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-economical);
  - 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

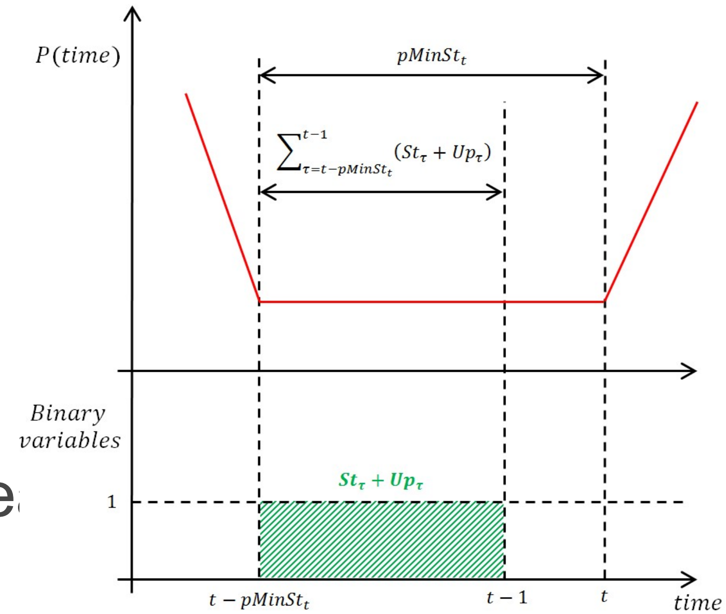
- **Main reasons cited for economic problems**
  1. Low natural gas prices, coupled with high efficiency combined cycle power units;
  2. Increased penetration of renewables, with zero marginal cost of production;
  3. Wind and solar, added to an already adapted system, are displacing conventional units;
  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



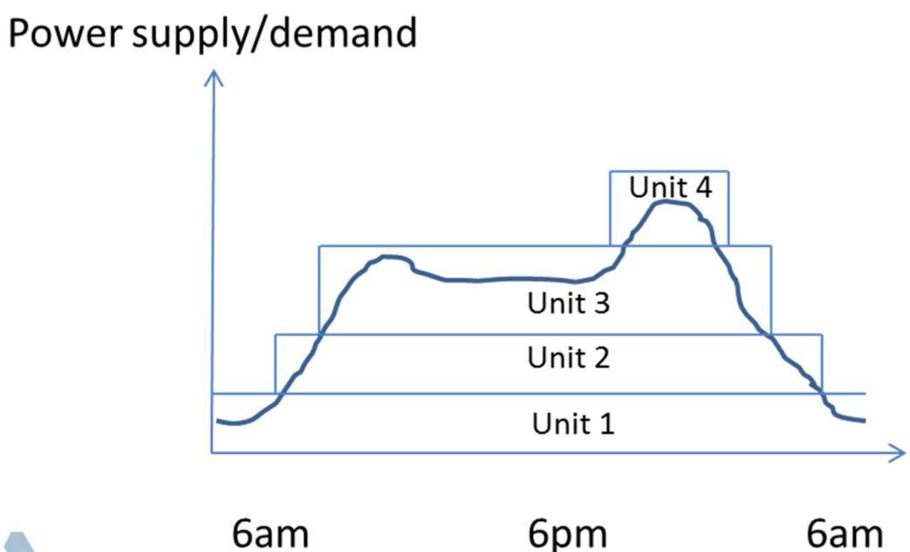
- **Technical constraints** (Light Water Re
  - ***Control rod movement***
    - Insertion into the core to reduce power output,
    - Withdraw to increase power output
  - ***Thermal and mechanical stresses*** -> fuel cladding cracking failure
  - ***Coolant temperature and pressure*** -> stress on 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

