Environmentally Sustainable Planning of Large Wind Farms for Wind Power Integration

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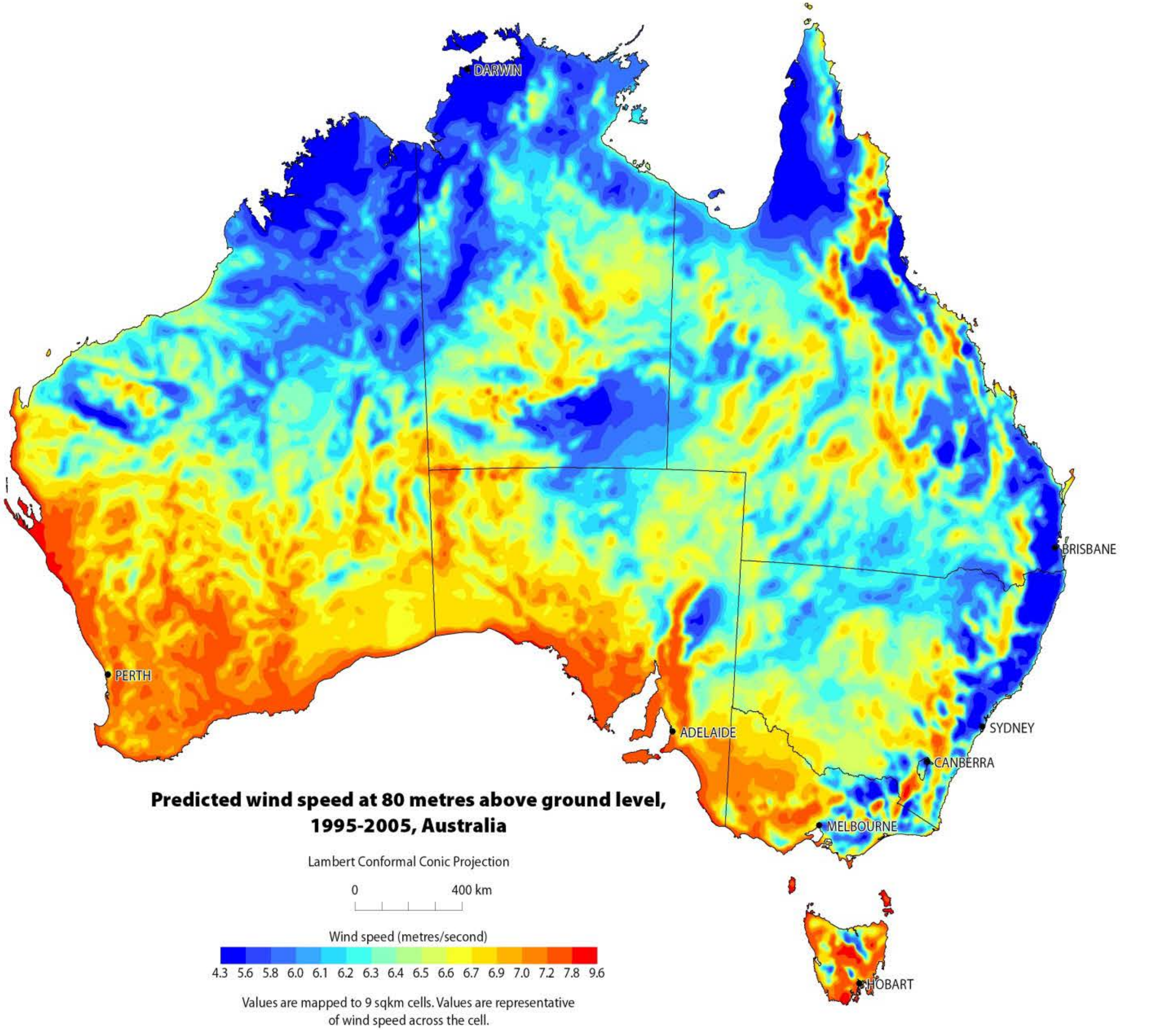
Wind Energy

- Wind energy, one of the fastest growing renewable energy sources for power generation, now meets a significant percentage of electrical demand worldwide.
- Along with the introduction of various emission reduction schemes, the cumulative installed wind capacity has increased markedly since the last decade around the world.
- Governments and organizations are promoting the construction of large wind farms, encouraging power companies and utilities with generous subsidies and with regulatory support.
- The ever-increasing level of wind energy with uncertainty and variability brings potential risk to power system operations.
- Furthermore, after direct participating in real-time electricity market, the high volatility of electricity price will further intensify the risk of wind energy.

Wind Energy in Australia

- Australian continent boasts some of the best wind resources in the world, primarily located along coastal regions and extended hundreds of kilometres to inland.
- The Australian government acknowledges the importance of renewable energy sources and has issued a series of national policies to promote research, development, commercialization of renewable energy projects, and to improve transition of latest research results into industrial applications.
- These policies, particularly the emission trading scheme and the renewable energy target are expected to underpin solid progress of wind energy industry in Australia.
- Furthermore, some power utilities have started grid upgrade for renewable energy integration. An essential part of the upgrade work is to strengthen or replace the existing facilities to accommodate the increasing wind power generation.

Background



Source: http://www.renewablessa.sa.gov.au/investor-information/resources/

❑ Selected Research Fields in Wind Power

- **Wind resource assessment**
- **Wind farm planning**

1. **Potential location selection;**
2. **Environmental impacts assessment;**
3. **Turbine model selection;**
4. **Wake effects modelling;**
5. **Micro-siting optimization;**
6. **Electrical layout optimization.**

- **Wind farm dispatch**

1. **Wind power forecast;**
2. **Flexible operational planning framework;**
3. **Wind farm dispatch considering carbon tax;**

Selected Research Fields in Wind Power (Cont.)

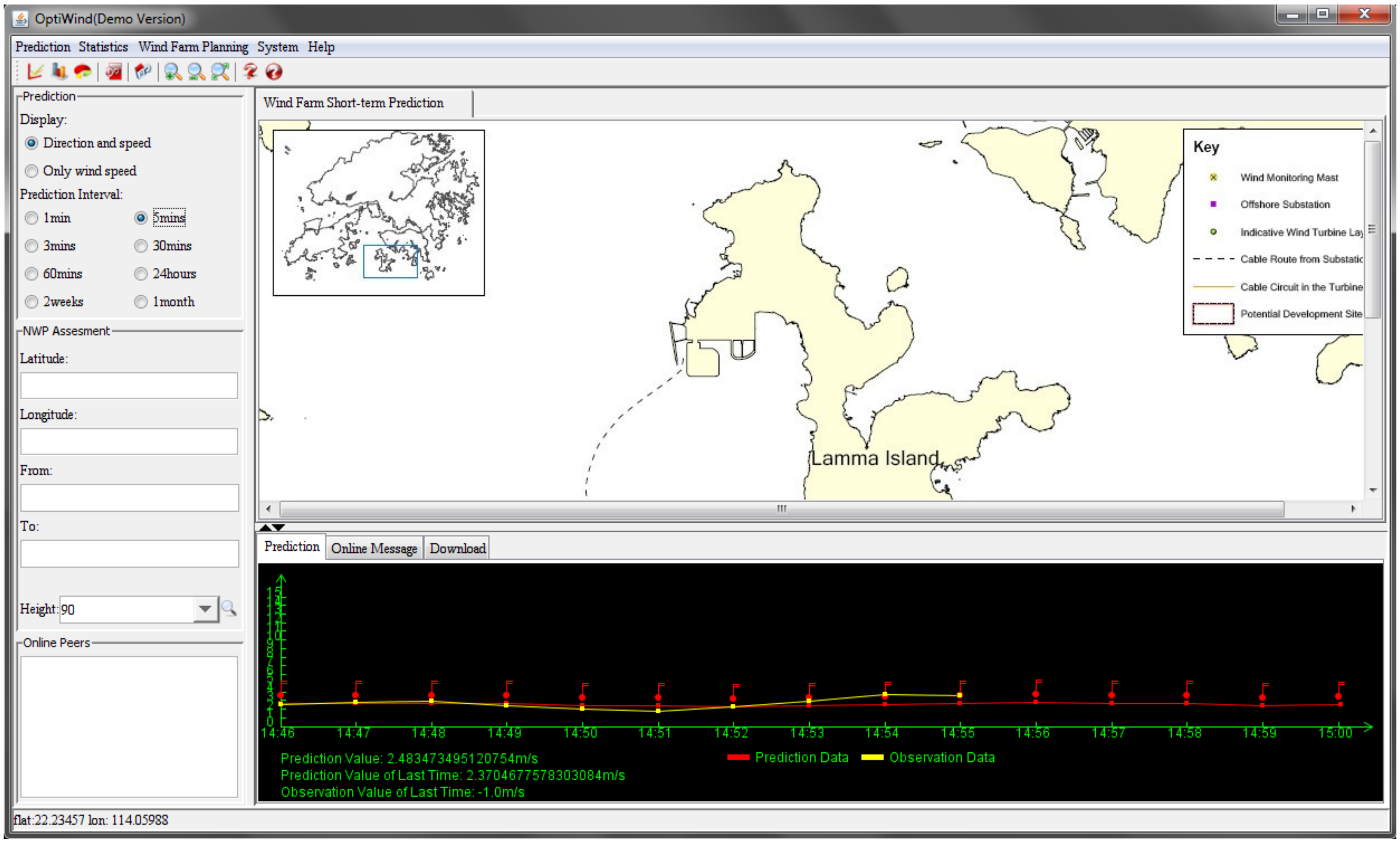
4. Coordinate dispatch with energy storage system;
5. Optimal allocation of energy storage system;
6. Operational risk mitigation with insurance strategy.

