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Reliability Constrained Wind Farm Network Design

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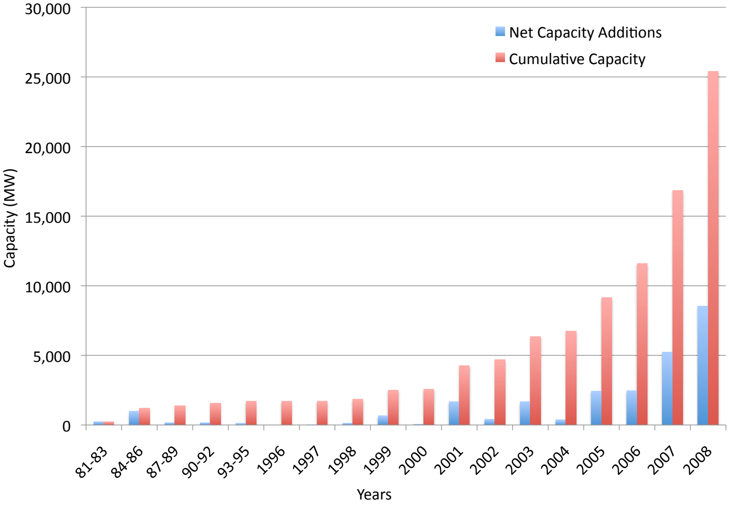
Motivation

- Wind is the fastest growing source of electricity in U.S. (AWEA 2008)



Motivation

- Much of the growth in renewable energy is a direct result of climate change concerns and increasing government support:
  - More than half the states passed Renewable Portfolio Standards
    - TX: 5,880MW (1%) by 2015, 10,000NW (2%) by 2025
    - CA: 30% by 2030
    - MI: 10% by 2015
  - American Recovery and Reinvestment Act of 2009
    - Production Tax Credit
    - Investment Tax Credit
- Wind is almost always the most cost-competitive renewable electricity source

Challenges

- Power system design models must now include wind-based generation
- Current models permit multiple types of generation (coal, natural gas, nuclear)
- Why can't we treat wind the same?
- Several important differences

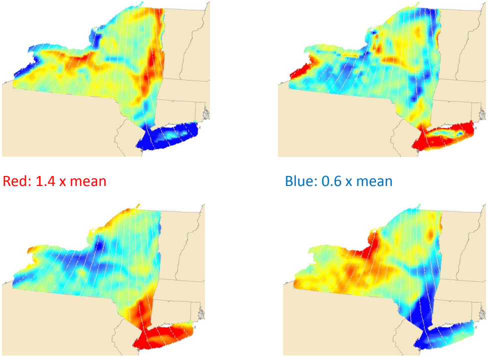
1. Spatial Variability of Wind Speed

- Wind speed varies over space
- Two coal generators at location A have the same capacity output and variability as two equivalent generators at location B
- Not true with wind!
- Can't separate capacity decisions from location decisions (integrated approach)

2. Temporal Variability

- At any given site, wind speed is also stochastic over time
- Because wind power can’t be efficiently stored, fluctuations are a real challenge

Deviations from Mean by Time of Day

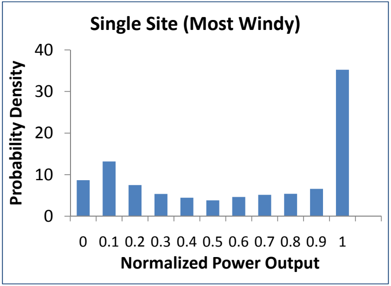


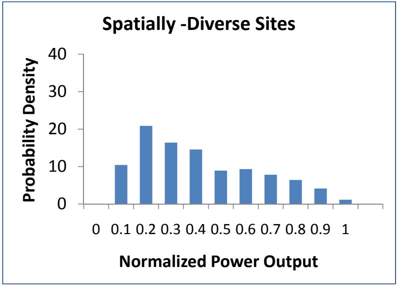
3. Co-Locating Production and Demand

- Conventional generators often located fairly close to load center (demand points)
  - Leads to reduced transmission costs
- Can't necessarily do this with wind
  - Best wind resources not necessarily near population centers
  - Transmission losses

