# Flexibility limits in Small modular reactors for enhanced load following

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**Abstract**

Variable Renewable Energy (VRE) sources like solar and wind have high intermittency, and as their share in the energy mix increases, dispatchable thermal generators in the same service area, including nuclear, must adapt and perform enhanced load following. The French experience and existing literature focus on load-following with nuclear in low VRE portfolios, revealing a gap in the context of high shares of VRE. Further, regulatory operational constraints limit nuclear flexibility by permitting a shift from 100% to 50% and back to 100% of rated power only once in 24 hours, and for a limited number of cycles. However, nuclear reactors inherently possess a substantial reactivity reserve, enabling them for enhanced load-following for a significant portion of their fuel cycles. In that regard, Small Modular Reactors (SMRs) present an opportunity for enhanced load-following owing to their flexibility by design and the multi-module operation or *fleet effect*. To systematically investigate nuclear flexibility, this study presents exhaustive fuel cycle numerics for enhanced load-following from beginning-of-life (BOL) to end-of-life (EOL) of the fuel load for PWR-gigawatt-reactors and PWR-SMRs, considering burnup, enrichment, ramp limits, declining reactivity, Xenon poisoning-induced deadtimes, and minimum power levels. Insights derived are used as inputs in a modified Unit Commitment model for accurate nuclear representation. The objective is to establish a constrained operational space within which a nuclear reactor, specifically a GW-class AP1000, or a fleet of the newly unveiled AP300 SMRs, can perform enhanced load-following. Our results show that SMRs lead to higher VRE penetration, lesser VRE curtailment, and lower dispatch costs. SMRs also dispatch reactors in their fleet efficiently, operating some reactors as *must-run* and others more flexibly to cumulatively result in higher fleet flexibility compared to GW-class reactors. These results highlight SMRs ability to integrate more flexibly in high renewable future grids.

## INTRODUCTION

As we add high amounts of variable renewable energy (VRE) into our grids, dispatchable thermal generators, including nuclear, are required to operate more flexibly [1] [2]. Traditionally, nuclear power plants (NPPs) are predominantly operated as a baseload generator, but the French routinely operate their fleet with significant flexibility [3]. And an increasing number of studies show how NPPs can participate in providing flexibility services while remaining economically viable and avoid early retirement [2][4][5][6].

The nuclear industry is heavily regulated, with oversight throughout the lifecycle of a plant, from design and construction to operation and decommissioning [7]. For example, a Westinghouse AP1000 reactor is allowed to load-follow in a predefined mode, reducing power from 100% to 50% and then back to 100% only once a day, for a limited number of cycles in a year [8]. In contrast, French reactors are allowed to reduce power from 100% to 20% within 30 minutes, twice a day [9]. These predefined operational modes influence the design of reactors and restrict operators from fully leveraging the flexibility of nuclear power plants (NPPs). Inevitably, this hinders from maximizing fleet profitability, a growing concern for nuclear in deregulated markets [4].

High shares of VREs in the energy mix make the net load curve increasingly variable, forcing NPPs to provide enhanced load following. Small Modular Reactors (SMRs), a new class of nuclear reactors, present an opportunity in that regard. They typically have electrical power output below 300MW, come arranged in pack of modules, and have a standard design that can be factory assembled [10][11][12] which are argued to reduce their cost. SMRs also project longer refuelling cycles and better reactor and fleet flexibility [13].

Unlike gas turbines or combined cycle power plants, NPPs have unique physical constraints that must be considered when studied against other dispatchable thermal generators in large-scale energy system models. Ponciroli et al. and Jenkins et al. made a case for NPP flexibility with Xenon poisoning constraints in a parametric fashion [4][2]. However, both these studies intrinsically assume that fuel degradation for flexible NPP operation is similar to full power operation. Alhadhrami et al. show that the refuelling time is extended and staggered with flexible operation which makes variations to fuel degradation an important consideration [14].

In that context, the scope of this work is twofold: 1) Develop a comprehensive techno-economic framework for the flexible operation of light water reactors (LWRs) by creating novel physics-informed constraints to ensure accurate representation of NPPs in a traditional Unit Commitment model and 2) Apply the modified UC to study GW-class reactors (Westinghouse AP1000) against SMRs (Westinghouse AP300) and perform flexibility analysis at the reactor and fleet level (i.e. multi-unit) in terms of production cost, VRE penetration and VRE curtailment.