- Power system security

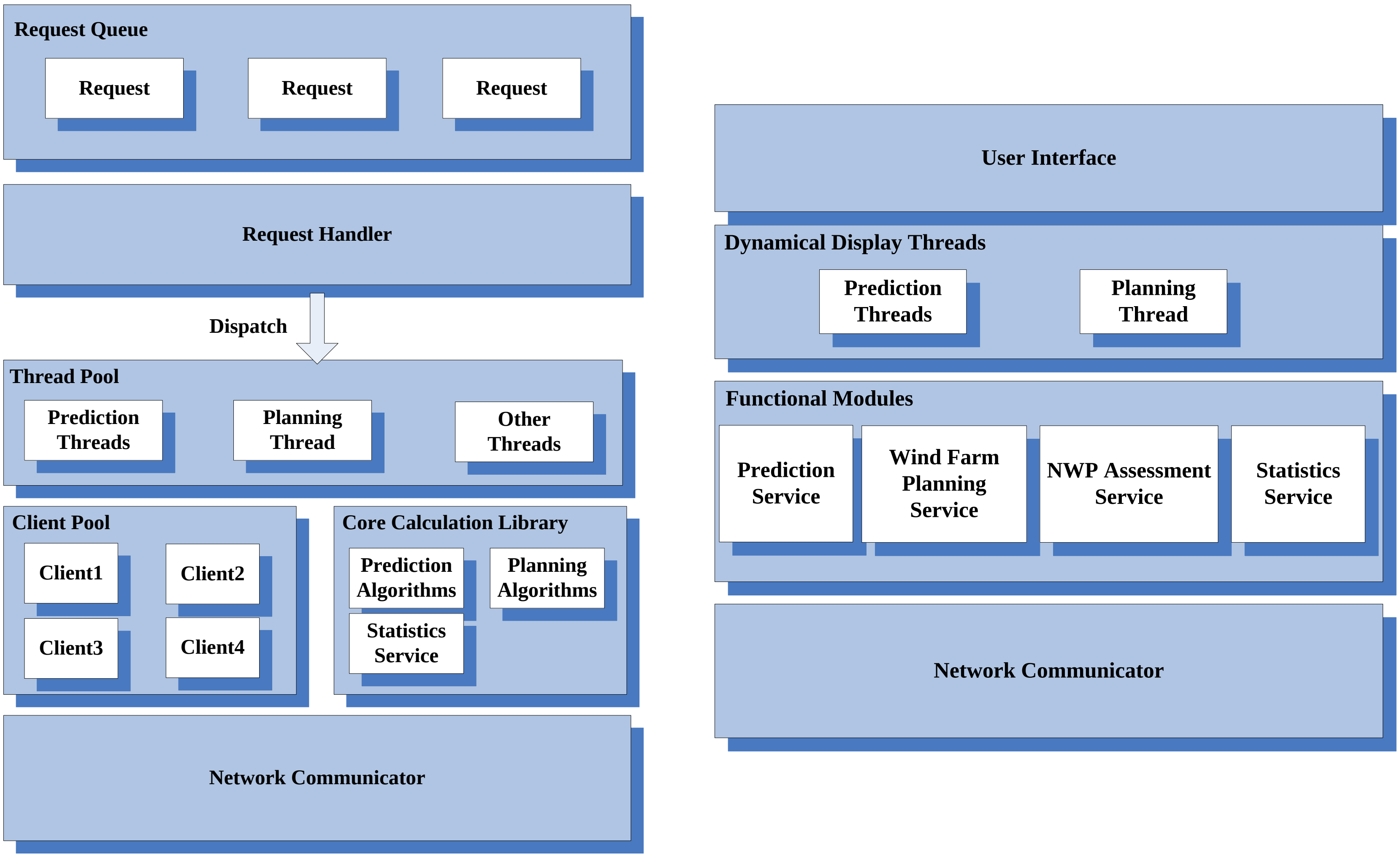
1. Low-voltage ride-through (LVRT) capability;
2. Dynamic security assessment;
3. Sub-synchronous resonance.

Wind Resource Assessment

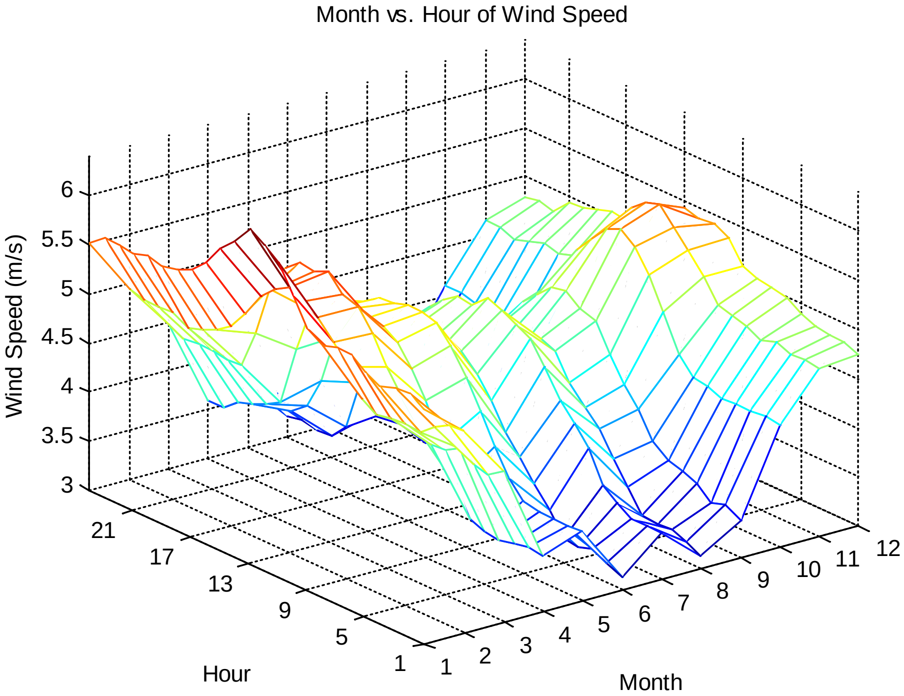
Wind Forecasting and Wind Farm Planning Software