4. Trade-off Between Transmission and Reliability

- More diverse network can mean greater reliability but higher transmission costs





Problem Overview

- How to design a network of wind farms to supply electricity across a large area, considering both system reliability and cost?
- All the challenges of designing traditional generation and transmission networks
- Additional challenges of spatial and temporal correlations of wind
- Current system planning studies focus on site-level optimization
  - selects sites based on average wind speed
  - neglects effect of spatio-temporal correlation across wind sites

An Integrated Planning Approach

- Wind and transmission are almost always built by separate organizations.
- Chicken-and-egg problem:
  - Wind developers not building if they can't access transmission
  - Transmission co. not building if no electrons flowing on wires
- Public agencies identifying resource in need of transmission
  - Incentives for transmission companies to build
  - If transmission is built, the wind developers will come
- Public agencies are engaging in centralized planning processes to determine the best location for this infrastructure (e.g. ERCOT's CREZ program, CA's RETI program)

Related Work

- Generation expansion
  - Bloom 1983, Gorenstin et al. 1993, Malcolm and Zenios 1994
- Transmission expansion
  - De la Torre et al. 1999, Oliveira et al. 2005, Shrestha et al. 2004
- Integrated transmission and generation expansion
  - McCusker and Hobbs 2003, Jirutitijaroen and Singh 2008
- Wind system expansion
  - Milligan and Factor 2000, Oh and Short 2009

Problem Statement (WFND)

$$\min \underbrace{\sum_{i\in\mathcal{N}} h_i z_i}_{\text{Gen. siting}} + \underbrace{\sum_{i\in\mathcal{N}}\sum_{g\in\mathcal{G}} c_i^g x_i^g}_{\text{Gen. capacity}} + \underbrace{\sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}:i<j} h_{ij} z_{ij}}_{\text{Trans. siting}} + \underbrace{\sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}:i<j}\sum_{t\in\mathcal{T}} c_{ij}^t x_{ij}^t}_{\text{Trans. capacity}} + \sigma \underbrace{\sum_{s\in\mathcal{S}} p^s Q(x,s)}_{\text{OM cost \& LOLC}}$$

s.t.

loss-of-load probability
$$\sum_{s\in\mathcal{S}} p^s d^s \geqslant (1-\alpha)$$

renewable portfolio standards
$$\sum_{i\in\mathcal{N}} \rho_i x_i^w \geqslant \text{RPS}$$

fixed charges
$$\begin{cases} x_i^g \leqslant M_i^g z_i, & \forall\, g\in\mathcal{G},\ i\in\mathcal{N} \\ x_{ij}^t \leqslant M_{ij}^t z_{ij}, & \forall\, t\in\mathcal{T},\ i,j\in\mathcal{N},\ i<j \end{cases}$$

variable integrality
$$\begin{cases} x_i^g \in \mathbb{Z}^+, & \forall\, g\in\mathcal{G},\ i\in\mathcal{N} \\ x_{ij}^t \in \mathbb{Z}^+, & \forall\, t\in\mathcal{T},\ i,j\in\mathcal{N},\ i<j \\ d^s \in \{0,1\}, & \forall\, s\in\mathcal{S} \\ z_i \in \{0,1\}, & \forall\, i\in\mathcal{N} \\ z_{ij} \in \{0,1\}, & \forall\, i,j\in\mathcal{N},\ i<j \end{cases}$$

- WFND is a two-stage stochastic program where first-stage decisions correspond to network design and second-stage decisions correspond to operating-maitenance (OM) cost and loss-of-load-cost (LOLC)

Recourse Function

$$Q(x,s) = \min \quad \underbrace{\sum_{i \in \mathcal{N}} \sum_{g \in \mathcal{G}} n_i^g p_i^g}_{\text{OM Cost}} + \underbrace{\sum_{i \in \mathcal{N}} c_i^\ell q_i}_{\text{LOLC}}$$

s.t.