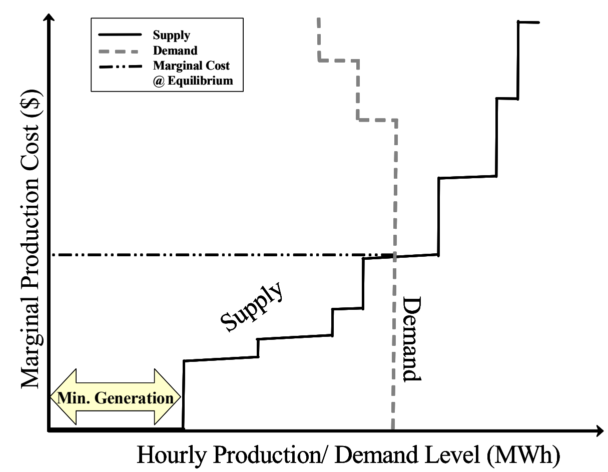
Power System/Market Operations

- 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?





Formulation

- ***Objective Function***

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

- ***Constraints***

(1) Load-generation balance for all hours.

$$\sum_{i} thermal\ power_{it} + wind\ power_t + PV\ power_t + unserved\ load_t = load_t$$

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

$$dist\ PV_t \leq PV\ power_t \leq\ dist + utility\ PV_t$$
$$0 \leq wind\ power_t \leq\ available\ wind\ power_t$$

Formulation

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

$$\sum_{i} reserve\ thermal\ unit_{it}\ + unserved\ reserve_t$$
$$\geq balancing\ reserve_t + contingency\ reserve_t$$

(4) Nuclear unit ramping down constraints

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

(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)

Technology	No. of Units	Maximum Capacity [MW]	Minimum Capacity [% of max]	Total Capacity [MW]	Fuel Price [$/MMBtu]
Nuclear* (ST)	3	387	100 (50 if flex.)	1,162	0.50
Coal* (ST)	8	108–488	45–55	1,982	1.96
Gas (ST)	4	70–100	25–48	361	5.85
Gas (CC)	9	88–672	25–30	3,206	5.85
Gas (CT)	41	19–103	25–50	2,945	5.85
Oil (CT)	2	16–54	50	70	27.40

* 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)

	Constant Nuclear			Flexible Nuclear		
Category	Load Factor[a] [% nameplate]	Capacity Factor[b] [% nameplate]	Energy [% total]	Load Factor[a] [% nameplate]	Capacity Factor[b] [% nameplate]	Energy [% total]
Nuclear (ST)	100.0	100.0	25.2	95.9	95.9	24.2
Coal (ST)	86.6	86.3	37.1	86.3	84.0	36.1
Gas (ST)	34.7	0.0	0.0	35.6	0.0	0.0
Gas (CC)	52.8	25.7	17.9	49.6	24.4	17.0
Gas (CT)	57.7	2.8	1.8	56.9	2.3	1.5
Oil (CT)	50.0	0.0	0.0	N/A	0.0	0.0
Solar	N/A	22.2	14.3	N/A	26.0	16.8
Wind	N/A	27.7	3.8	N/A	32.9	4.5
Total			100.0			100.0

[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).

