Flexibility limits in Small Modular Reactors (SMRs) for enhanced load-following

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International Conference on small modular reactors and their applications

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Nuclear is traditionally a baseload generator:

Main Reasons:

- **(technical)** Complex technology and designed primarily for baseload operation
- **(economic)** High CapEx, low OpEx
- **(regulatory)** Nuclear industry is heavily regulated and are required to stick to predefined operations modes

VRE penetration increases the demand for flexible generation:

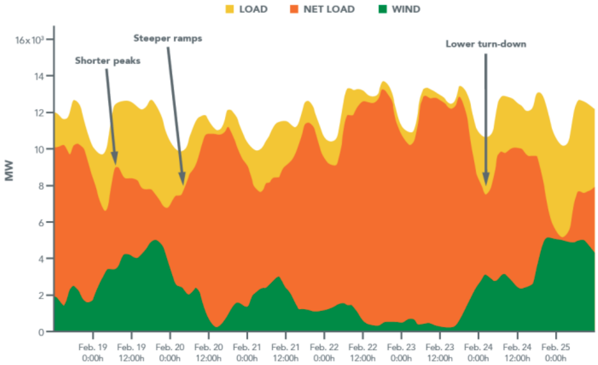


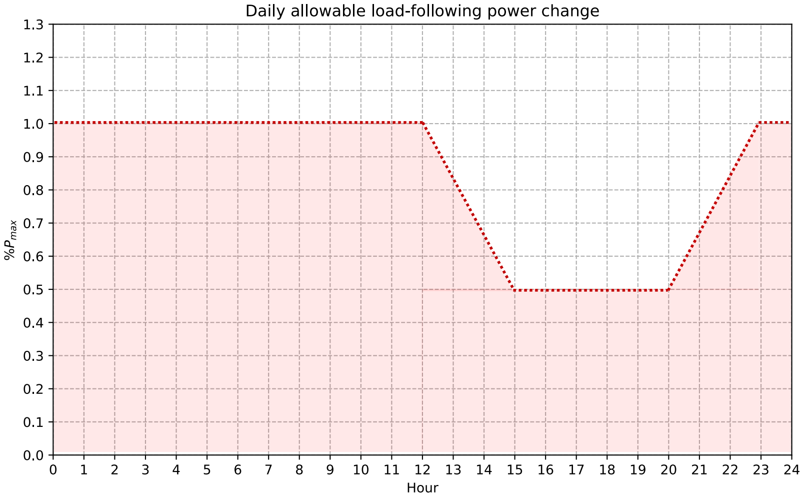
Figure 3. Wind (and solar) generation can lead to greater need for flexibility

Source: Cochran et al. 2014

More VRE → high variability *net-load* curve → thermal fleet needs to operate more flexibly. **This applies to nuclear too.**

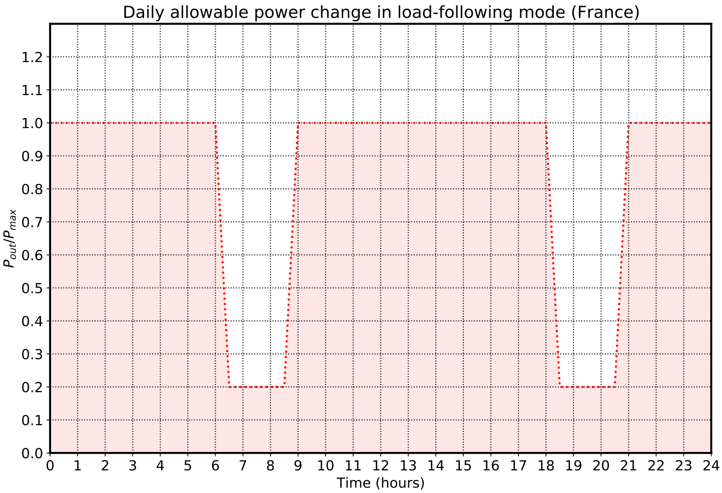
Current Nuclear flexibility (US):

Currently due to regulations [1], nuclear reactors are allowed a *once-daily* 100%-50%-100% rated power change in a sequence of 12-3-6-3 hr transitions while in *load-following* mode.

