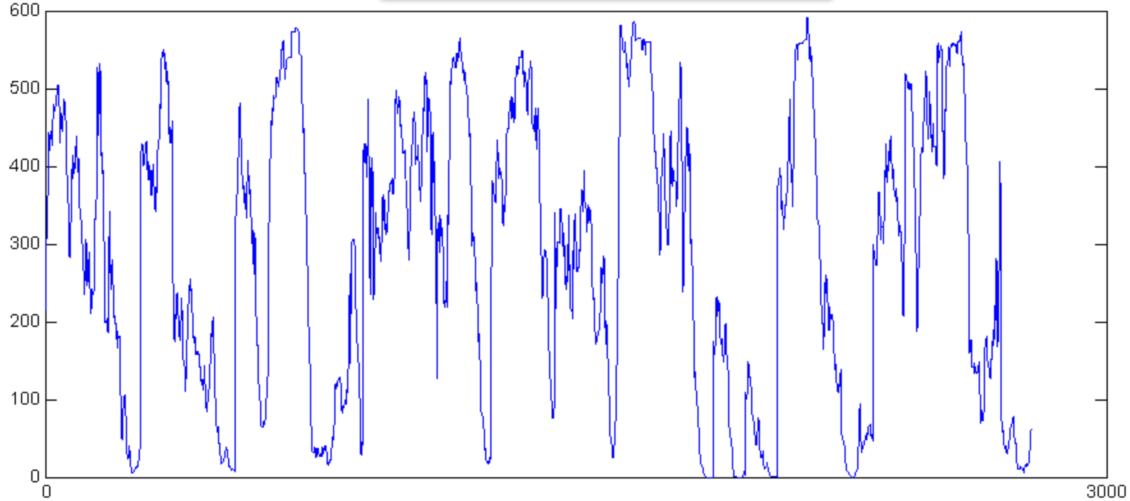


Wind speed (m/s)



Wind Capacity Blocks and Their Probabilities Can Be Determined using a Wind Power Stochastic Model

Wind power (MW)



Mean = 284.1
St. dev. = 182.1

Blocks & Probabilities

n	Range	Average Value	Probability
0	0	0	0.0143
1	0-60	30	0.1652
2	60-120	90	0.0756
3	120-180	150	0.0821
4	180-240	210	0.0792
5	240-300	270	0.0792
6	300-360	330	0.1047
7	360-420	390	0.1190
8	420-480	450	0.0986
9	480-540	510	0.0946
10	540-600	570	0.0875

Mean = 285.5
St. dev. = 181.2

Data Processing for Multi-Block Approach

Example:

Wind speed (m/s)

Date	Hour	70m Wind speed (m/s)
1-Sep-06	0	7.10
	1	8.10
	2	6.78
	3	7.37
	4	2.47
	5	1.83
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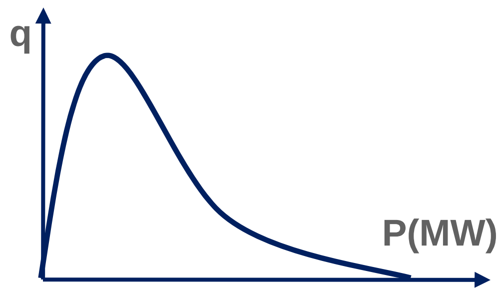
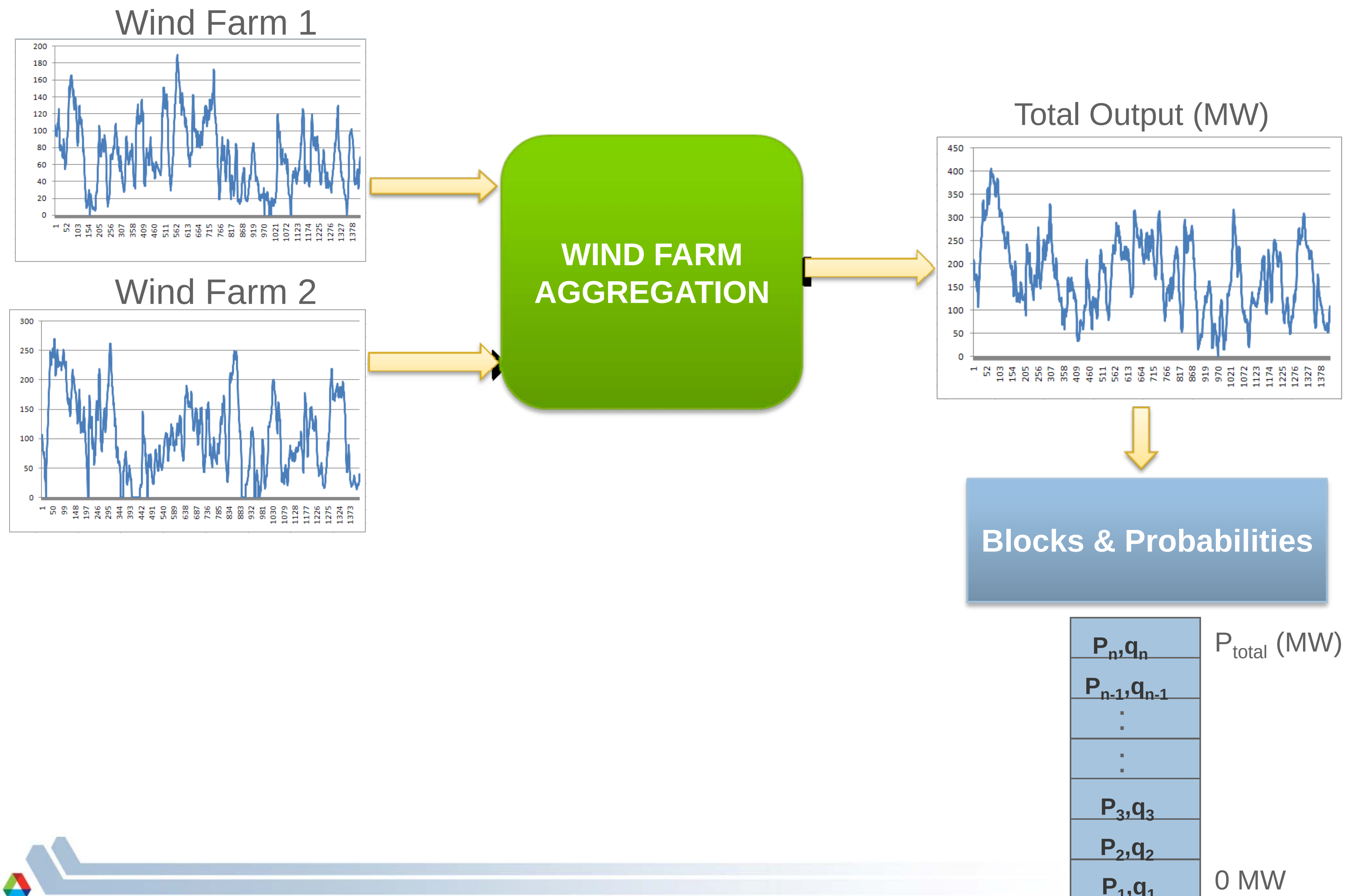
14	1500
15	1500
16	1500
17	1500
18	1500
19	1500
20	1500
21	1500
22	1500

