MARKET-BASED RESOURCE ADEQUACY ASSESSMENT FRAMEWORK UNDER HIGH WIND PENETRATIONS

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BACKGROUND

- Resource adequacy
  - The ability to provide adequate supply during peak load and stressed system conditions
  - Typically measured using long-term reliability standards (e.g. LOLE, LOLH, LOLP)

- Resource adequacy requirements
  - E.g., planning reserve margin
    : translates the reliability standards into a reserve margin
MARKET DESIGN FOR RESOURCE ADEQUACY

- Vertically integrated system
  - Centralized generation expansion planning
  - Integrated resource planning

- Restructured electricity markets
  - Market-based mechanisms to promote investments to meet resource adequacy requirements

- Energy-only markets (ERCOT)

- Capacity remuneration mechanisms (CRMs)
  - Capacity obligation and market (ISO-NE, MISO, NYISO, PJM)
  - Capacity obligation (CAISO, SPP)
  - Capacity payments
  - Strategic reserves
RESEARCH MOTIVATION

- Investigate resource adequacy in a competitive market environment
  - Main driver: Individual profit-maximizing generating companies (GenCos)
  - Various market designs and conditions to consider:
    - Electricity market design, in particular CRMs
    - Industry structure and level of competition
    - VRE penetration level

- Traditional centralized capacity expansion models
  - Minimizes system cost, cannot capture the decision making of individual generation GenCos
  - Limited ability to assess the effectiveness of capacity remuneration mechanisms

- Other tools needed to investigate market dynamics and resource adequacy in a competitive market environment
MULTI-AGENT RESOURCE PLANNING MODEL

- Captures strategic interactions between individual GenCos’ investment decisions
- Considers revenues from capacity + energy/reserve markets
- Bi-level programming formulation

![Diagram](image-url)
MULTI-AGENT RESOURCE PLANNING MODEL

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Goal: Find an equilibrium investment and retirement solution
Philosophy: Stackelberg leader-follower games
Method: Diagonalization Method
SOLUTION APPROACH

- A GenCo’s decision solved individually as Stackelberg leader-follower game
- Nash Equilibrium among GenCos found with “diagonalization method”
LEAST-COST MODEL FOR COMPARISON

- **Least-cost model**: finds optimal generation portfolio while minimizing system-wide costs

- **Individual Genco model**: finds optimal generation portfolio while maximizing own profits

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**Least-Cost Generation Planning Model**
*(Single-level, MILP)*

- Min. Cost_EM + Capital Cost + O&M Cost – Capacity Demand
- Investment / Retirement Constraints
- Capacity demand constraints
- (Lower Level 2, Scenario 1) Energy & Reserve Market (SCED)
- (Lower Level 2, Scenario 2) Energy & Reserve Market (SCED)

**Multi-Agent Generation Planning Model**
*(Bi-level, MINLP)*

- Max. Revenue_CM + Profit_EM – Capital Cost – O&M Cost
- Investment / Retirement Constraints
- (Lower Level 1) Capacity Market
- (Lower Level 2, Daytype 1) Energy & Reserve Market (SCED)
- (Lower Level 2, Daytype D) Energy & Reserve Market (SCED)
INDIVIDUAL GENCO PROBLEM

- Mathematical Problem with Equilibrium Constraints (MPEC)
- MPEC re-formulated as a MILP
- Further computational performance enhancement using a decomposition method
CASE STUDY

- Simplified “ERCOT”-like system for 2030
  - Projected peak load: 86,613 MW (1.57% increase per year)
  - Simple transmission system (9 nodes, 34 lines)
  - 30 representative days (scenario reduction)

- Generation Portfolio and GenCos
  - Total system capacity: 94,916 MW (ICAP), 77,218 MW (UCAP)
  - No. of existing thermal units: 176 → 51
  - No. of existing GenCos: 23 - No. of new entrants: 8

