Modeling Nuclear Power as a Flexible Resource for the Power Grid

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Outline

- Background and Motivation

- Market Operation with Nuclear Plant Flexibility
  - Nuclear Plant Flexibility
  - System Operation

- Test Case
  - A Vertical Utility Power System
  - System Operation Analysis

- Conclusion and Future Work
Background: Nuclear energy is increasingly economically challenged in the U.S. deregulated electricity markets

- **Recent nuclear plant closures for economic reasons:**
  - San Onofre 2 and 3 in California (closed in 2013 to avoid repair costs);
  - Crystal River 3 in Florida (closed in 2013 to avoid repair costs);
  - Kewaunee in Wisconsin (closed in 2013, simply un-economic);
  - Vermont Yankee, in Vermont (closed in 2014).

- **Large uprates being cancelled:**
  - Prairie Island, 1; LaSalle, 1 and 2; Limerick, 1 and 2.

- **Exelon and Entergy indicated that certain units in deregulated markets are unprofitable, and may need to be closed:**
  - Byron; Clinton; Quad Cities; Fitzpatrick (scheduled for Jan 27th, ’17);...

- **5 new reactors being built, all in regulated markets:**
  - 4 new builds (2 AP1000 units each at Summer, SC and Vogtle, GA);
  - 1 completion of a previously halted project (TVA’s Watts Bar 2).
Motivation

• Main reasons cited for economic problems
  1. Low natural gas prices, coupled with high efficiency combined cycle power units;
  2. Increased penetration of renewables, with zero marginal cost of production;
  3. Wind and solar, added to an already adapted system, are displacing conventional units;
  4. Resulting in low and highly variable electricity prices and low profit margins for nuclear units.

• Objective:

  Understand whether and how nuclear plants can adapt to this situation, both from an economic and technical perspective.
Nuclear Power Plant Flexibility Modeling

- **Expected flexible power operations**
  - Planned load following
  - Frequency regulation
  - Spinning reserve
  - Dynamic price-responsive operations

- **Technical constraints** (Light Water Reactor)
  - **Control rod movement**
    - Insertion into the core to reduce power output,
    - Withdraw to increase power output
  - **Thermal and mechanical stresses** -> fuel cladding cracking failure
  - **Coolant temperature and pressure** -> stress on other components
  - Longer-term changes in the **equilibrium concentration** of Xenon 135 (a powerful neutron absorber)
  - burn-up of fuel throughout the fuel cycle may effect the maneuverability
Power System/Market Operations

- **Stage 1: Unit Commitment**
  - Given: Load forecasting, Available units, Time horizon – Days, Weeks…
  - Determine: Units that should be placed online for production or reserve on each hour
  - Objective: Minimize production Cost/ Maximize Social Welfare
  - Subject to: Supply and Demand Balance, Unit minimum up and down time, Ramp-up and Ramp-down rates, Operating Reserve, Transmission network…

- **Stage 2: Economic Dispatch**
  Given commitment schedule on generation units and probably with more accurate load forecast, how much electricity should each of the committed unit produce?

Power supply/demand
Formulation

- **Objective Function**

\[
\text{Min} (\text{total cost of day}) = \sum_{t=1}^{24} \{\text{fuel costs} + \text{penalty unserved load} + \text{penalty unserved reserve} + \text{startup costs}\}_t
\]

- **Constraints**

  (1) Load-generation balance for all hours.

\[
\sum_i \text{thermal power}_{it} + \text{wind power}_t + \text{PV power}_t + \text{unserved load}_t = \text{load}_t
\]

(2) PV (distributed and utility-scale) and wind dispatch for all hours.

\[
\text{dist} \ PV_t \leq \ PV \text{ power}_t \leq \text{dist} + \text{utility} \ PV_t \\
0 \leq \text{wind power}_t \leq \text{available wind power}_t
\]
Formulation

(3) Spinning up/down and non-spinning reserve up requirements for all hours.

\[ \sum_i^{\text{reserve thermal unit}_{it}} + \text{unserved reserve}_t \geq \text{balancing reserve}_t + \text{contingency reserve}_t \]

(4) Nuclear unit ramping down constraints

\[ (U_{p_t} - U_{p_{t-1}}) \cdot (p_{\text{MinSt}} - 1) \leq \sum_{\tau = t-p_{\text{MinSt}}}^{t-1} (St_\tau + Up_\tau) \]