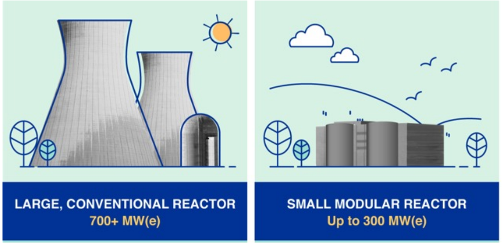


Current Nuclear flexibility (France):

France allows a 100%-20% in 30 mins and again after 2 hours, or twice in 24 hours [2].



Small Modular Reactors (SMRs)–a solution for better nuclear flexibility?



Small Modular Reactors (SMRs) are a new class of advanced nuclear reactors with three key features:

- **Small:** Less than 300 MWe in size.
- **Modular:** Factory-built with standardized designs for cost-efficiency and faster construction.
- **Advanced:** Higher enrichment, equipped with inherent safety features, and greater operational flexibility.

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Central idea of this study:

Comparison of GW reactor fleet vs SMR fleet

More specifically:

- Build a physics informed stylized LWR representation of nuclear reactor
- A modified energy system model (Unit Commitment Framework) for nuclear dispatch in various VRE mixes
- **Case study:** GW-class reactors (Westinghouse AP1000) vs SMRs (Westinghouse AP300)
  - Flexibility analysis in high VRE scenarios—Production cost, VRE penetration, VRE curtailment
  - Sensitivity analysis

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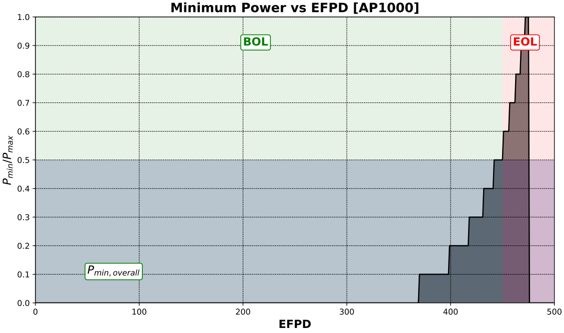
New Nuclear Constraint: 1) Minimum Power levels for load-following

Based on exhaustive reactor physics computation we come up with *minimum allowable power levels* based on the state of fuel degradation.