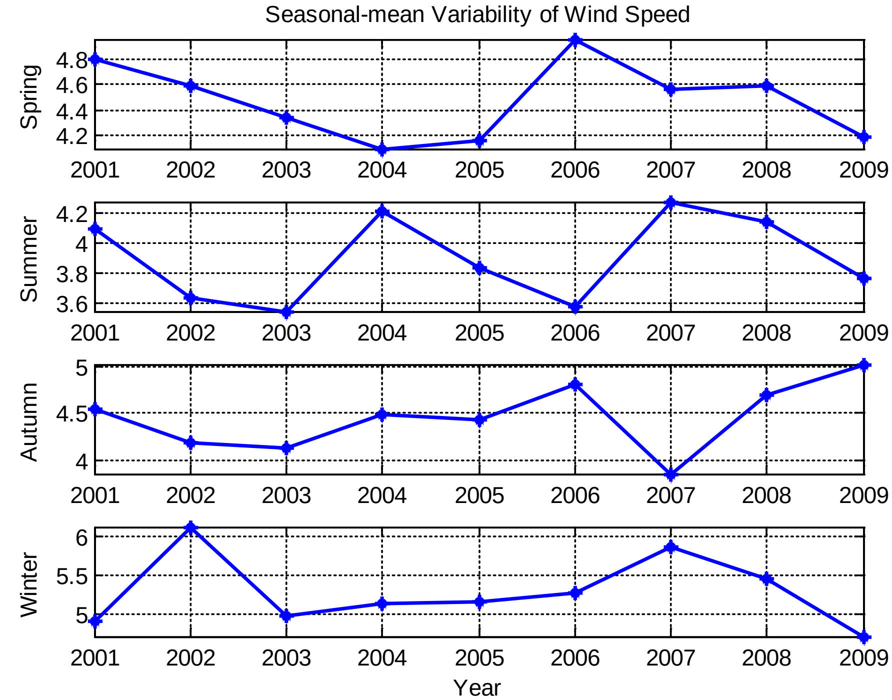


Wind Forecasting and Wind Farm Planning Software

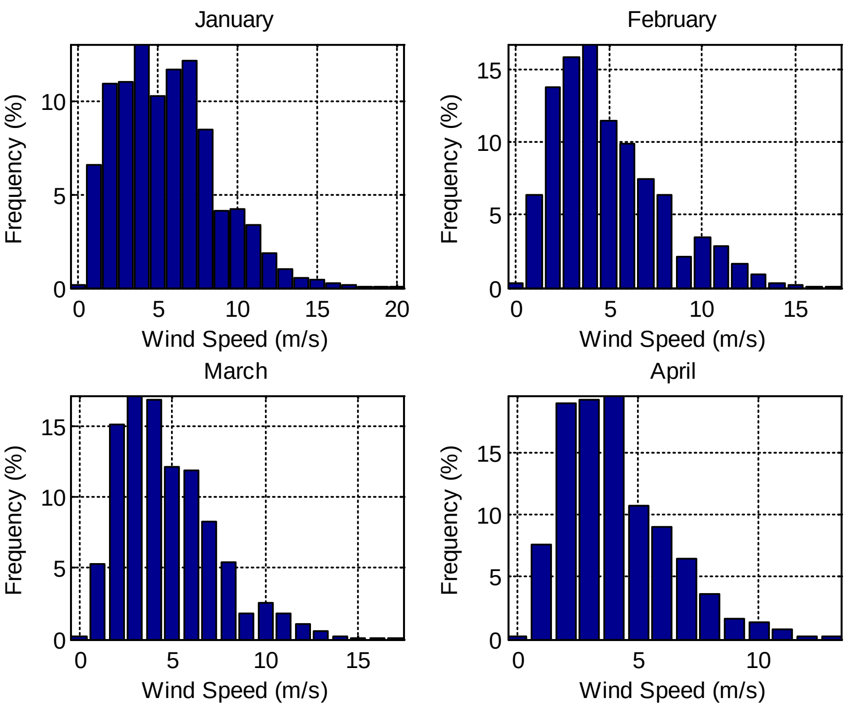


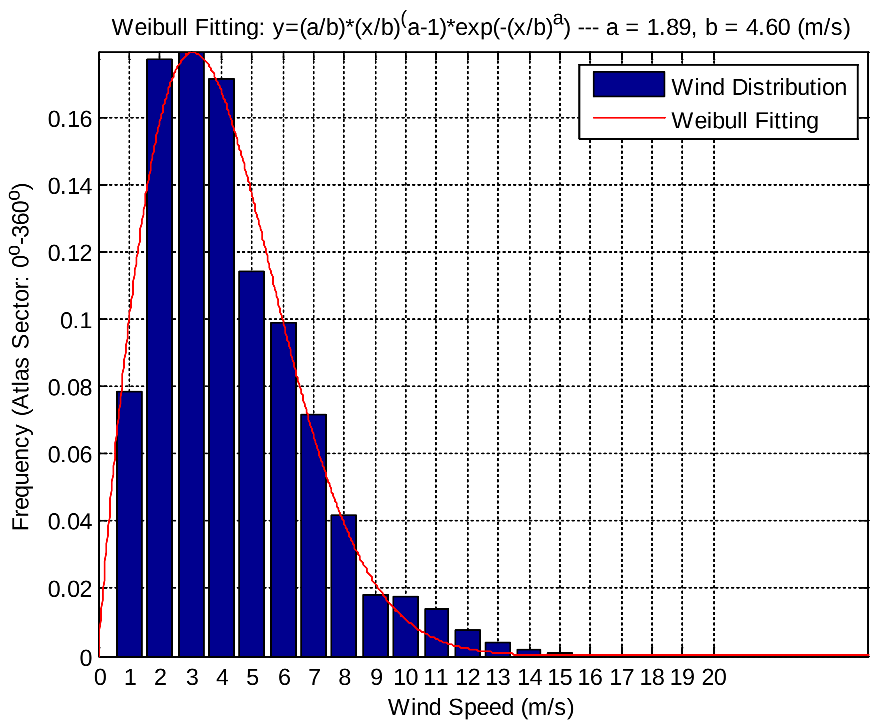
Statistics Analysis (Wind Speed)



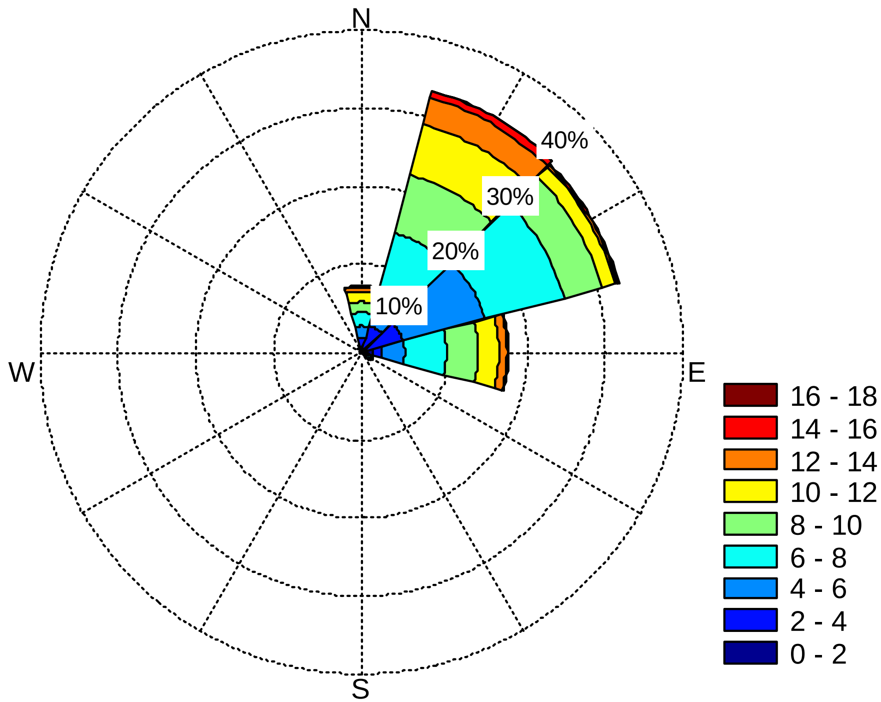


Statistics Analysis (Wind Speed)





❑ Statistics Analysis (Wind Direction)



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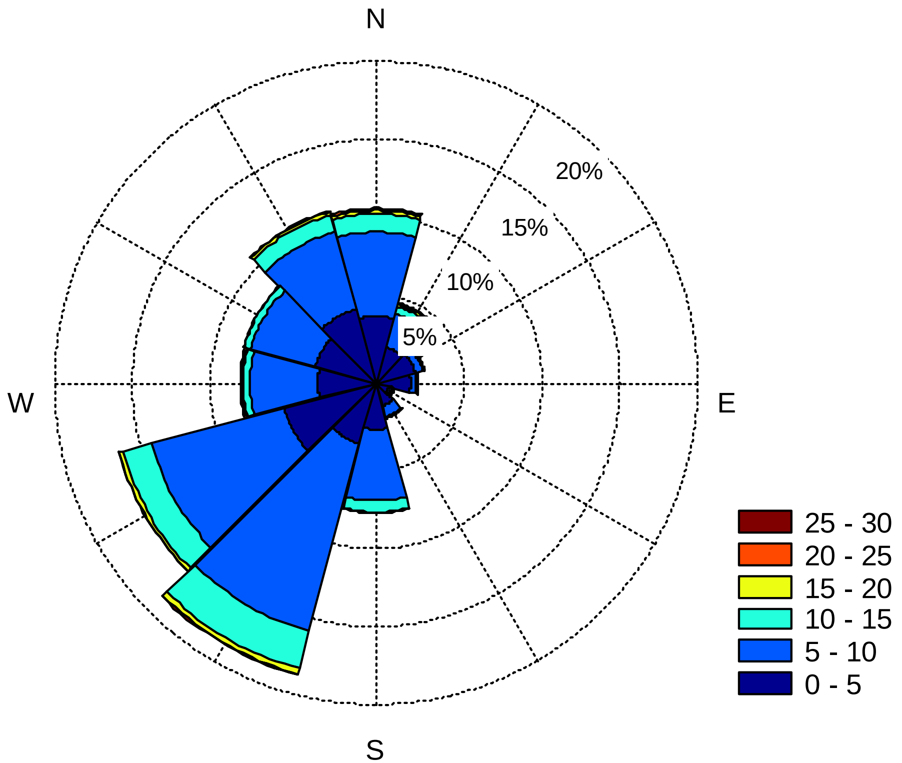

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Wind Farm Planning

Wind Farm Planning

Power Output Estimation

- **Wind Turbine Selection**
  - Up to 20 kinds of wind turbines;
  - Power output ranges from 800KW to 3.6MW;
  - Power output curve;
- **Surface Roughness Selection**
  - Up to 17 kinds of surface roughness;
  - Roughness ranges from 0.0001 (water area) to 1 (city);
- **Hub Height Speed Estimation**
  - Observation station altitude, measuring height, hub height;
  - Air density, wind speed, surface roughness;
- **Mean Power Output Calculation**

Wind Farm Planning

Index	Turbine Model	Diameter (m)	Hub Height (m)
1	Nordex N50 (800KW)	50	50
2	Nordex N60 (1300KW)	60	50
3	Vestas V52 (850KW)	52	55
4	Vestas V66 (1650KW)	66	67
5	Vestas V66 (1750KW)	66	67
6	Vestas V66 (2000KW)	66	67
7	Vestas V80 (1800KW)	80	67
8	Vestas V80 (2000KW)	80	67
9	Vestas V80 (2000KW Offshore)	80	67
10	Vestas V90 (1800KW)	90	80
11	Vestas V90 (2000KW)	90	80
12	Vestas V90 (3000KW)	90	80
13	Vestas V112 (3000KW Offshore)	112	100
14	SWT-2.3-82 (2300KW)	82.4	80
15	SWT-2.3-93 (2300KW)	93	80
16	SWT-3.6-107 (3600KW)	107	80
17	Sinovel-30-90 (3000KW)	90	80/90
18	Sinovel-30-100 (3000KW)	100	80/90/100/110
19	Sinovel-30-105 (3000KW)	105	80/90/100/110
20	Sinovel-30-113 (3000KW)	113	90/100/110