Wind Farm (6 MW)

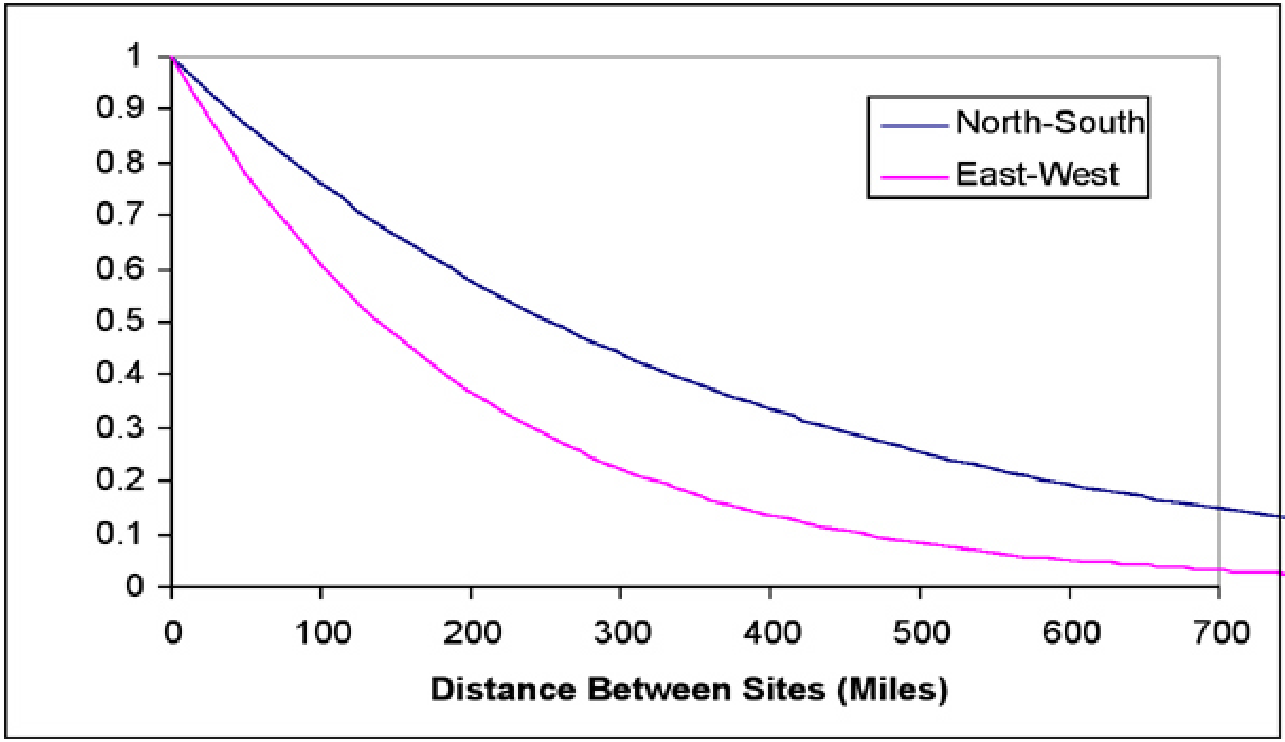
Block	Power Output	Probability
0	0	0.1306
1	0.6	0.1204
2	1.2	0.2056
3	1.8	0.1194
4	2.4	0.0278
5	3	0.1042
6	3.6	0.0602
7	4.2	0.1000
8	4.8	0.0167
9	5.4	0.0306
10	6	0.0847



Wind Power Aggregation



Wind Farm Correlation



Source: NREL

- Correlation in wind farm power output is decreasing with the distance between the wind farms
- In the US, correlation factors are different for N-S and E-W directions