flow balance
$$\left\{ \quad \sum_{g \in \mathcal{G}} p_i^g + \sum_{j \in \mathcal{N}} \sum_{t \in \mathcal{T}} \left[\mathcal{L}(p_{ji}^t) - p_{ij}^t \right] = b_i^s - q_i, \quad \forall\, i \in \mathcal{N} \right.$$

line capacity
$$\left\{ \quad p_{ij}^t \leqslant \kappa^t \cdot (e_{ij}^{ts} + x_{ij}^t), \quad \forall\, t \in \mathcal{T},\ i,j \in \mathcal{N} \right.$$

generation capacity
$$\left\{ \quad p_i^g \leqslant \kappa_i^{gs} \cdot (e_i^{gs} + x_i^g), \quad \forall\, g \in \mathcal{G},\ i \in \mathcal{N} \right.$$

demand fulfillment
$$\left\{ \quad \sum_{i \in \mathcal{N}} q_i \leqslant M \cdot (1 - d^s), \quad \forall\, g \in \mathcal{G},\ i \in \mathcal{N} \right.$$

nonnegativity
$$\left\{ \begin{array}{ll} p_{ij}^t \geqslant 0, & \forall\, t \in \mathcal{T},\ i,j \in \mathcal{N} \\ q_i \geqslant 0, & \forall\, i \in \mathcal{N} \\ p_i^g \geqslant 0, & \forall\, g \in \mathcal{G},\ i \in \mathcal{N} \end{array} \right.$$

Power Flow Models

- Node balance constraints
  - No Loss

$$\sum_{g \in \mathcal{G}} p_i^g + \sum_{j \in \mathcal{N}} \sum_{t \in \mathcal{T}} [p_{ji}^t - p_{ij}^t] = b_i^s - q_i, \quad \forall\, i \in \mathcal{N}$$

  - Linear Loss

$$\sum_{g \in \mathcal{G}} p_i^g + \sum_{j \in \mathcal{N}} \sum_{t \in \mathcal{T}} [(1 - \alpha_{ij}^t) p_{ji}^t - p_{ij}^t] = b_i^s - q_i, \quad \forall\, i \in \mathcal{N}$$

  - Quadratic Loss

$$\sum_{g \in \mathcal{G}} p_i^g + \sum_{j \in \mathcal{N}} \sum_{t \in \mathcal{T}} [p_{ji}^t - \frac{\beta ji^t}{e_{ji}^{t\omega} + x_{ji}^t} (p_{ji}^t)^2 - p_{ij}^t] = b_i^s - q_i, \quad \forall\, i \in \mathcal{N}$$

- Transportation model
  - Line capacity
- Linearized Direct Current (DC) model
  - Line capacity
  - Line flow constraints

WFND Variants

1. Relaxed Wind Farm Network Design (R–WFND)
    - No LOLP constraint
2. Scenario Selection for WFND (in progress)
    - α fraction of the scenarios can be ignored
3. Full Farm Network Design (in progress)

Solution Approach for R–WFND

- No probability constraint that binds across scenarios
  - Decomposible by scenarios
- Standard Benders Decomposition (S–BD)
  - performs poorly
- Accelerated Benders Decomposition (A–BD)
  - Necessary conditions
    - Network connectivity requirements
    - Demand fulfillment requirements – (I) area loads and (II) total system load
  - Valid inequalities
  - Multi-cut generation

Network Connectivity Requirements

- In early iterations of BD, transmission capacity and generation capacity are added piecemeal, resulting in network designs that are unconnected
  - Large LOLC
  - Weak UB
  - Increase size of integer RMP
- Enforcing network connectivity in RMP:
  Let D be an artificial demand-sink node and let y_{ij} be the flow of electricity from node i to node j.