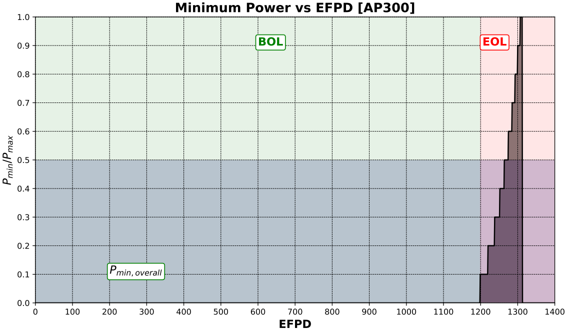


Figure: Evolving P_{min} for AP1000 and AP300 to remain in *load-following* mode

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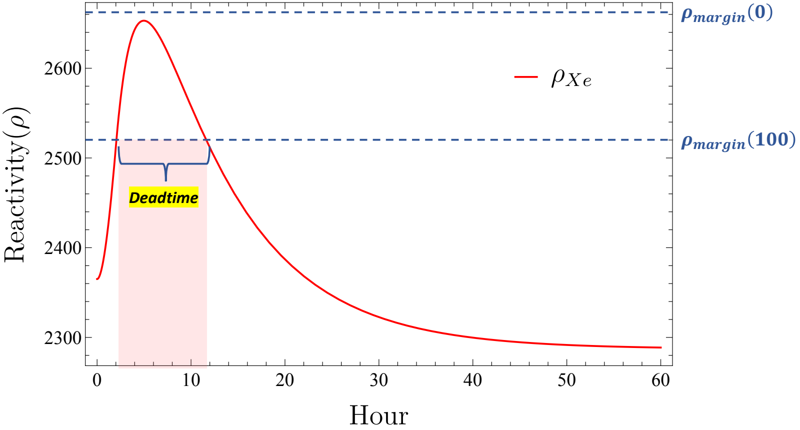
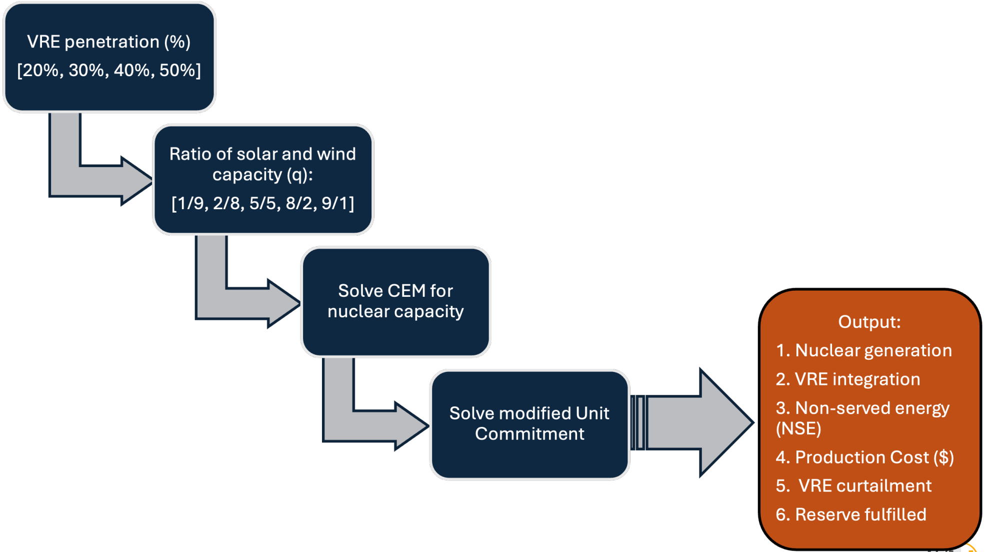
New Nuclear Constraint: 2) Downtime/Deadtime based on fuel degradation state

If we shutdown a reactor, the downtime (also called Deadtime) will depend on fuel degradation state. Higher degradation translates to longer deadtimes.



Scenario Design and Model Framework:



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Scenario Design and Model Framework:

Individual reactors in each fleet are operated in two modes—inflexible and flexible.

INFLEXIBLE:

The reactor can generate power between [P_{max} , 0] or only as ON/OFF

FLEXIBLE:

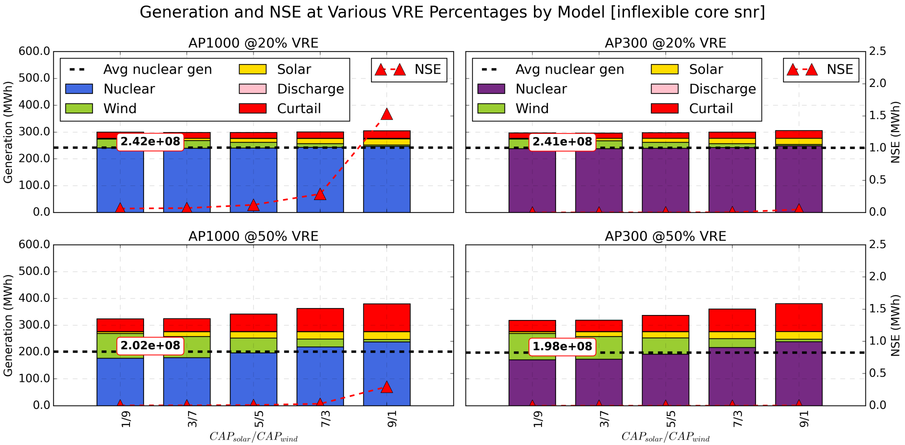
The reactor can generate power between [P_{max} , P_{min}] in addition to operating ON/OFF

Results: Broad highlight

SMRs perform better in most metrics—on some of them marginally on others significantly

Results: Generation and Non-served energy (NSE)

- Both flexible and inflexible generator less energy compared to GW fleet
- Inflexible GW reactors accumulate significant NSE in high-solar mixes, inflexible SMRs can avoid most of it. No NSE in flexible operation.