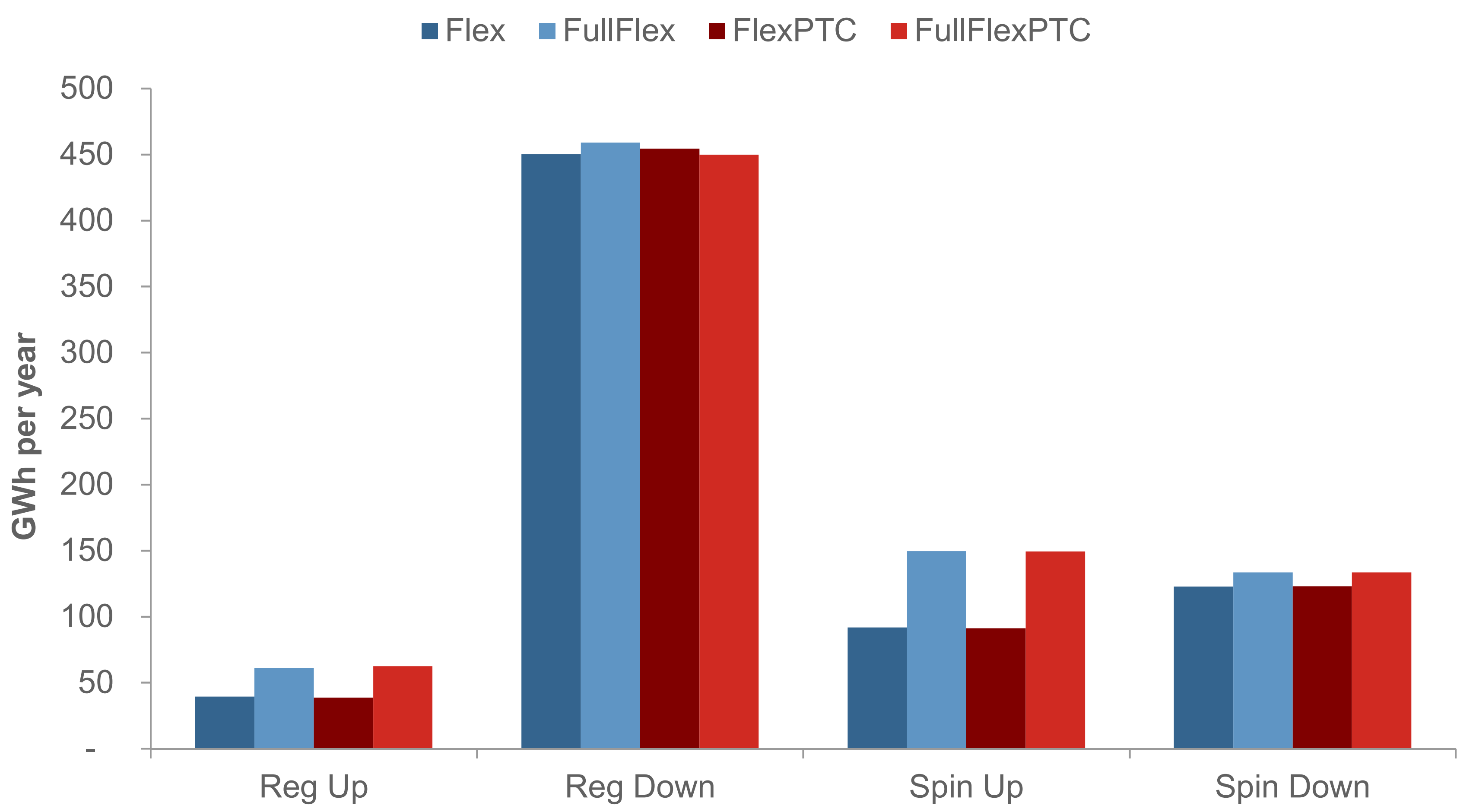
[b] Capacity factor is the ratio of average energy to the total nameplate capacity for all units in a category.

Nuclear Flexibility Study: Case Design

	Case Name	Flexible nuclear capabilities	Production tax credit for wind
1	NoFlex	No	No
2	Flex	Yes *pMinStable = 3 hrs* *pMin = 50%*	No
3	FullFlex	Yes *pMinStable = 1 hr* *pMin = 15%*	No
4	NoFlexPTC	No	Yes *$23/MWh*
5	FlexPTC	Yes *pMinStable = 3 hrs* *pMin = 50%*	Yes *$23/MWh*
6	FullFlexPTC	Yes *pMinStable = 1 hr* *pMin = 15%*	Yes *$23/MWh*