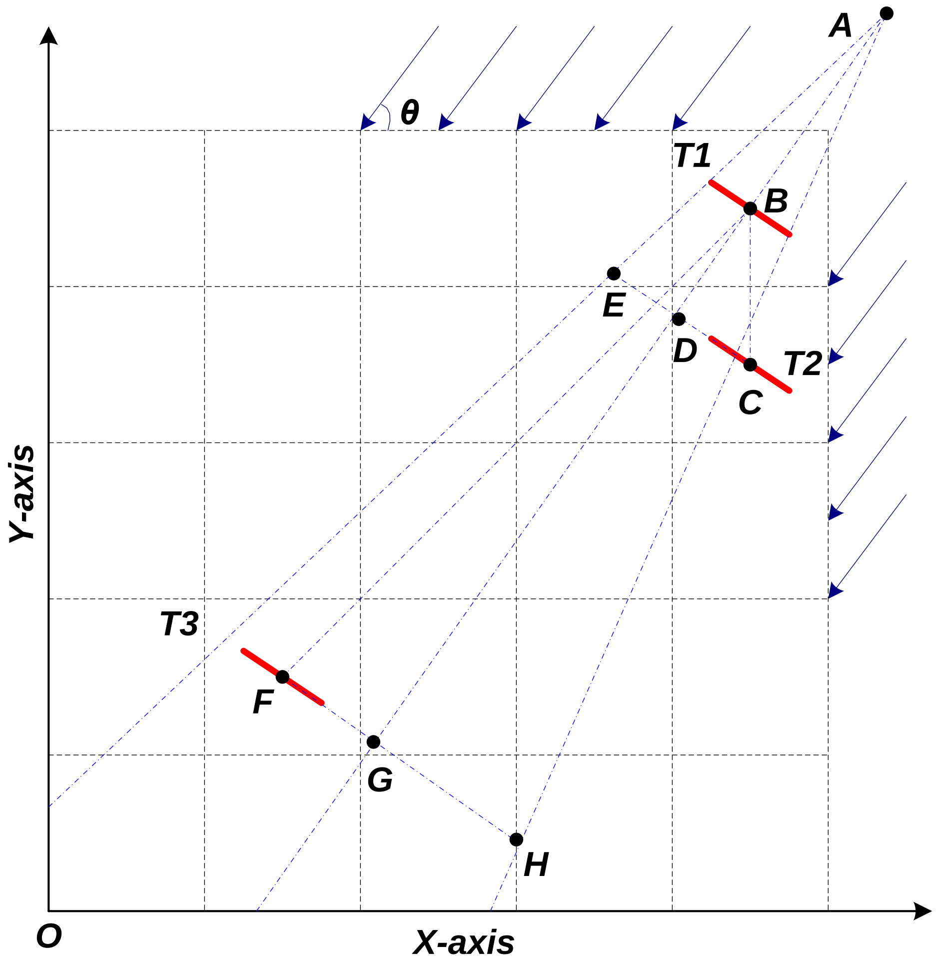
z_0 [m]	Terrain Surface Characteristics
1.00	City
0.80	Forest
0.50	Suburbs
0.40	---
0.30	Shelter belts
0.20	Many trees and/or bushes
0.10	Farmland with closed appearance
0.05	Farmland with open appearance
0.03	Farmland with very few buildings/trees
0.02	Airport areas with buildings and trees
0.01	Airport runway areas
0.008	Mown grass
0.005	Bare soil (smooth)
0.001	Snow surfaces (smooth)
0.0003	Sand surfaces (smooth)
0.0002	---
0.0001	Water areas (lakes, fjords, open sea)

Wake Effect Impacts

- **Low capacity**
- **Limited wind farm site**
- **Wake losses (reduction of wind speed and increase of turbulence downwind of a turbine)**
- **Intermittent and stochastic nature**

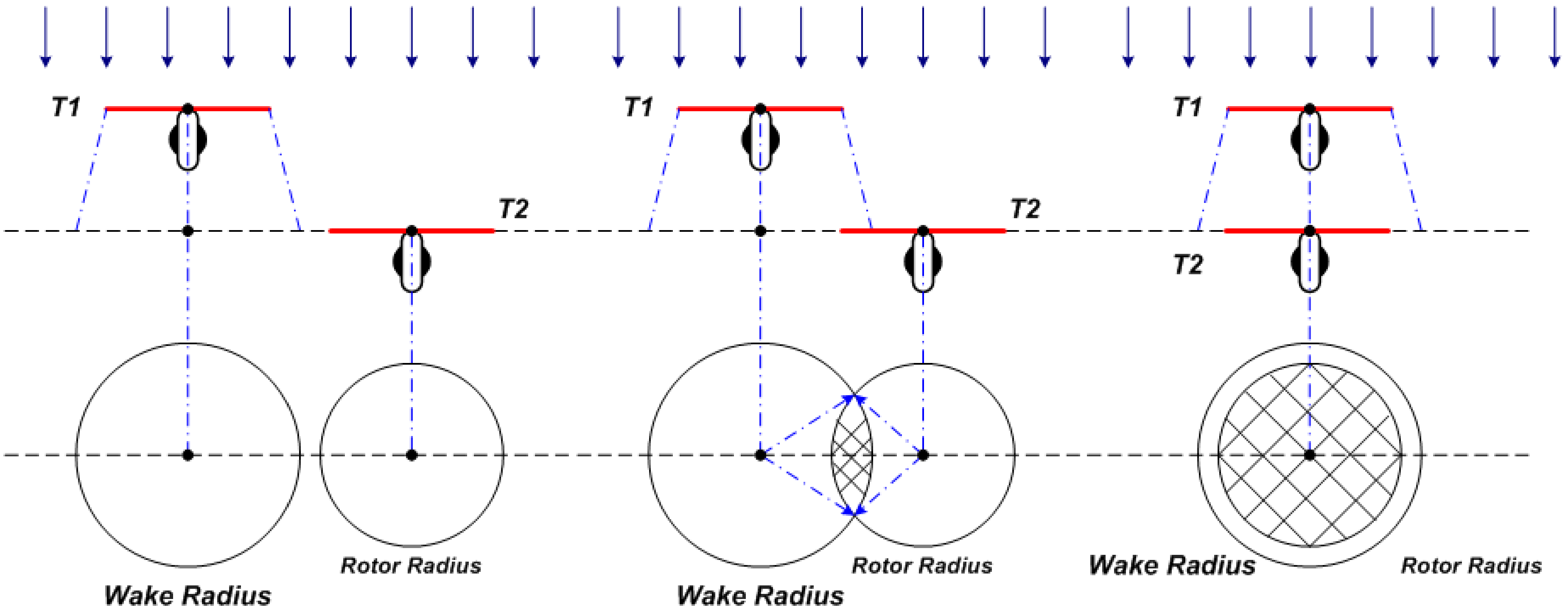
Wake Effect Modeling

- **Wake loss is an important factor in the design of wind turbine micro-siting optimization.**
- **Normally, when a uniform incoming wind encounters a wind turbine, a linearly expanding wake behind the turbine occurs.**
- **In a wind farm, the turbines can be affected by the wakes of several turbines located upstream.**



Wake Effect Modeling (Cont.)

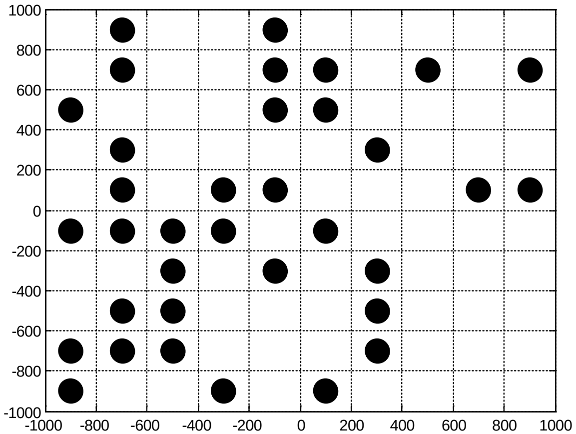
- **There are three different mutual effects, fully effect, no effect, and partial effect.**



Wake Effect Modeling (Cont.)

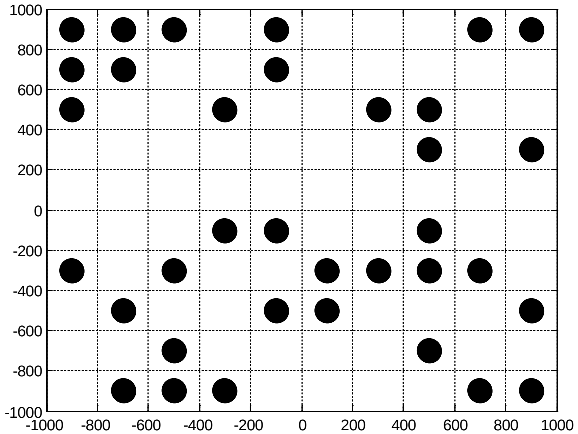
- **Fitness Function**
  - **Maximize mean power output;**
  - **Or minimize mean power losses.**
- **Challenges**
  - **Kinds of constraints;**
  - **Mixed with trigonometric function;**
  - **Mixed with definite integration;**
  - **Difficult to be solved by conventional approaches (linear programming, nonlinear programming, Quadratic programming).**