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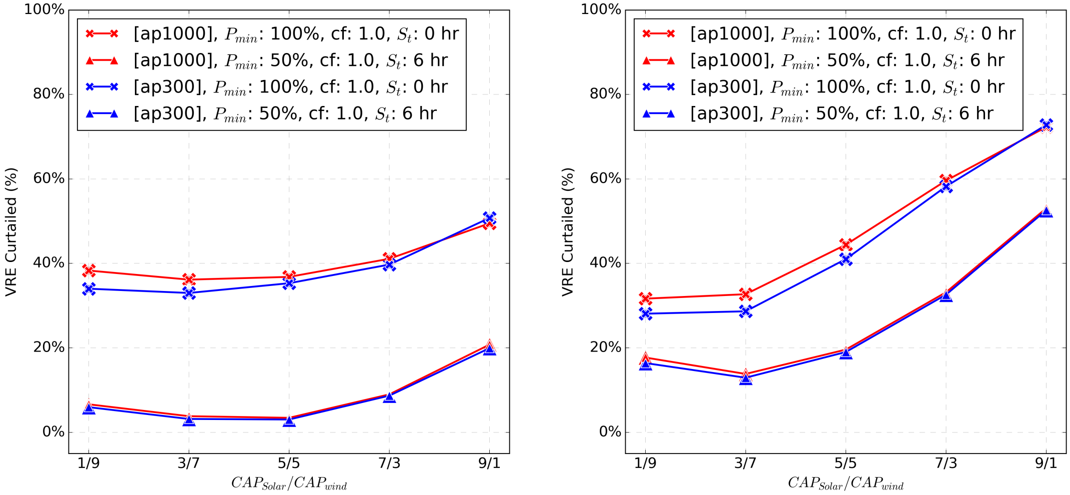
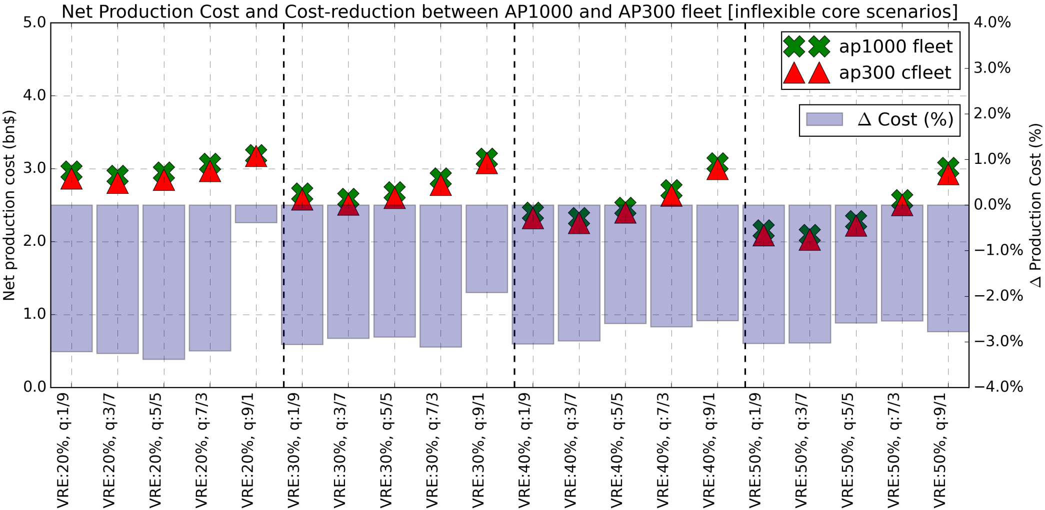
Results: VRE Curtailment