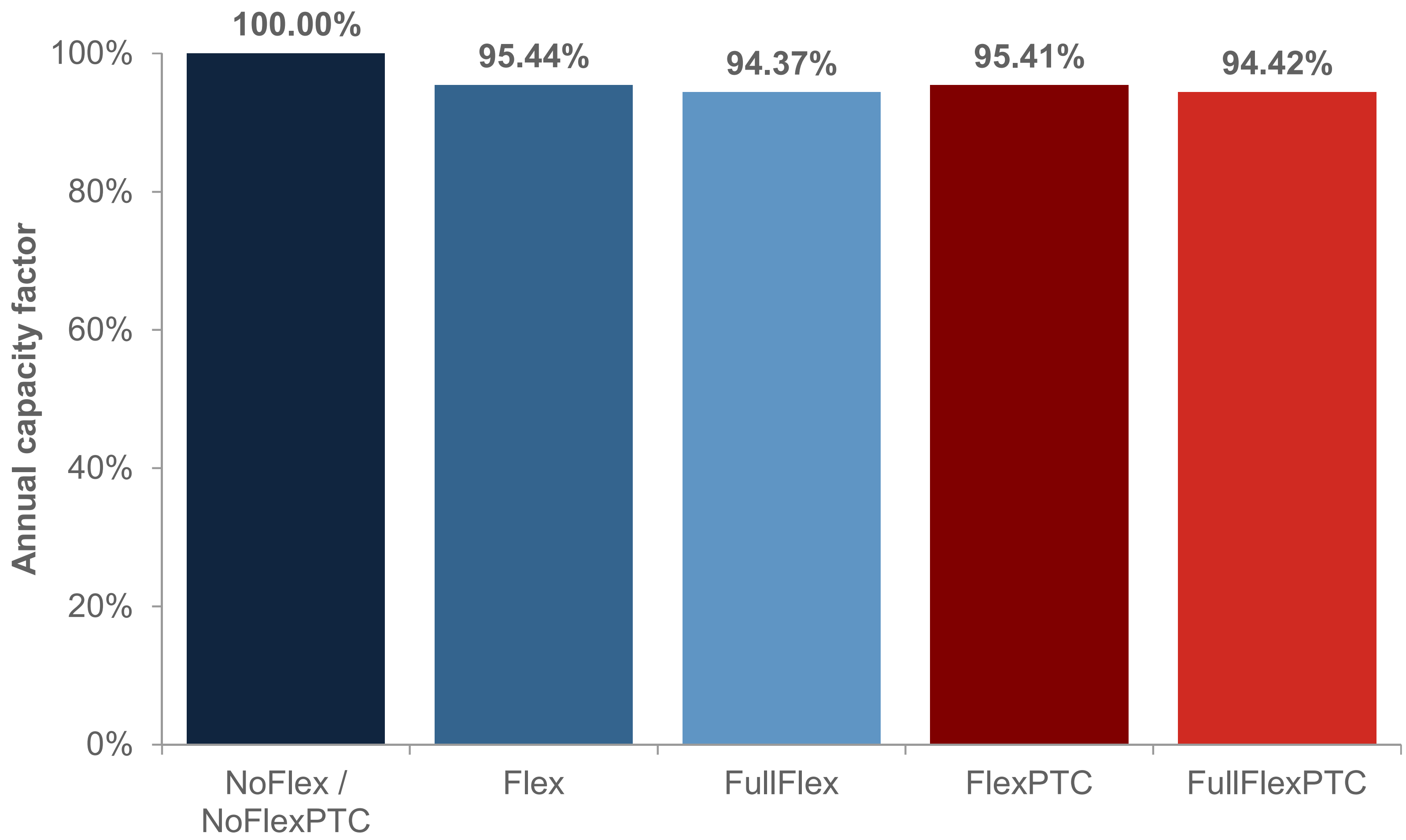
Nuclear Flexibility Study: Selected Results (I)