Wind Farm Planning



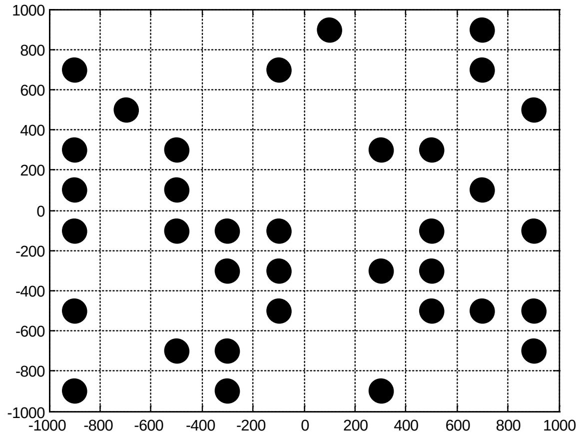
9.76%

Mean Power Output = 7.8700 MW
Mean Power Losses = 0.7679 MW



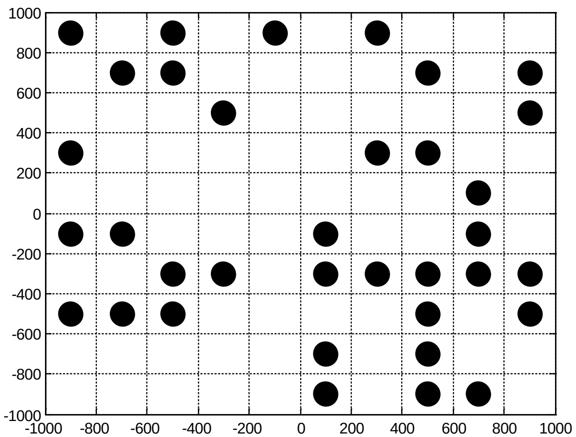
8.13%

Mean Power Output = 7.9883 MW
Mean Power Losses = 0.6496 MW



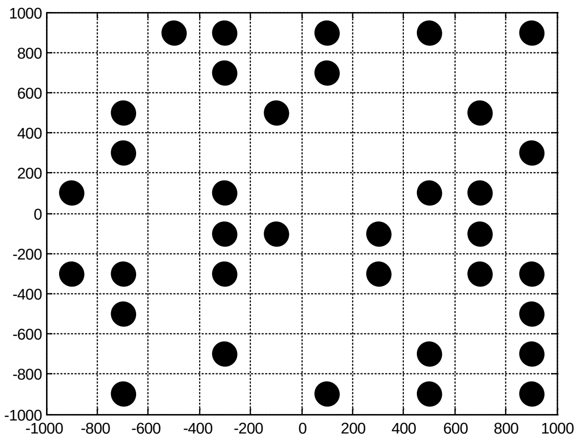
7.00%

Mean Power Output = 8.0725 MW
Mean Power Losses = 0.5654 MW



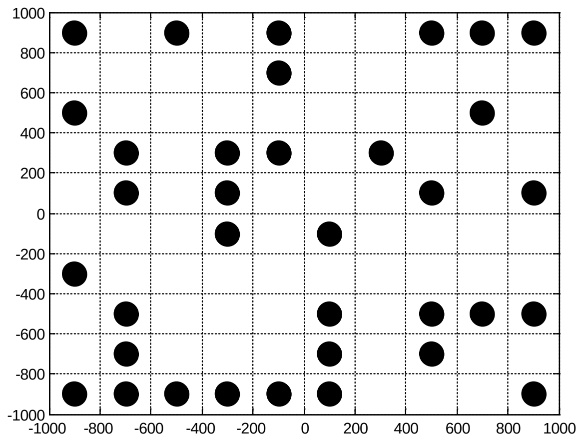
5.66%

Mean Power Output = 8.1751 MW
Mean Power Losses = 0.4628 MW



5.29%

Mean Power Output = 8.2034 MW
Mean Power Losses = 0.4345 MW



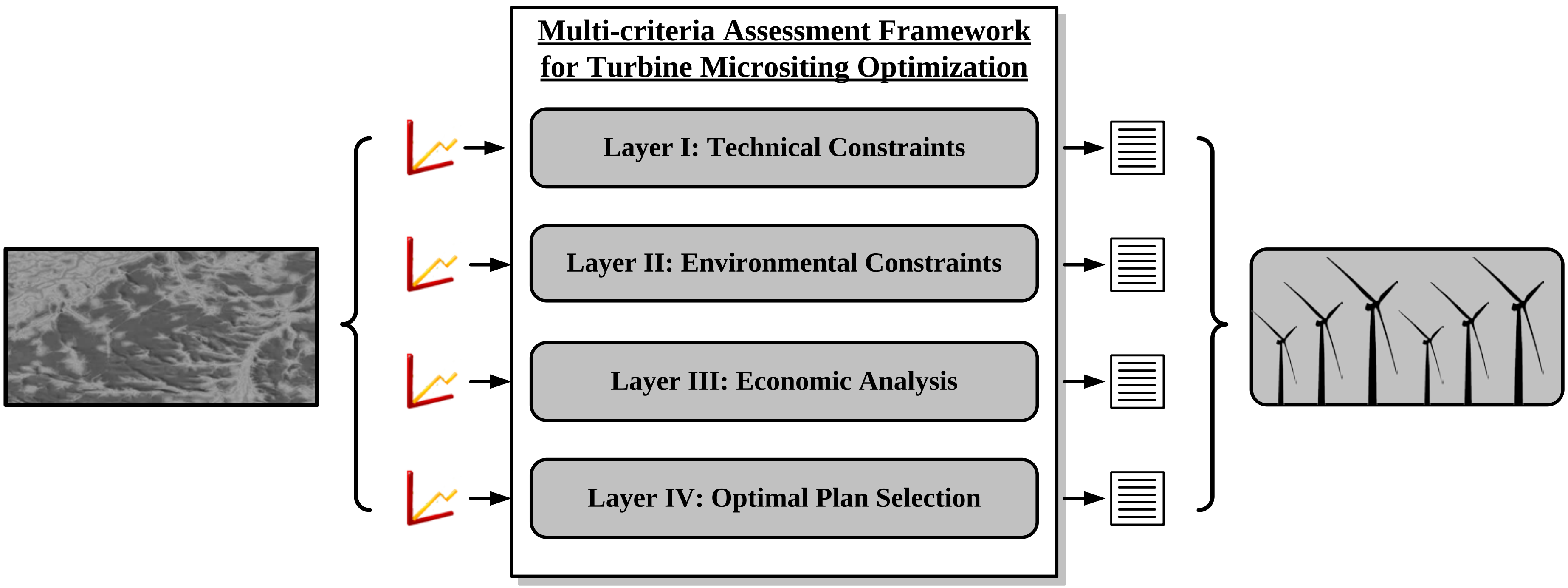
4.26%

Mean Power Output = 8.2852 MW
Mean Power Losses = 0.3527 MW

Micro-siting Optimization (Cont.)

- **Aside from the two constraints discussed above, the following criteria should be considered:**
  - **Wind predictability: Improper site selection may magnify the intense of wind power fluctuations, leading to inaccurate wind resource prediction, ending up with being penalized by electricity market;**
  - **Site accessibility: Improper site selection may cause extra costs for equipment transportation, installation, and maintenance;**
  - **Terrain complexity: Overlooking may cause extra costs relative to more transmission lines and towers to support stronger mechanical stress;**
  - **Flora and Fauna: Violation may cause damage to species in imminent danger;**
  - **Obstacles and infrastructures: Improper design may cause extra costs related to signalization equipment (aviation) or obstacle avoiding (heritage, transportation, rivers, telecommunications, etc.).**

❑ Micro-siting Optimization (Cont.)

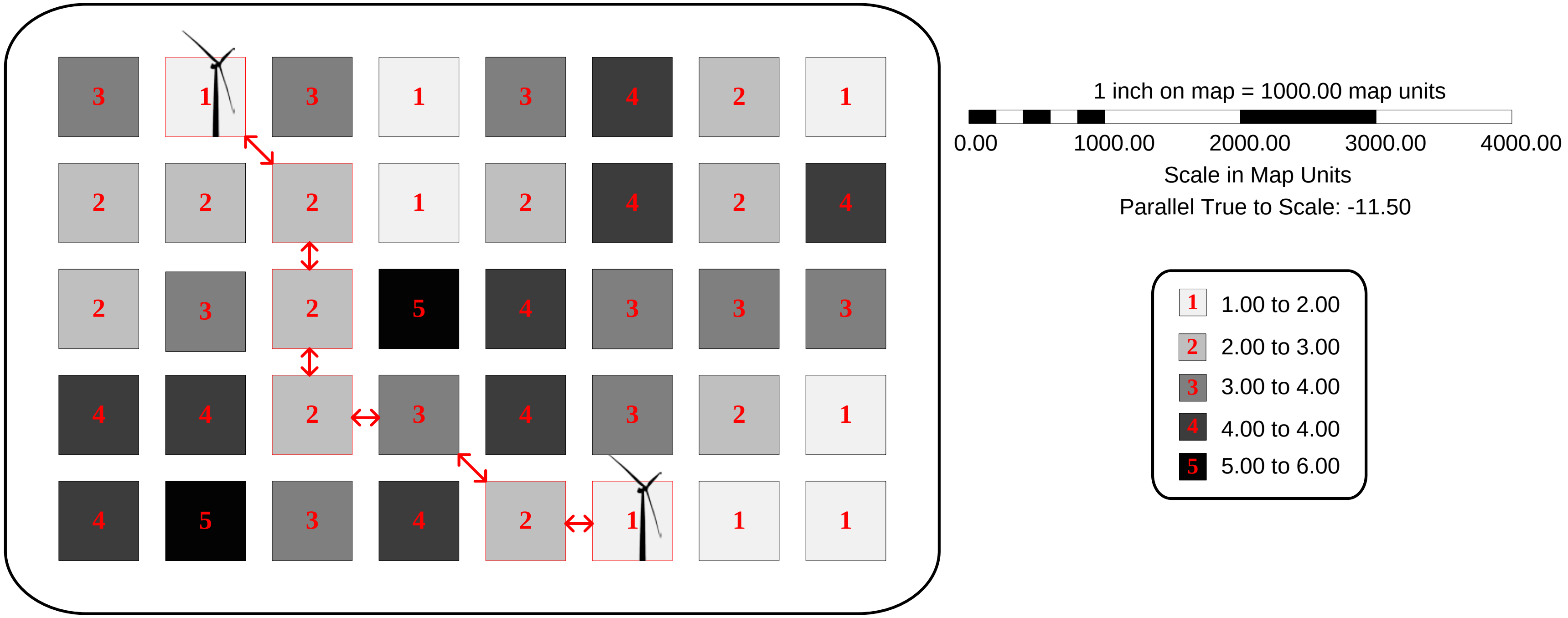


Electrical Layout Optimization

- **Electrical layout design is an engineering task that optimizes the equipment installation and maintenance costs subject to geographic, environmental, social, and legal constraints.**
- **The planner decides the path and areas crossed by the facilities taking existing constraints into account:**
  - **For small wind farms, the electrical layout problem can be solved by hand, or by using exhaust search techniques that try all possible cable types and layouts.**
  - **However, this problem quickly becomes infeasible, due to the increasing number of wind turbines. The cost of a cable connecting one turbine to another depends on the type of cable used, and the terrain where it crossed.**
- **We developed an efficient optimal electrical layout design approach for large-scale offshore wind farms to minimize the capital cost, power loss cost, and network maintenance cost, taking into account the constraints of wind turbines, electrical cables, substations.**

❑ Electrical Layout Optimization (Cont.)