- Inflexible SMRs reduce curtailment in high-wind mixes at all levels of VRE penetration
- No significant difference in curtailment between flexible SMRs and GW reactors



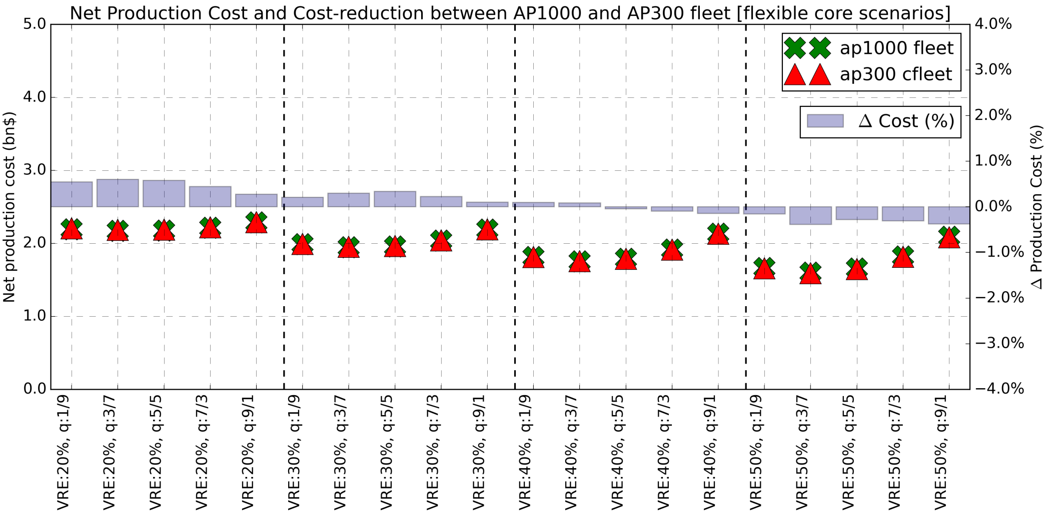
Results: Production Cost [inflexible]

- Inflexible SMR fleet consistently lowers production cost at all levels of VRE compared to inflexible GW fleet



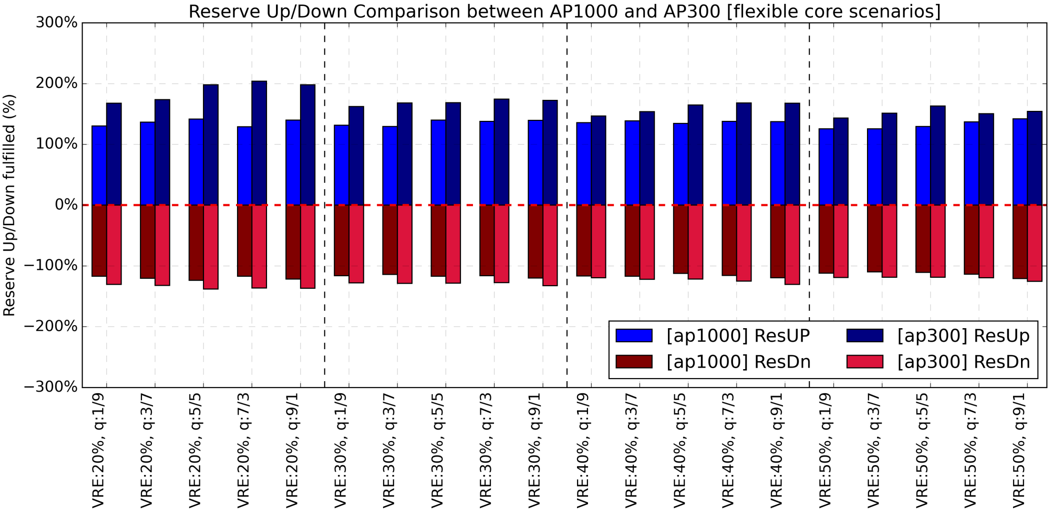
Results: Production Cost [flexible]

- Flexible SMRs increase production costs marginally at low VRE and then reduce it at higher VRE when startup/shutdown costs are lower than savings from VRE.