$$\sum_j y_{ij} - \sum_j y_{ji} = z_i, \qquad \forall\, i$$

$$\sum_i y_{iD} = \sum_i z_i$$

$$y_{ij} \leqslant N \sum_t (x^t_{ij} + e^t_{ij}), \qquad \forall\, i,j$$

$$y_{ij} \geqslant 0, \qquad \forall\, i,j$$

Demand Fulfillment Requirements

- Network connectivity alone not sufficient to ensure adequate generation and transmission capacity is added
- Lower bound approximation of transmission and generation capacity to meet:
  - Area loads

$$
\begin{aligned}
p_i^d + \sum_j p_{ji}^d - \sum_j p_{ij}^d &= 0, && \forall\, i \neq d \\
p_i^d + \sum_j p_{ji}^d - \sum_j p_{ij}^d &= b_d, && i = d \\
p_i^d &\leqslant \sum_g m_{\text{cap}}^g \cdot (e_i^g + x_i^g), && \forall\, i \\
p_{ij}^d &\leqslant \sum_t m_{\text{cap}}^t \cdot (e_{ij}^t + x_{ij}^t), && \forall\, i,j
\end{aligned}
$$

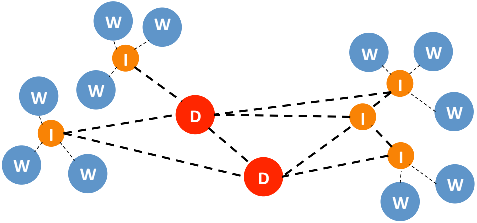
  - Total system load

Valid Inequalities and Multicut Generation

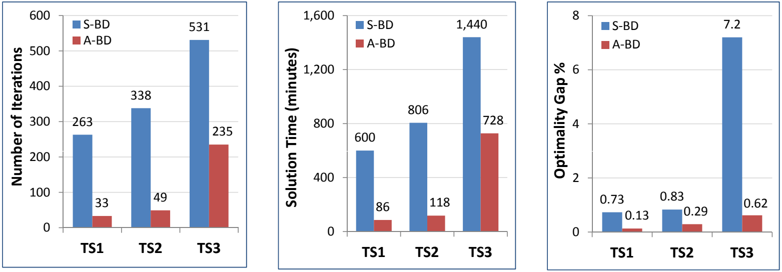
- Knapsack constraints derived using optimality cuts generated by BD iterations and incumbent upper bound (UB) (Santoso et. al 2005)
  - Used in conjunction with standard optimality cuts
  - As BD progress, knapsack inequalities tightens
- Multicut Generation (Birge and Louveaux 1988)
  - Block structure allows multiple cuts (one per scenario) to be generated simultaneously
    - 6-12 optimality cuts per iteration works best
    - Aggregate 732 to 1,464 hourly scenarios into each optimality cut

Computational Experiments

- 3 Test Systems (18-34 nodes, 25-38 arcs), 8784 scenarios
- Demand nodes represent five large meltropolitan areas in the West coast (hourly load data FERC 2004)
- Coincidental wind speed data from NREL's Western Wind Data Set (same period as load)
- Candidate wind sites randomly selected out of 32,043 candidate locations
- 24 hour runtime limit (AMD Opteron 8218, 1.5 GB RAM, CPLEX 11.0)



Computational Results



- Using S–BD, TS3 did not finish within the 24 hour runtime limit.
- Using S–BD a large number of iterations (long runtime) is required for convergence.

Ongoing Efforts

1. Scenario Selection for WFND
   - α fraction of the scenarios can be ignored
   - Progressive Hedging (PH) for scenario selection (Watson et al. 2010)
2. Wind Farm Network Design
   - Simultaneously considering both LOLC and LOLP across all $|\mathcal{S}|$ scenarios
   - A Two-pronged approach using Benders Decomposition and Progressive Hedging

Future Research Directions

- Developing cut augmentation procedure to improve convergence of Benders
- Optimizing the location of transmission interconnection
- Generalization for a broader class of stochastic facility location problems (e.g. disaster relief)

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Questions?