- **The topography of terrain is modelled using a grid of units, where each unit represent a certain type of terrain and will be assigned a weight (cost coefficient) by decision makers according to its characteristic.**



Electrical Layout Optimization (Cont.)

- **Constraints:**
  - **Active power flow constraints:**

$$P_i^g = \sum_{j=1}^{N} V_i V_j \left[G_{ij} \cos\left(\delta_i - \delta_j\right) + B_{ij} \sin\left(\delta_i - \delta_j\right) \right]$$

  - **Reactive power flow constraints:**

$$Q_i^g = \sum_{j=1}^{N} V_i V_j \left[G_{ij} \sin\left(\delta_i - \delta_j\right) - B_{ij} \cos\left(\delta_i - \delta_j\right) \right]$$

  - **Capability limits of cables:**

$$\left| S_{ij} \right| \le S_{\max}, \forall i \in N$$

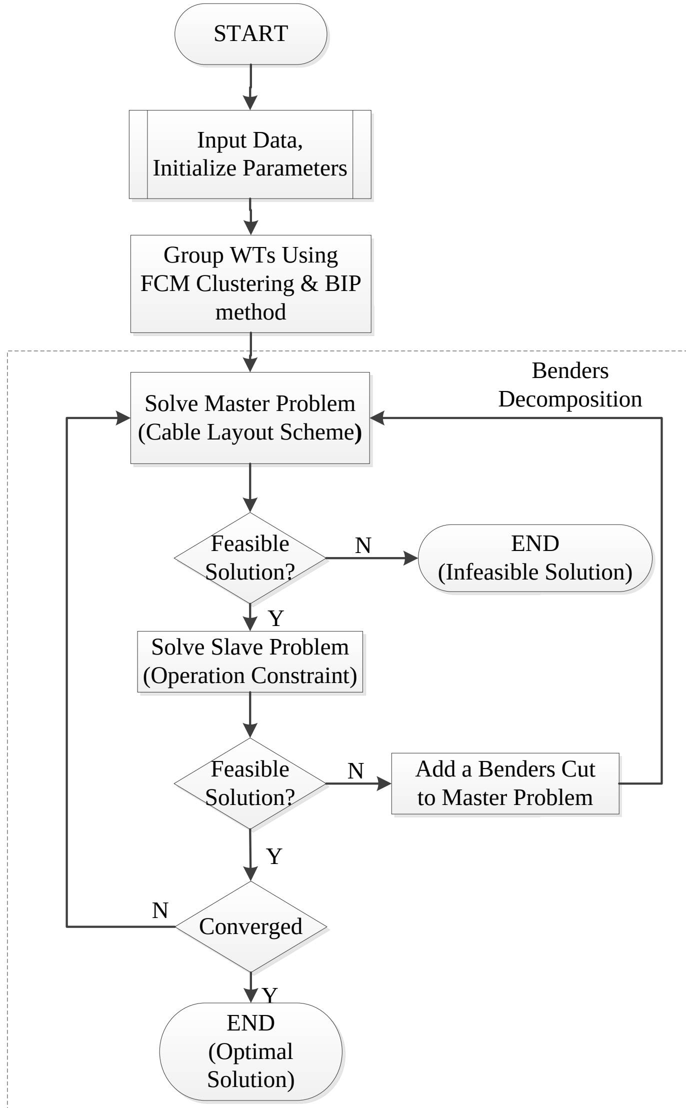
  - **Bus voltage limits:**

$$V_{\min} \le V_i \le V_{\max}, \forall i \in N$$

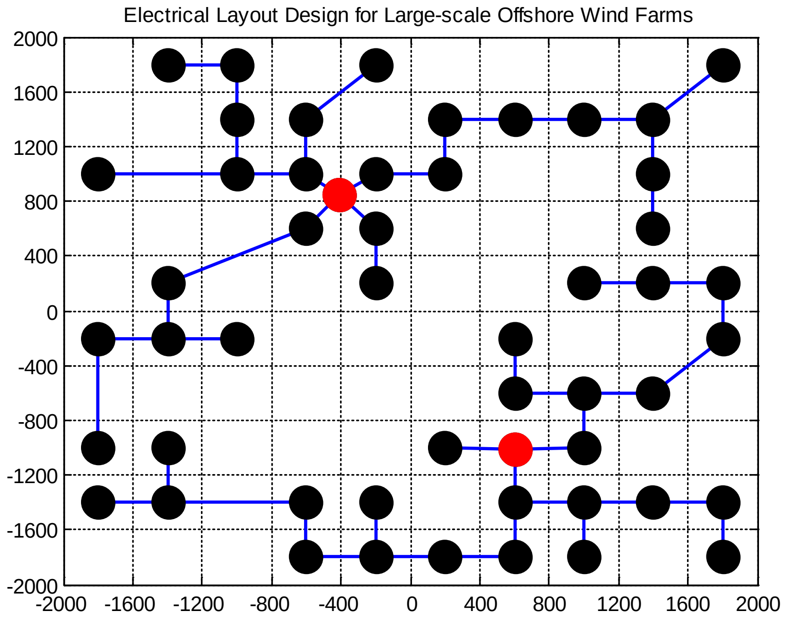
$$\delta_{\min} \le \delta_i \le \delta_{\max}, \forall i \in N$$

  - **Radial constraints:**

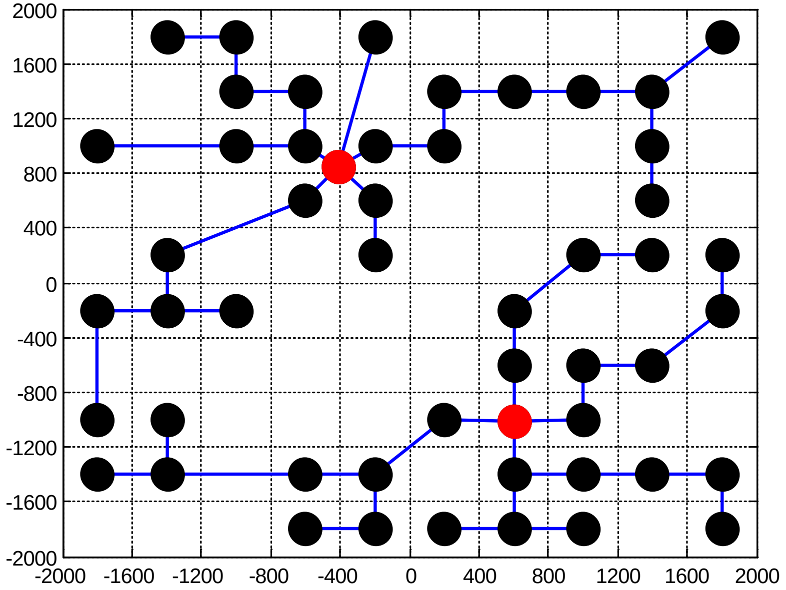
$$\sum_{i=1, i \ne j}^{N} x_{ij} \le 1, \forall j \in N$$



Electrical Layout Optimization (Cont.)