Results: Spinning upwards/downwards reserve

- Flexible SMRs fulfill more spinning upward and downward reserve across all scenarios



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Results: Summary for core scenarios

- Across similar operational parameters SMR fleet benefits depends on VRE context. SMR is well suited for high-wind scenarios. In high-solar scenarios, SMRs substantially reduce NSE.
- SMR results are more profound when the longer refueling is considered.

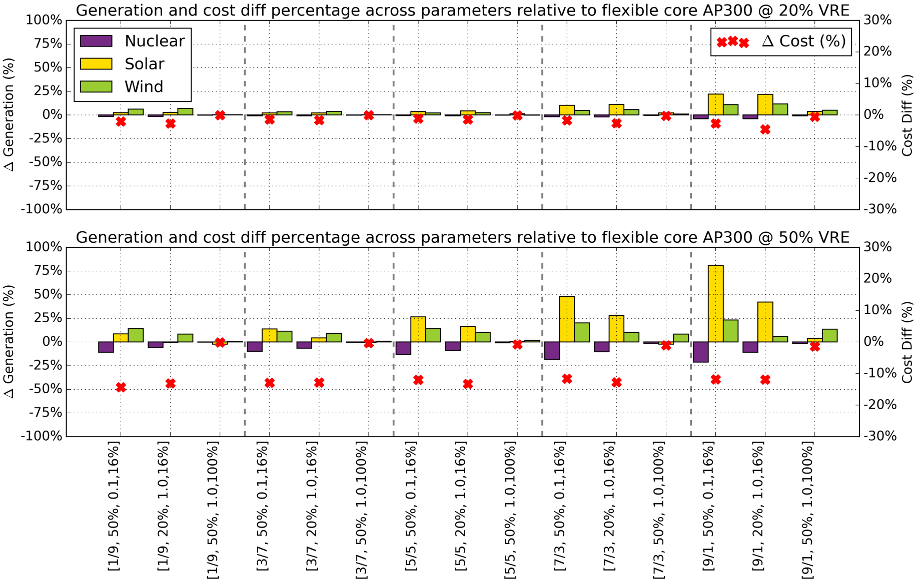
Sensitivity analysis:

What parameters affect flexible dispatch and what kind of policy support can we enforce for greater SMR flexibility?

Parameters highlighted:

- Minimum power levels
- Ramp rates
- Startup/Shutdown costs

Results: Generation and Cost change from base



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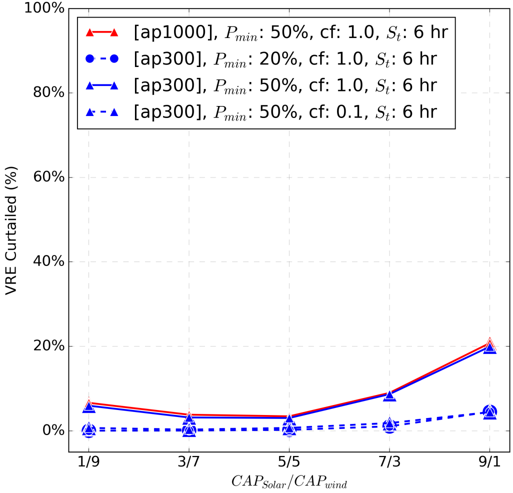
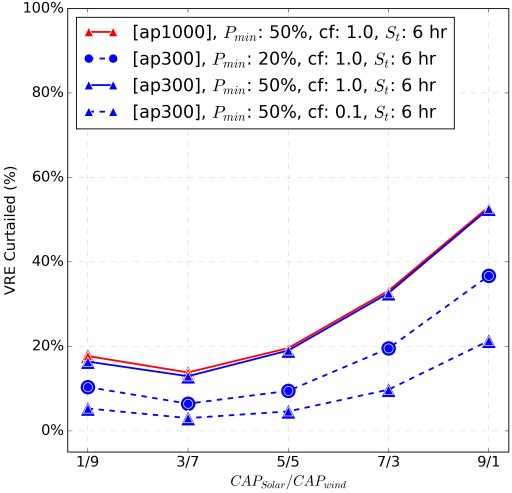
Results: VRE curtailment