- Flexible reactors contribute to frequency regulation and spinning reserves



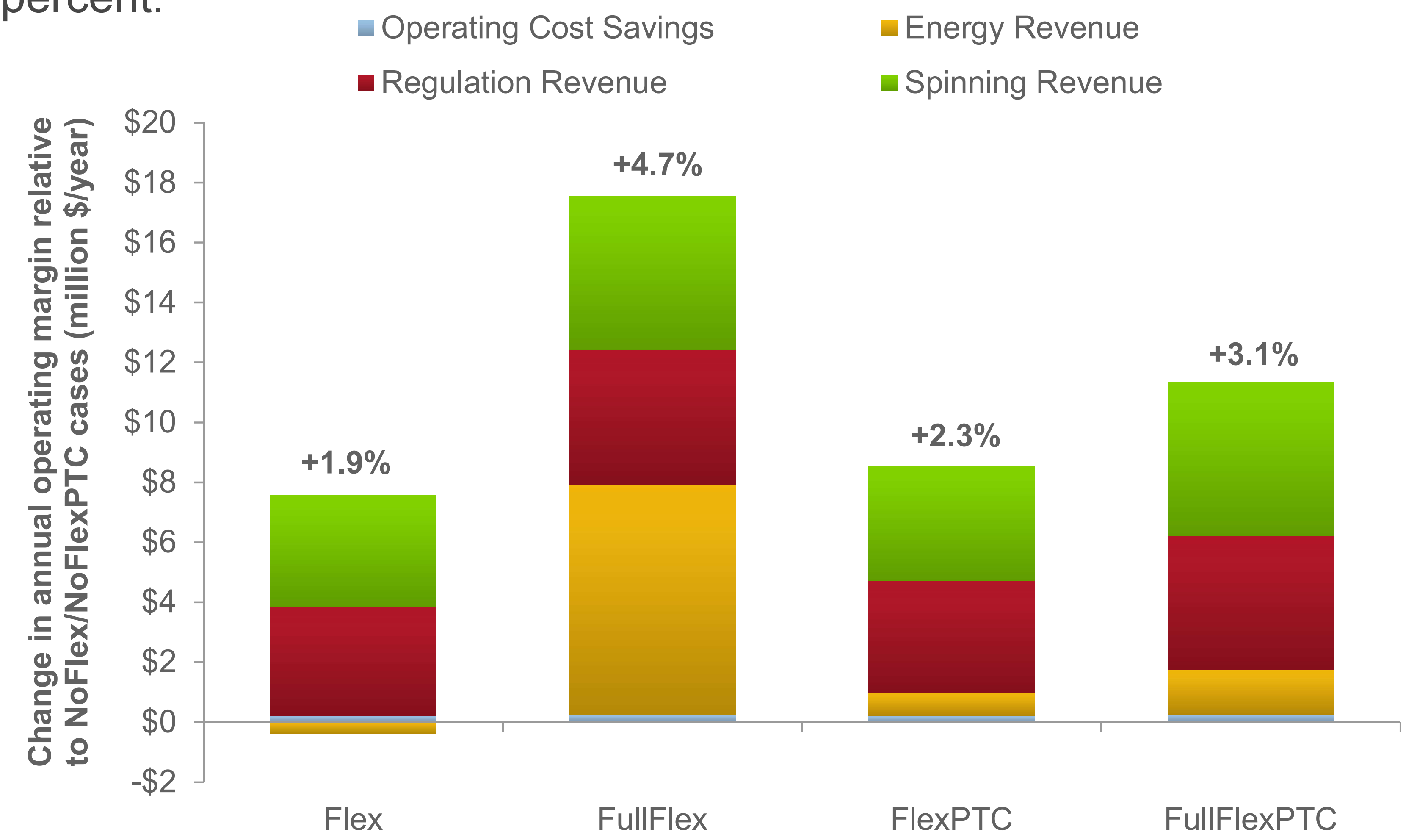
Nuclear Flexibility Study: Selected Results (II)