Only considering cable cost



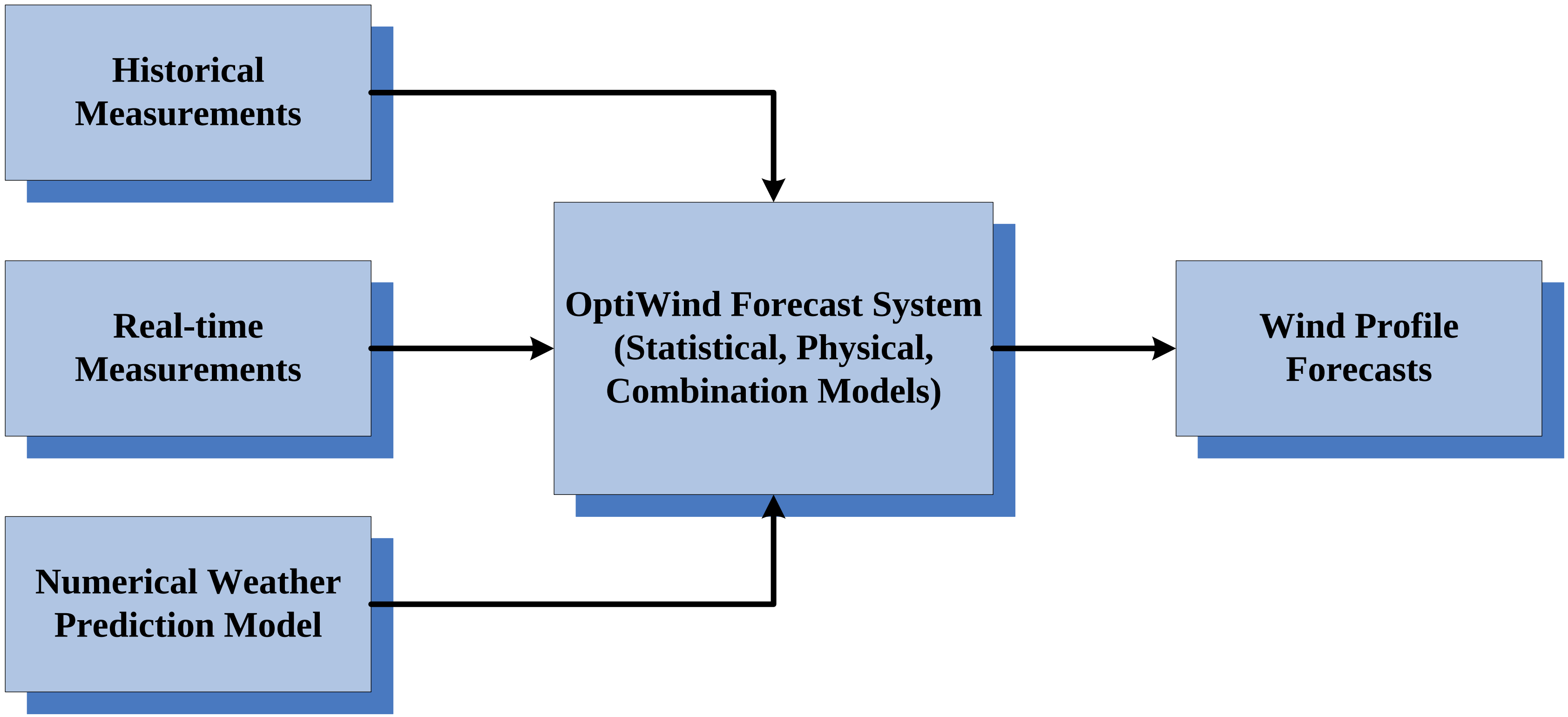
Considering cable cost, power loss cost, and maintenance cost

Wind Farm Dispatch

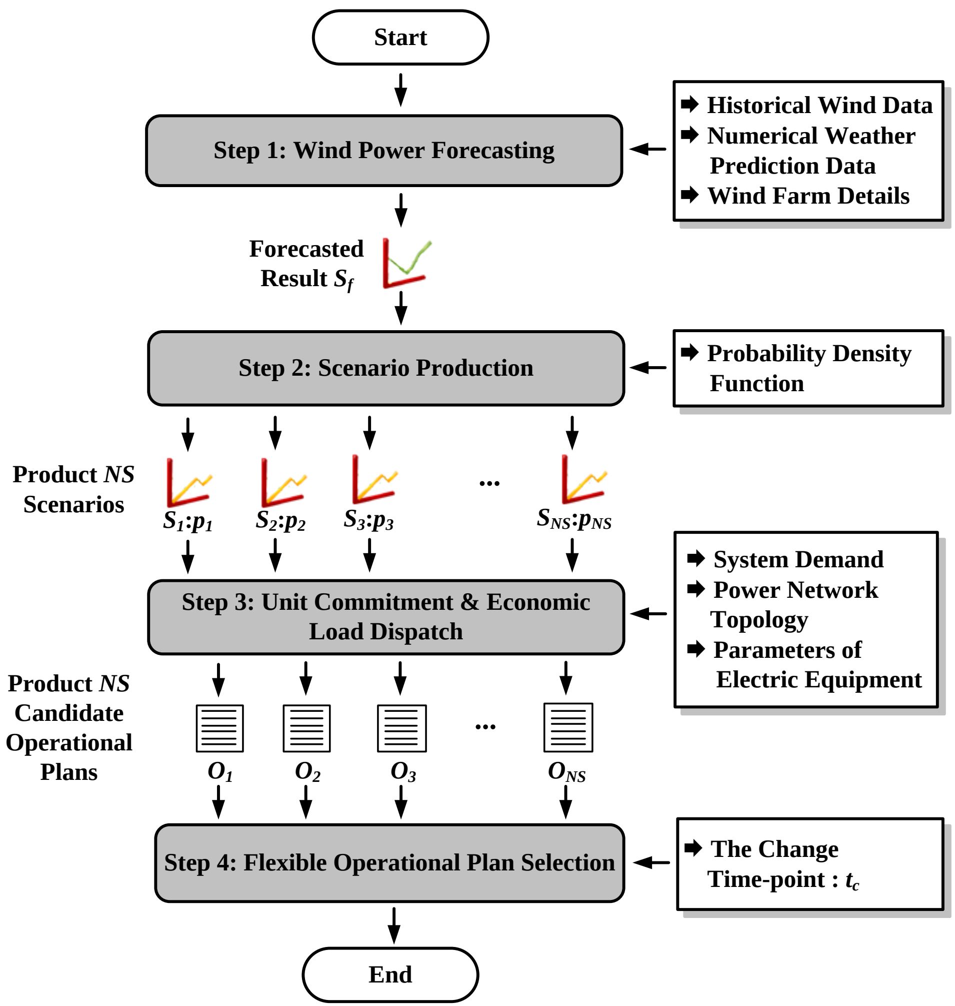
Wind Power Forecast

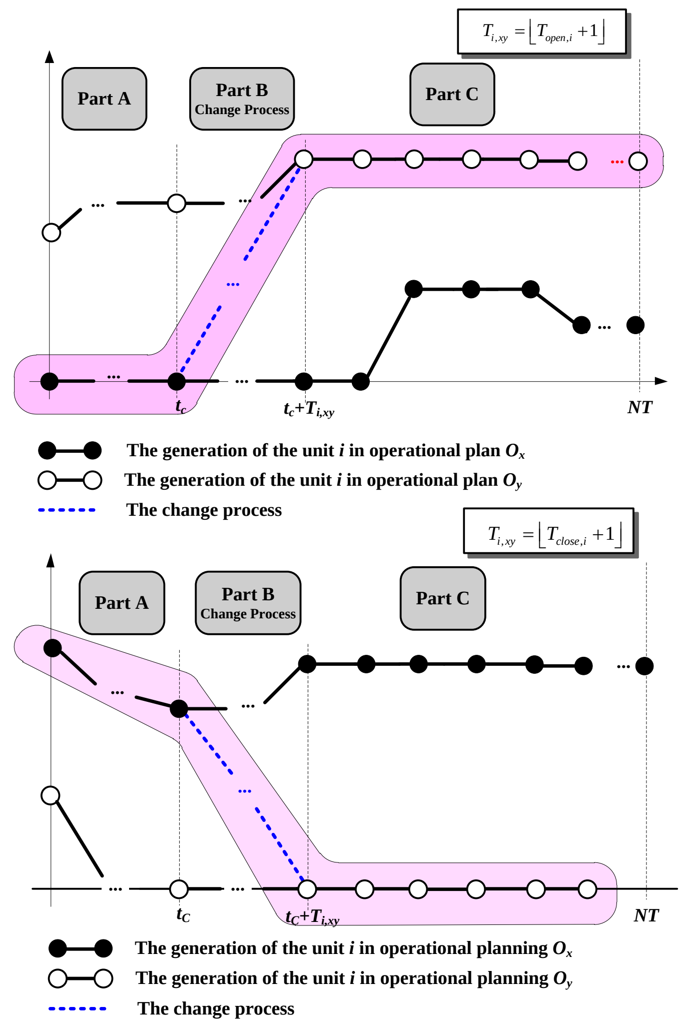
- **Long-term Forecast**
  - **Numerical Weather Prediction (NWP) model;**
- **Short-term Forecast**
  - **K-nearest Neighbor (KNN);**
  - **Generalized Autoregressive Conditional Heteroskedasticity (GARCH);**
  - **Wavelet Decomposition (WAD);**
  - **RBF Neural Network (RBFNN);**
  - **Support Vector Machine (SVM);**
  - **Relevance Vector Machine (RVM).**

Wind Power Forecast (Cont.)