(5) Regular UC constraints for thermal plants that include minimum and maximum generation, block-wise heat rate curves, maximum ramp rates, and minimum up and down times
Flexible Operations of Nuclear Units in Power System/Market Operations

**Modeling Settings**

- Total System operations cost minimization
- Energy and ancillary service co-optimization and market clearing simultaneously.
- Generation mix including thermal plants with diverse fuels/capacity, renewable energy.
- Variable O&M cost is set to a low value ($0.5/MWh in current model)
- Ramp at most 20% of its capacity in one hour;
- Contribute at most 5% of its capacity to regulation service;
- Minimum output is 50% of its capacity;
- the minimum time on stable stage before ramping up is 3 hours.
Simulated Power Systems

- A vertical utility system in Southwest U.S. projections for 2027
- Generation Mix

**Table 6. Generator Capacity and Fuel Price by Technology (ST-steam, CC-Combined Cycle, CT-Combustion Turbine)**

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear (ST)</td>
<td>3</td>
<td>387</td>
<td>100 (50 if flex.)</td>
<td>1,162</td>
<td>0.50</td>
</tr>
<tr>
<td>Coal (ST)</td>
<td>8</td>
<td>103-468</td>
<td>45-55</td>
<td>1,952</td>
<td>1.96</td>
</tr>
<tr>
<td>Gas (ST)</td>
<td>4</td>
<td>70-100</td>
<td>25-48</td>
<td>361</td>
<td>5.85</td>
</tr>
<tr>
<td>Gas (CC)</td>
<td>9</td>
<td>85-672</td>
<td>25-30</td>
<td>3,206</td>
<td>5.85</td>
</tr>
<tr>
<td>Gas (CT)</td>
<td>41</td>
<td>15-103</td>
<td>25-50</td>
<td>2,945</td>
<td>5.85</td>
</tr>
<tr>
<td>Oil (CT)</td>
<td>2</td>
<td>16-54</td>
<td>50</td>
<td>70</td>
<td>27.40</td>
</tr>
</tbody>
</table>

* The three nuclear units and 5 of the coal units are partly owned and must-run.

**Table 14. Summary of HA Energy Scheduling Results for High-PV Scenarios (2027)**

<table>
<thead>
<tr>
<th>Category</th>
<th>Load Factor(^a) [% nameplate]</th>
<th>Capacity Factor(^b) [% nameplate]</th>
<th>Energy [% total]</th>
<th>Load Factor(^a) [% nameplate]</th>
<th>Capacity Factor(^b) [% nameplate]</th>
<th>Energy [% total]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear (ST)</td>
<td>100.0</td>
<td>100.0</td>
<td>25.2</td>
<td>95.9</td>
<td>95.9</td>
<td>24.2</td>
</tr>
<tr>
<td>Coal (ST)</td>
<td>86.6</td>
<td>86.3</td>
<td>37.1</td>
<td>86.3</td>
<td>84.0</td>
<td>36.1</td>
</tr>
<tr>
<td>Gas (ST)</td>
<td>34.7</td>
<td>0.0</td>
<td>0.0</td>
<td>35.6</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Gas (CC)</td>
<td>52.8</td>
<td>25.7</td>
<td>17.9</td>
<td>49.8</td>
<td>24.4</td>
<td>17.0</td>
</tr>
<tr>
<td>Gas (CT)</td>
<td>57.7</td>
<td>2.8</td>
<td>1.8</td>
<td>56.9</td>
<td>2.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Oil (CT)</td>
<td>50.0</td>
<td>0.0</td>
<td>0.0</td>
<td>N/A</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Solar</td>
<td>N/A</td>
<td>22.2</td>
<td>14.3</td>
<td>N/A</td>
<td>26.0</td>
<td>16.6</td>
</tr>
<tr>
<td>Wind</td>
<td>N/A</td>
<td>27.7</td>
<td>3.6</td>
<td>N/A</td>
<td>32.9</td>
<td>4.5</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
<td></td>
<td></td>
<td></td>
<td>100.0</td>
</tr>
</tbody>
</table>

\(^a\) Load factor is the ratio of the average energy from a unit when it is on to the unit nameplate capacity (average of individual unit load factors, not considering units that are never dispatched).