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



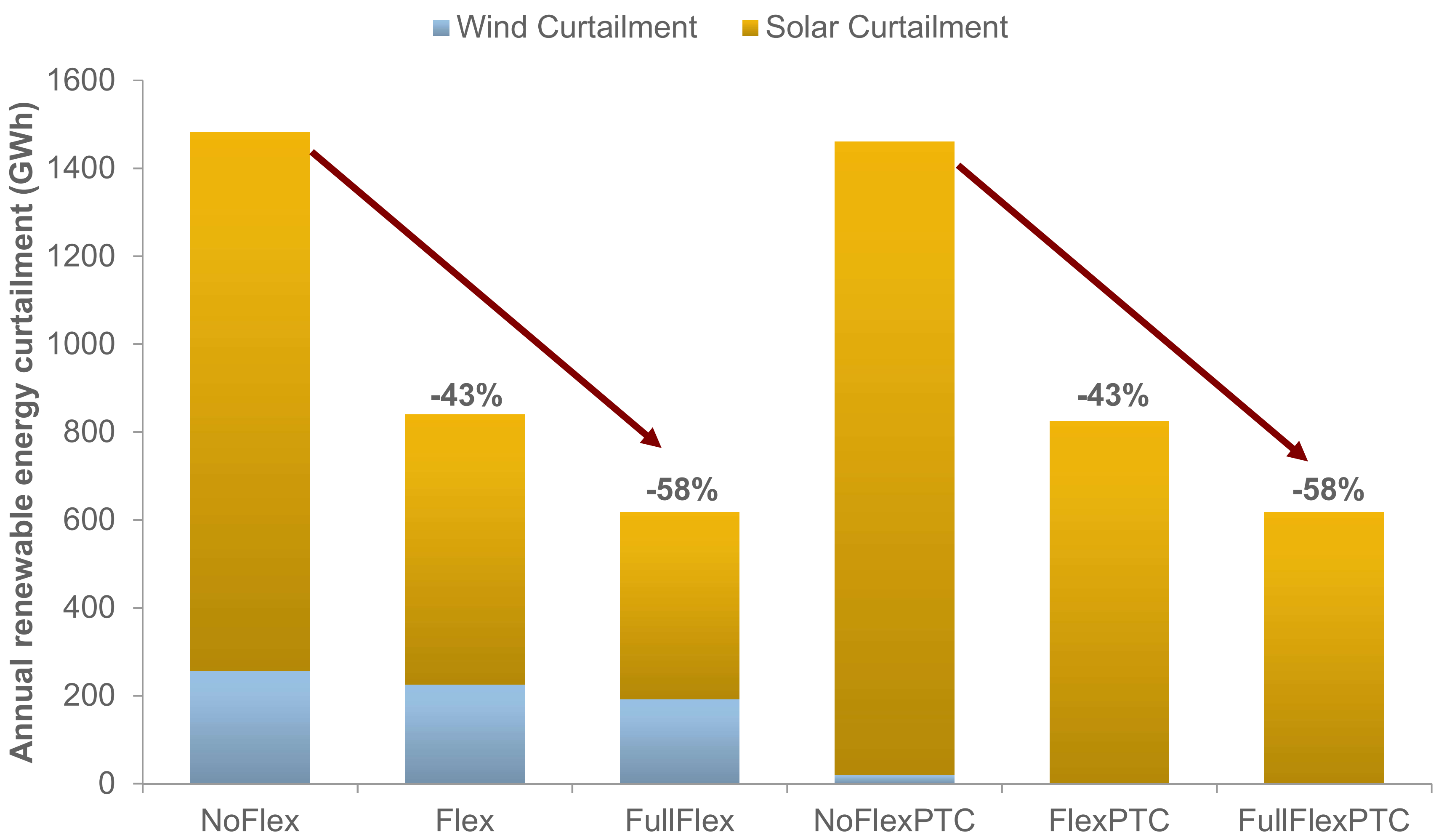
Nuclear Flexibility Study: Selected Results (III)

