Risk-Constrained Multi-Stage Wind Power Investment

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Univ. Castilla – La Mancha, 2013
Problem:
Investment in production facilities
Motivation

Energy problems are important!
Motivation

How many coal plants are currently being built in planet Earth?
Motivation

- Major uncertainty: stochastic production facilities

- No such thing in the past (just demand uncertainty)

- No such thing in models for industry (production facilities are generally deterministic)
Motivation

- Complex uncertainty: multiple dependencies

  - Spatial correlations (i) among production facilities, (ii) among demands, and (iii) among demands and production facilities.

  - Temporal correlations for demands and production facilities
Motivation

• **Multi-stage** modeling is a must: future investment cost in stochastic sources is highly uncertain: the technology is not mature
  
  – No two-stage stochastic models
  – No adaptive robust optimization
Motivation

• Complex network structure
Motivation

• The functioning of the market needs to be represented: prices are highly affected by wind production. **Complementarity** models are thus required.
Motivation

• Electricity is ubiquitous and its supply is very reliable
• Electricity is very cheap: €1 to €2 per day per person

• Will this be like this in the future?
Contents

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1. Approach

Wind power investor: seeks to determine the wind power capacity to be built that maximizes its expected profit and minimizes the risk of its profit volatility.

✓ Where to build?
✓ When to build?
✓ Which capacity to build?
1. Motivation and approach

✓ Where to build?

- At nodes where construction is possible
- At nodes with the best wind power conditions
- At nodes “well connected” to the system
1. Motivation and approach

✓ When to build?

It depends on:

- Investment cost uncertainty
- Demand growth uncertainty
1. Motivation and approach

✓ Which capacity to build?

It depends on:

- Wind production uncertainty
- Demand growth uncertainty
- Prices
1. Motivation and approach

- Which type of model?
  - Complementarity model
  - Stochastic multi-stage model
  - Risk-constrained model
2. Problem description

- Maximization of the profit of the wind investor
- Minimization of the risk of profit volatility
- Pool based electricity market:
  - The wind producer offers at zero price (price taker!)
  - The wind producer is paid the LMP of its node
- Given transmission capacity (dc model)
2. Problem description

✓ Time framework:

Period 1

Investment 1

Period 2

Investment 2

Period T

Investment T

Reference year

Reference year
2. Problem description

• Scenarios: (i) demand growth uncertainty & (ii) investment cost uncertainty per
  – Time period (set of years)
  – Demand-wind condition
2. Problem description

✓ Demand & wind-production correlation modeling:

K-means clustering technique:

Historical data set → Reduced data set

Spatial and temporal correlation is preserved!
2. Problem description

1 wind location
1 demand location
2. Problem description

✓ demand growth scenario tree:

INVESTMENT 1

Scenario DW1
Scenario DW2
Scenario DW3
Scenario DW4

INVESTMENT 2
MARKET CLEARING 1

MARKET CLEARING 2
2. Problem description

✓ Investment cost uncertainty:

- INVESTMENT 1
- INVESTMENT 2
- MARKET CLEARING 1
- MARKET CLEARING 2

Scenario WPIC1
Scenario WPIC2
2. Problem description

✓ Demand growth + Investment cost uncertainty:

- Scenario DW1
- Scenario DW2
- Scenario DW3
- Scenario DW4

- Scenario WPIC1
- Scenario WPIC2
2. Problem description

✓ Demand growth + Investment cost uncertainty:

- Scenario WPIC1+DW1
- Scenario WPIC1+DW2
- Scenario WPIC1+DW3
- Scenario WPIC1+DW4
- Scenario WPIC2+DW1
- Scenario WPIC2+DW2
- Scenario WPIC2+DW3
- Scenario WPIC2+DW4
2. Problem description

Each scenario per time period (several years represented by 1 year) is defined by:

✓ Demand growth values
✓ Investment cost values
✓ Set of demand/wind conditions (from the K-means algorithm)
2. Problem description

Additional sources of uncertainty:

☑ Fuel prices
☑ Equipment outages
☑ Other market agents’ investments
2. Problem description

Wind levels are (approximately) stationary across years; wind productions are not.
2. Problem description

Decision sequence:

1) At the beginning of 1\textsuperscript{st} period: investment decisions (here-and-now)

2) Market clearing for each scenario realization (demand growth and investment cost) and for each demand/wind condition (that represent what happens throughout the period); 1\textsuperscript{st} period (wait-and-see)

3) Investment decisions for 2\textsuperscript{nd} period (wait-and-see & here-and-know)

4) Market clearing for each scenario realization (demand growth and investment cost) and for each demand/wind condition; 2\textsuperscript{nd} period (wait-and-see)
3. Model formulation

\[
\begin{aligned}
\text{Minimize} & \{x\} \cup \{x^1, \ldots, x^n\} \cup \{\lambda^1, \ldots, \lambda^n, \mu^1, \ldots, \mu^n\} \\
& f(x, x^1, \ldots, x^n, \lambda^1, \ldots, \lambda^n, \mu^1, \ldots, \mu^n) \\
\text{subject to:} & \\
& h(x, x^1, \ldots, x^n, \lambda^1, \ldots, \lambda^n, \mu^1, \ldots, \mu^n) = 0 \\
& g(x, x^1, \ldots, x^n, \lambda^1, \ldots, \lambda^n, \mu^1, \ldots, \mu^n) \leq 0 \\
& \text{Minimize}_{x^1} f^1(x, x^1, \ldots, x^n) \\
& \text{subject to:} \\
& h^1(x, x^1, \ldots, x^n) = 0(\lambda^1) \\
& g^1(x, x^1, \ldots, x^n) \leq 0(\mu^1) \\
& \vdots \\
& \text{Minimize}_{x^i} f^i(x, x^1, \ldots, x^n) \\
& \text{subject to:} \\
& h^i(x, x^1, \ldots, x^n) = 0(\lambda^i) \\
& g^i(x, x^1, \ldots, x^n) \leq 0(\mu^i) \\
& \vdots \\
& \text{Minimize}_{x^n} f^n(x, x^1, \ldots, x^n) \\
& \text{subject to:} \\
& h^n(x, x^1, \ldots, x^n) = 0(\lambda^n) \\
& g^n(x, x^1, \ldots, x^n) \leq 0(\mu^n) \\
\end{aligned}
\]
3. Model formulation

**UPPER-LEVEL**
Maximize Expected Profit – $\beta \times$ Risk Profit Measure

**LOWER-LEVEL**
Maximize SW

MARKET CLEARING 1  MARKET CLEARING 2  …  MARKET CLEARING N

Different demand growth and investment cost scenarios, periods and wind/demand conditions!
3. Model formulation

UPPER-LEVEL PROBLEM

Maximize

Expected Profit – \( \beta \times \) Risk Profit Measure

subject to

Investment constraints
Wind power availability
Price = LMP
CVaR constraints
Non-anticipativity constraints
3. Model formulation

LOWER-LEVEL PROBLEMS

Maximize

subject to

- Power Balance
- Power Production Limits
- Transmission Capacity Limits
- Voltage Angle Limits

1 lower-level problem per demand growth and investment cost scenario, period and demand/wind condition!

λ : LMP
3. Model formulation

Upper-level & lower-level have to be solved jointly

KKT conditions lower-level problems

- Bilevel problem:
  - Two levels
  - Non linear

- MPEC problem:
  - Single level
  - Non linear
3. Model formulation

MPEC problem:
- Single level
- Non linear

MILP problem:
- Single level
- Linear

Nonlinearities:
- Objective function: Production $\times$ Price
  - Strong duality equality
- Complementarity constraints: $a \perp b$
  - Fortuny-Amat transformation: MILP
3. Model formulation

Problem structure:

- Benders’ decomposition

Convexification as the number of scenarios grows!
4. Case studies

3-bus system:

- Two five-years periods
4. Case studies

- Demand/wind conditions
4. Case studies

- Demand/wind conditions: reduced
4. Case studies

3-bus system: Just investment cost uncertainty

- Investment cost known in period 1
- 3 investment cost scenario realizations in period 2: high (H), medium (M) and low (L)
- Risk-neutral ($\beta=0$) and risk-averse ($\beta=1$) solutions
# 4. Case studies

## Results

3-bus system: **Investment cost uncertainty**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Risk-neutral</th>
<th>Risk-averse</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Period 1</td>
<td>Period 2</td>
</tr>
<tr>
<td>H</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>M</td>
<td>114.3 MW</td>
<td>39.0 MW</td>
</tr>
<tr>
<td>L</td>
<td>185.7 MW</td>
<td>146.7 MW</td>
</tr>
</tbody>
</table>
4. Case studies

3-bus system: Just demand growth uncertainty

✓ 3 demand growth scenario realizations in period 1: H, M and L
✓ 3 demand growth scenario realizations in period 2 for each demand growth realization in period 1: H, M and L
✓ Risk-neutral ($\beta=0$) and risk-averse ($\beta=1$) solutions
4. Case studies

Results

3-bus system: Demand growth uncertainty

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Risk-neutral Period 1</th>
<th>Risk-neutral Period 2</th>
<th>Risk-averse Period 1</th>
<th>Risk-averse Period 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH, HM, HL</td>
<td>108.3 MW</td>
<td></td>
<td>108.3 MW</td>
<td></td>
</tr>
<tr>
<td>MH, MM, ML</td>
<td>152.3 MW</td>
<td>0.8 MW</td>
<td>60.7 MW</td>
<td>92.3 MW</td>
</tr>
<tr>
<td>LH, LM, LL</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

July 12, 2013

Antonio J. Conejo
4. Case studies

3-bus system: Investment cost and demand growth uncertainty

- Investment cost known for period 1
- Two scenario realizations of investment cost in period 2: M, L
- 2 demand growth scenario realizations in period 1: H, L
- 2 demand growth scenario realizations in period 2 for each demand growth realization in period 1: H, L
- Risk-neutral ($\beta=0$) and risk-averse ($\beta=1$) solutions
4. Case studies

Results -- 3-bus system: Investment cost and demand growth uncertainty

<table>
<thead>
<tr>
<th>Investment cost scenario</th>
<th>Demand growth scenario</th>
<th>Risk-neutral Period 1</th>
<th>Risk-neutral Period 2</th>
<th>Risk-averse Period 1</th>
<th>Risk-averse Period 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>HH, HL</td>
<td>67.2 MW</td>
<td>198.8 MW</td>
<td>136.0 MW</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>LH, LL</td>
<td>92.4 MW</td>
<td>78.7 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>HH, HL</td>
<td>67.2 MW</td>
<td>232.8 MW</td>
<td>130.0 MW</td>
<td>170.0 MW</td>
</tr>
<tr>
<td>L</td>
<td>LH, LL</td>
<td>232.8 MW</td>
<td>170.0 MW</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. Case studies

3-bus system: Investment cost and demand growth uncertainty (efficient frontier)
4. Case studies

IEEE 118-bus system:

- 3 five-year periods
- 32 demand growth & investment cost scenarios
- 2 potential locations of wind plants
- Risk-neutral ($\beta=0$) and risk-averse ($\beta=1$) solutions
4. Case studies

IEEE 118-bus system: results

✓ Different risk-aversion levels result in different investment strategies

✓ Computational issues:
  ✓ Intractable if MILP is solved directly
  ✓ Using Benders: about 20 h on a Linux-based server with 4 processors clocking at 2.9 GHz and 250 GB of RAM (compatible with time requirements in investment studies)
5. Conclusions

1. A risk-constrained multi-stage modeling is a must for deciding wind investment
2. Uncertainties and correlations difficult to model
3. Heavy computational burden
4. Decomposition is possible (Benders)
5. Tractable model for systems of realistic size
6. Different risk-aversion levels: different investment strategies
Reading

thank you