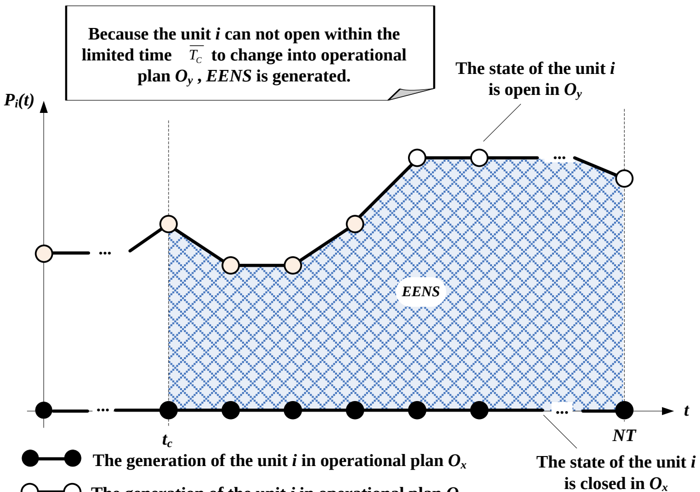


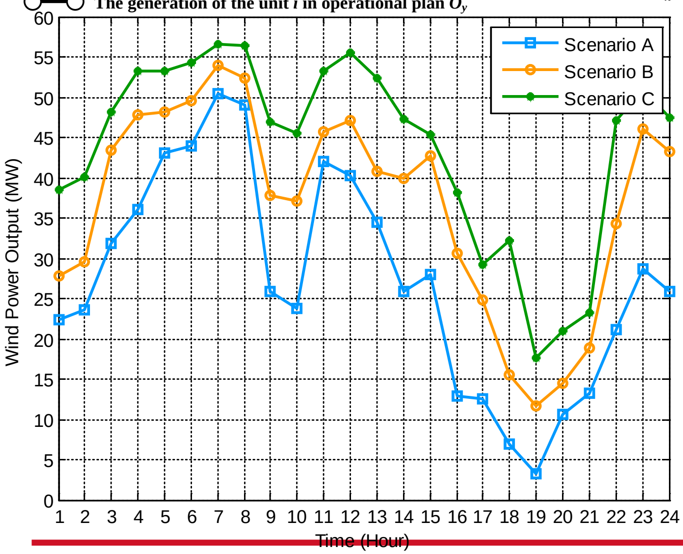
Flexible Operational Planning Framework





Flexible Operational Planning Framework (Cont.)





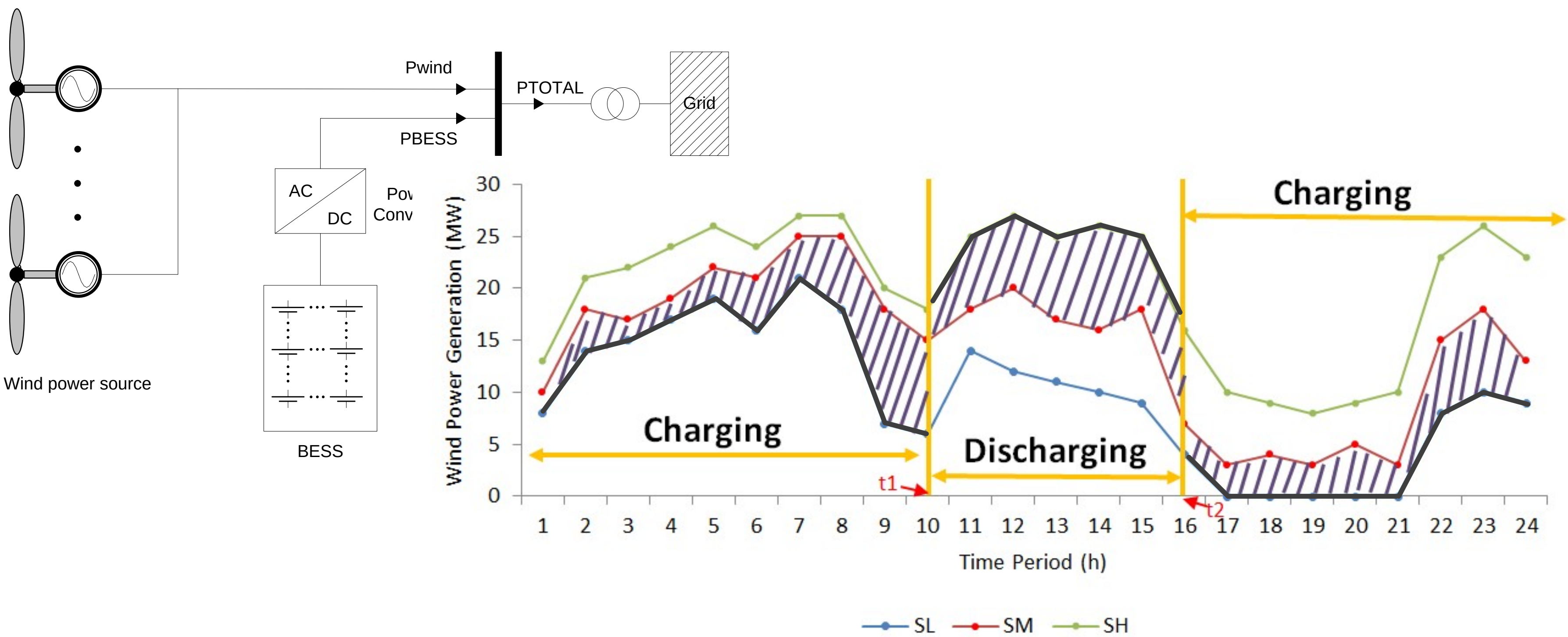
Operational Plan	Combined Operational Plan	Total Cost of Combined Operational Plan ($) Wind Changes at 05:00	Total Cost of Combined Operational Plan ($) Wind Changes at 13:00
A	A→A	523,126.07	523,126.07
	A→B	523,463.95	522,940.60
	A→C	517,618.45	517,837.46
B	B→A	518,368.36	516,225.70
	B→B	519,678.92	519,678.92
	B→C	513,347.13	512,756.43
C	C→A	518,758.95	515,873.99
	C→B	519,583.22	517,507.86
	C→C	514,224.09	514,224.09
Least Adaption Cost		517,255.16	515,869.17
Optimal Operational Plan		B	C

Wind Farm-BESS Dispatch Scheme

- **Advantages**
  - **Proven and reliable (most RE systems use them);**
  - **Many solution options (Lead-acid, NaS, NiCd, NiZn, NiMH, and Li-ion).**
- **Disadvantages**
  - **Relatively high capital cost;**
  - **Heavy (low energy density);**
  - **Require regular maintenance;**
  - **Low charging/discharging efficiency (70-80%);**
  - **Short lifespan (5-10 yrs.).**

❑ Wind Farm-BESS Dispatch Scheme (Cont.)

- **The benefits of this idea are, the wind power output can be controlled; the maximum capacity of battery storage system can be reduced, the optimal size can be estimated; the lifetime of energy storage device can be prolonged.**



Publications

- ***Technical Reports:***

- “Study on Transient Stability of HK Electric System with Offshore Wind Farm,” K. Meng, Z.Y. Dong, and K.P. Wong, Hong Kong Polytechnic University, Jul. 2011. To: ***Hong Kong Electric Company***.
- “Wind Forecast for Wind Power Generation in Hong Kong,” K. Meng, Z.Y. Dong, K.P. Wong, and F.J. Luo, Hong Kong Polytechnic University, Feb. 2011. To: ***Hong Kong Innovation and Technology Fund (ITF)***.

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- ***Selected Journal Papers:***

- Y. Zheng, Z.Y. Dong, F.J. Luo, K. Meng, J. Qiu, and K.P. Wong, "Optimal allocation of energy storage system for risk mitigation of DISCOs with high renewable penetrations," accepted by ***IEEE Transactions on Power Systems***, 17 Jul. 2013.
- D.L. Xie, Z. Xu, L.H. Yang, J. Østergaard, Y.S. Xue, and K.P. Wong, "A Comprehensive LVRT Control Strategy for DFIG Wind Turbines with Enhanced Reactive Power Support," ***IEEE Transactions on Power Systems***, vol. 28, no. 3, pp. 3302-3310, Aug. 2013.
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- Y. Chen, Z. Xu, and J. Østergaard, "Security Assessment for Intentional Island Operation in Distribution Network with Distributed Generations," ***Electric Power System Research***, vol. 81, no. 9, pp. 1849-1857, Sep. 2011.
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- L.Z. Xu, G.Y. Yang, Z. Xu, ZY Dong, J. Stergaard, and Y.J. Cao, "Composite microgrid dispatch considering wind power and CHP", ***Automation of Electric Power Systems*** (in Chinese), v35, no. 9, pp. 53-60,66, May 2011.

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- ***Selected Journal Papers (Cont.):***

- F.X. Li, W. Qiao, H.G. Sun, H. Wan, J.H. Wang, Y. Xia, Z. Xu, and P. Zhang, "Smart Transmission Grid: Vision and Framework," ***IEEE Transactions on Smart Grid***, vol. 1, no. 2, Sep. 2010.
- L.H. Yang, G.Y. Yang, Z. Xu, Z.Y. Dong, K.P. Wong, and X.K. Ma, "Optimal controller design of a doubly fed induction generator wind turbine system for small signal stability enhancement," ***IET Generation, Transmission & Distribution***, vol. 4, no. 5, pp. 579-597, 2010.
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- R. Bansal, V. Kumar, S. Kong, Z.Y. Dong, W. Freitas, and HD Mathur, "Three-Phase Doubly-Fed Induction Generators: An Overview", ***IET Electric Power Applications***, vol. 4, no. 2, pp. 75-89, 2010.
- Y. Mishra, S. Mishra, M. Tripathy, N. Senroy, and Z.Y. Dong, "Improving Stability of a DFIG-Based Wind Power System With Tuned Damping Controller", ***IEEE Transactions on Energy Conversion***, vol. 24, no. 3, pp. 650- 660, Sep. 2009.
- L.B. Shi, Z. Xu, and Z.Y. Dong, "Wind turbine model and initialization analysis with high penetration of grid-connected wind farms of DFIG type", ***Automation of Electric Power systems*** (in Chinese), vol. 3, pp 44-48, 2008.
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- ***Peer Reviewed Conference Papers:***

- F.J. Luo, Z.Y. Dong, Y.Y. Chen, K. Meng, G. Chen, H.Q. Tian, and K.P. Wong, "A novel short-term dispatch scheme for wind farm with battery energy storage system," *PES 2013: IEEE Power Engineering Society General Meeting*, Vancouver, BC, Canada, Jul. 2013.
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Thanks!
Any Questions?

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