\(^b\) Capacity factor is the ratio of average energy to the total nameplate capacity for all units in a category.
## Nuclear Flexibility Study: Case Design

<table>
<thead>
<tr>
<th>Case Name</th>
<th>Flexible nuclear capabilities</th>
<th>Production tax credit for wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 NoFlex</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>2 Flex</td>
<td>Yes $p_{MinStable} = 3\text{ hrs}$ $p_{Min} = 50%$</td>
<td>No</td>
</tr>
<tr>
<td>3 FullFlex</td>
<td>Yes $p_{MinStable} = 1\text{ hr}$ $p_{Min} = 15%$</td>
<td>No</td>
</tr>
<tr>
<td>4 NoFlexPTC</td>
<td>No</td>
<td>Yes $23\text{/MWh}$</td>
</tr>
<tr>
<td>5 FlexPTC</td>
<td>Yes $p_{MinStable} = 3\text{ hrs}$ $p_{Min} = 50%$</td>
<td>Yes $23\text{/MWh}$</td>
</tr>
<tr>
<td>6 FullFlexPTC</td>
<td>Yes $p_{MinStable} = 1\text{ hr}$ $p_{Min} = 15%$</td>
<td>Yes $23\text{/MWh}$</td>
</tr>
</tbody>
</table>
Flexible reactors contribute to frequency regulation and spinning reserves.
**Nuclear Flexibility Study: Selected Results (II)**

- Flexible reactors moderate output to integrate renewables, save variable costs when prices fall to zero, and avoid negative prices.

### Annual Capacity Factor

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Capacity Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoFlex / NoFlexPTC</td>
<td>100.00%</td>
</tr>
<tr>
<td>Flex</td>
<td>95.44%</td>
</tr>
<tr>
<td>FullFlex</td>
<td>94.37%</td>
</tr>
<tr>
<td>FlexPTC</td>
<td>95.41%</td>
</tr>
<tr>
<td>FullFlexPTC</td>
<td>94.42%</td>
</tr>
</tbody>
</table>
Nuclear Flexibility Study: Selected Results (III)

- Flexibility increases nuclear operating margins (profit) by roughly 2-5 percent.

- [Bar chart showing change in annual operating margin relative to NoFlex/NoFlexPTC cases (million $/year)]
  - Flex: +1.9%
  - FullFlex: +4.7%
  - FlexPTC: +2.3%
  - FullFlexPTC: +3.1%
Nuclear Flexibility Study: Selected Results (IV)

- Flexible nuclear operation cuts renewable energy curtailment by half

![Bar chart showing annual renewable energy curtailment (GWh) for different scenarios: NoFlex, Flex, FullFlex, NoFlexPTC, FlexPTC, FullFlexPTC.

- Wind curtailment decreased by 43% for Flex and 58% for FullFlex.

- Solar curtailment decreased by 43% for Flex and 58% for FullFlex.

Annual renewable energy curtailment (GWh)

- NoFlex: 1500 GWh
- Flex: 840 GWh (-43%)
- FullFlex: 500 GWh (-58%)
- NoFlexPTC: 1500 GWh
- FlexPTC: 840 GWh (-43%)
- FullFlexPTC: 500 GWh (-58%)
Flexible nuclear operation reduces system operating costs by 1.3-1.7%
Conclusion and Future Directions

Conclusions

- Nuclear power plant flexibility is modeled and the constraints is integrated in a traditional unit commitment and economic dispatch framework
- Nuclear power plants flexible operations can
  - increase the revenue/profit
  - Increase renewable utilization
  - Decrease system operational cost

Direction

- Dynamic stable time constraints;
**Representing Operating Limits**

- **Fact:** After a Power Drop, Nuclear Units must remain at Stable Output for a certain Time Lag ($pMinSt_t$) before Ramping-Up again. A dedicated Constraint representing this Operating Limit is introduced.

\[
(Up_t - Up_{t-1}) \cdot (pMinSt_t - 1) \leq \sum_{\tau=t-pMinSt_t}^{t-1} (St_\tau + Up_\tau)
\]

- **Time at Stable Power after Ramp-Down** is the Approach currently used in literature.

- But this approach is a Simplification and an Idealization that does not accurately represent the Xenon Poisoning effect (function of Power history, Time Scale of Hours, Non-Linear Dynamics)