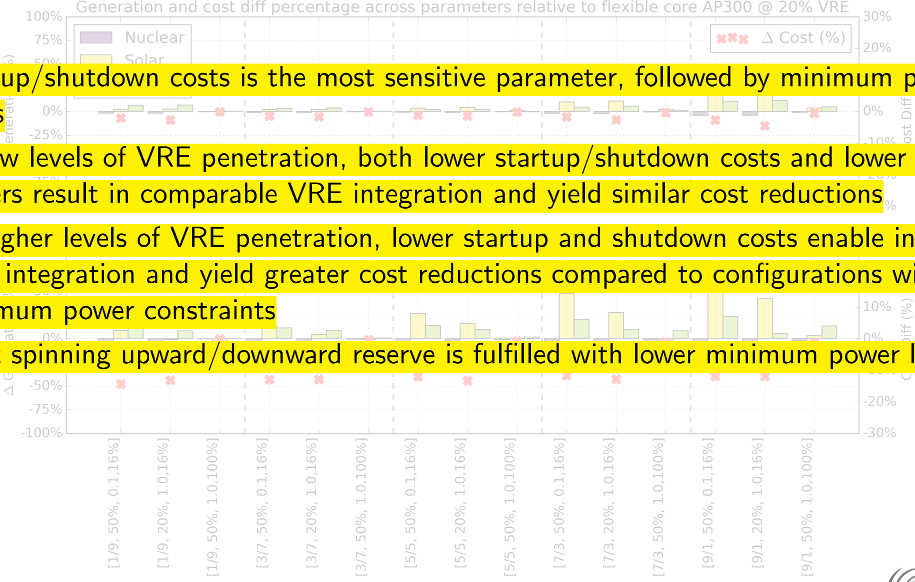
- Lower startup/shutdown cost impacts VRE curtailment the most





Results: Findings

- Startup/shutdown costs is the most sensitive parameter, followed by minimum power levels
- At low levels of VRE penetration, both lower startup/shutdown costs and lower minimum powers result in comparable VRE integration and yield similar cost reductions
- At higher levels of VRE penetration, lower startup and shutdown costs enable increased VRE integration and yield greater cost reductions compared to configurations with higher minimum power constraints
- Most spinning upward/downward reserve is fulfilled with lower minimum power levels



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Recommendations:

- Smaller reactors reduce VRE curtailment, NSE, and net production costs more effectively than larger ones, especially at higher VRE penetration.
- For enhanced flexibility and VRE integration, lowering startup/shutdown costs and minimum power levels are more effective than faster ramping SMR reactors.
- SMRs are compatible with various VRE mixes, can be collocated with VRE to minimize overbuild, curtailment, and nuclear waste.
- Current nuclear reactors have the capability to operate more flexibly, though flexible operation is not economically lucrative. Define an out-of-market payment to value nuclear flexibility and incentivize flexible operation.

Thank you for listening!

[1] *Advanced Nuclear Technology: Advanced Light Water Reactor Utility Requirements Document, Revision 13*. URL: https://www.epri.com/research/products/000000003002003129 (visited on 10/11/2024).

[2] Patrick Morilhat et al. *Nuclear Power Plant flexibility at EDF*. en. Jan. 2019. URL: https://edf.hal.science/hal-01977209 (visited on 09/06/2024).

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