<table>
<thead>
<tr>
<th>Node</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>Total ICAP</th>
<th>Capacity Factor</th>
<th>Total UCAP</th>
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<tbody>
<tr>
<td>Coal</td>
<td>2,127</td>
<td>8,347</td>
<td>1,770</td>
<td>1,804</td>
<td>538</td>
<td>925</td>
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<td>0</td>
<td>0</td>
<td>15,511</td>
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<tr>
<td>NGCC</td>
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<td>11,854</td>
<td>6,914</td>
<td>1,758</td>
<td>498</td>
<td>300</td>
<td>3,259</td>
<td>0</td>
<td>0</td>
<td>33,035</td>
<td>1.00</td>
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<td>NGCT</td>
<td>5,373</td>
<td>5,040</td>
<td>804</td>
<td>2,646</td>
<td>1,845</td>
<td>811</td>
<td>672</td>
<td>1,210</td>
<td>0</td>
<td>18,401</td>
<td>1.00</td>
<td>18,401</td>
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<td>Nuclear</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4,960</td>
<td>1.00</td>
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<tr>
<td>Wind</td>
<td>0</td>
<td>3,756</td>
<td>4,967</td>
<td>12,793</td>
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<td>0</td>
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<td>21,516</td>
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<tr>
<td>Solar</td>
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<td>1,493</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1,493</td>
<td>0.75</td>
<td>1,120</td>
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<tr>
<td>Total</td>
<td>15,952</td>
<td>31,325</td>
<td>18,581</td>
<td>19,001</td>
<td>2,881</td>
<td>2,035</td>
<td>3,932</td>
<td>1,210</td>
<td>0</td>
<td>94,916</td>
<td></td>
<td>77,218</td>
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</table>
ANALYSIS DESIGN

- Investment Options

<table>
<thead>
<tr>
<th>Type</th>
<th>Size (MW)</th>
<th>Overnight cost ($/kW)</th>
<th>Life Cycle</th>
<th>Fixed O&amp;M Cost ($/kW/Year)</th>
<th>Variable O&amp;M Cost ($/MWh)</th>
<th>Fuel Cost ($/MMBTU)</th>
<th>Weighted Average Cost of Capital (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGCC</td>
<td>400</td>
<td>1,026</td>
<td>30</td>
<td>10.25</td>
<td>3.08</td>
<td>4.64</td>
<td>5.3</td>
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<tr>
<td>NGCT</td>
<td>200</td>
<td>873</td>
<td>30</td>
<td>12.30</td>
<td>7.18</td>
<td>4.64</td>
<td>5.3</td>
</tr>
</tbody>
</table>

- Cost of New Entry (CONE)
  - $177.6/MW-day
  - Capital cost, fixed O&M cost, and life cycle of NGCT unit
  - Net CONE = CONE – revenue offset from energy/reserves (30%)

- Target installed reserve margin (IRM):
  - 13.75%

- VRE Penetration Levels

<table>
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<tr>
<th>Scenario</th>
<th>Wind Capacity (MW)</th>
<th>Penetration Level (%)</th>
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</thead>
<tbody>
<tr>
<td>Base</td>
<td>21,516</td>
<td>18.4</td>
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<tr>
<td>Modest</td>
<td>30,070</td>
<td>25.7</td>
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<tr>
<td>High</td>
<td>38,625</td>
<td>33.1</td>
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</table>
MARKET DESIGN OPTIONS

- Market design parameters

<table>
<thead>
<tr>
<th>Market Design</th>
<th>Load Shedding Penalty</th>
<th>Reserve Shortage Penalty</th>
<th>Capacity Market Demand Curve</th>
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</thead>
<tbody>
<tr>
<td>Energy-only (EO)</td>
<td>$9,001</td>
<td>ORDC ($9,000 Max)</td>
<td>N/A</td>
</tr>
<tr>
<td>Vertical Capacity Demand Curve (VDC)</td>
<td>$3,500</td>
<td>$3,500 (<del>4%); $2,250 (4</del>96%); $200 (96~100%)</td>
<td>Vertical (Fixed)</td>
</tr>
<tr>
<td>Sloped Capacity Demand Curve (SDC)</td>
<td>$2,100</td>
<td>$850 (<del>96%); $300 (96</del>100%)</td>
<td>Sloped</td>
</tr>
</tbody>
</table>

<ERCOT Operating Reserve Demand Curve (ORDC)*>

<MISO Capacity Market Demand Curve>

<PJM Capacity Market Demand Curve>

RESULTS

- Comparison of the generation portfolio in terms of ICAP and PRM from the market-based model
RESULTS

- Comparison of the additional investment capacity (ICAP) from the least-cost and the market-based model
CONCLUSIONS

- VRE influence electricity markets
  - Incentive schemes may have substantial impacts on prices

- Open questions around resource adequacy with VRE
  - Capacity markets are complex and not well understood
  - Solutions need to enable economic entry and exit

- A multi-agent model for capacity expansion
  - Considers market interactions between competing GenCos
  - Models revenues from energy, reserves, and capacity markets

- Case study results
  - Energy only design may work well
  - Capacity markets benefit from using a sloped capacity demand curve
  - Proper market signals can guide the market outcome towards a least-cost optimum, also with high VRE levels
FUTURE WORK AND EXTENSIONS

- Incorporate transmission expansion planning
- Investigate other capacity remuneration policies
- Further enhance the computational performance
- Heuristics to find an equilibrium solution
REFERENCES AND ACKNOWLEDGEMENTS

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THANK YOU