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



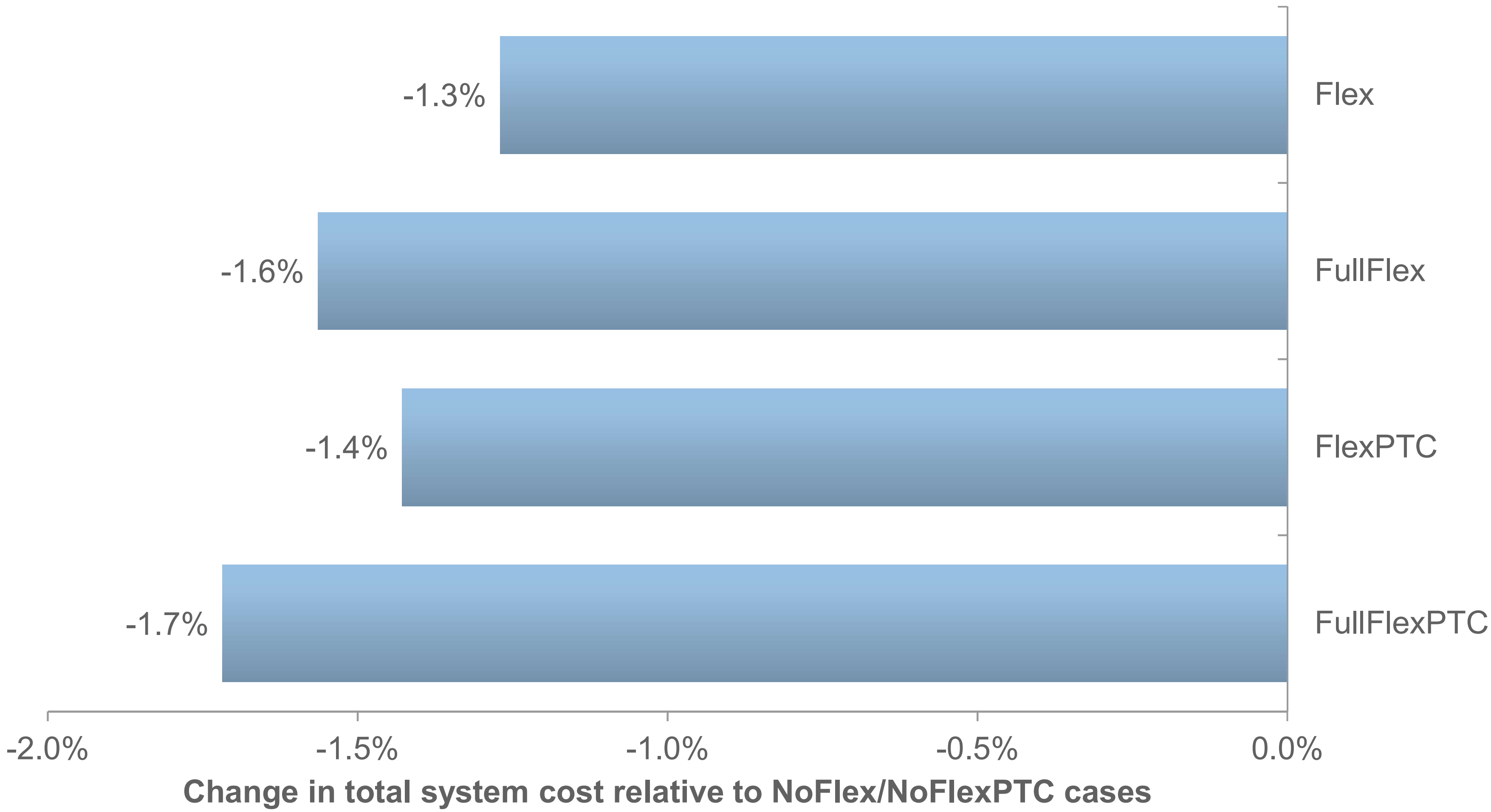
Nuclear Flexibility Study: Selected Results (IV)

- Flexible nuclear operation cuts renewable energy curtailment by half



Nuclear Flexibility Study: Selected Results (V)

- 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.

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

- *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)