## Nuclear flexibility

For LWRs, flexibility can be achieved by ramping the core power or by venting the steam before it reaches the turbine [15]. Core ramping is typically performed using control rods or by varying boron concentration. A limitation to core ramping comes from the generation of powerful neutron-absorbing poisons such as Xenon-135 or Xe-135, among others, primarily during ramp-down events [16]. Typically, the effect of Xe-135 is overridden with control rod movement without changing boron concentration [17]. The control rods consist of a mix of highly absorbing ‘black rods’ and partially absorbing ‘grey rods’, each with different neutron absorption cross-sections. By carefully inserting or removing these rods, operators can adjust the population of fissile neutrons and achieve the desired power changes. However, fission products are trapped within the fuel rods through the life of the fuel assembly which leads to a reduced range of power manoeuvres as the reactor core ages.

In this study, we aim to focus on the core ramping ability of LWR reactors by developing a stylized one-point reactor model to emulate the decreasing flexibility through a reactor’s life. Using this model, exhaustive computations of different power ramping scenarios were performed. Further, we explore the fleet effect, where reactors arranged in packs demonstrate revolving dispatch. Some units operate as baseload and have higher burnups, while others operate more flexibly, see lower burnups, and result in longer refuelling cycles.

### Xenon-Poisoning

During power ramp-down, the concentration of Xe-135 goes up due to radioactive decay of the fission product, I-135. Xe-135 is a powerful neutron absorber or a *poison*, and its concentration keeps increasing for many hours after the ramp-down has ended [16]. This so-called *Xenon poisoning* arises from the absorption of fission neutrons by Xe-135 which, and if it becomes large enough, makes it difficult to sustain a positive reactivity within the reactor core. The peak Xe-135 concentration depends on 1) the power level from which the ramp-down event begins and 2) the depth of the ramp-down. This phenomenon is governed by Equation. (1) and (2), which determine the one-point Xe-135 and I-135 concentration evolution in response to a change in operating power. Equation (3) then describes the time-varying neutron flux within reactor.

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| $$\frac{dI}{dt}=-λ\_{I}⋅I(t)+γ\_{I}⋅ϕ(t)⋅\overbar{Σ}\_{f} $$ | (1) |

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| --- | --- |
| $$ \frac{dXe}{dt}=+λ\_{I}⋅I(t)-λ\_{Xe}⋅Xe(t)+γ\_{Xe}⋅ϕ(t)⋅\overbar{Σ}\_{f}-σ\_{abs}^{Xe}⋅ϕ(t)⋅Xe(t)$$ | (2) |

|  |  |
| --- | --- |
| $$ ϕ\left(t\right)=ϕ\_{0}⋅\left(\frac{P\left(t\right)}{P\_{max}}\right)$$ | (3) |

The equilibrium concentration of Xe-135 and I-135 is computed from the steady-state solution to Equations. (1) and (2) and are given by Equation. (4) and (5). Xe-135 introduces a negative reactivity in the core, also called *Xenon Defect*. It is calculated using from Equation.(6) in *per cent mille* or pcm.

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| $$ I\_{eq}=\frac{γ\_{I}⋅ϕ\_{0}⋅\overbar{Σ}\_{f}}{λ\_{I}}$$ | (4) |
| $$ Xe\_{eq}=\frac{ϕ\_{0}⋅\overbar{Σ}\_{f}⋅\left(γ\_{I}+γ\_{Xe}\right)}{λ\_{Xe}+σ\_{abs}^{Xe}⋅ϕ\_{0}}$$ | (5) |
| $$ ρ\_{Xe}(t)≅\frac{σ\_{abs}^{Xe}⋅Xe(t)}{v\overbar{Σ}\_{f}}×10^{5}$$ | (6) |

To derive an operational space within which the reactors can operate flexibly, a careful accounting of the *Xenon defect* (due to Xenon poisoning) alongside the available reactivity margin (explained in Section. 2.2) is necessary. To that end, starting from these equilibrium values, several ramping scenarios were simulated for different P(t) trajectories, to observe the *Xenon defect* evolution. A few representative scenarios shown in Figure 2). The primary conclusions drawn from these solutions are:

1. Xe-135 concentration decreases initially during ramp-up and then increases to equilibrium concentration at that flux level computed using Equation. (5).
2. Xe-135 concentration increases during ramp-down and then decreases to equilibrium concentration at that flux level computed using Equation. (5).
3. The peak Xe-135 concentration depends on the power level from which the ramp-down starts, the higher the power level, the higher the Xe-135 peak concentration.
4. Peak Xe-135 concentration depends on the depth of the ramp-down scenario.
5. Peak Xe-135 concentration and subsequent *Xenon defect* are higher for higher ramp rates.

### $k\_{eff}$ degradation

The extent of operational flexibility achievable within the reactor is determined by the reactivity margin available to ensure that the time-varying ramping-induced *Xenon defect* can be overridden by the positive reactivity provided by the remaining fissile concentration in the fuel rods. The reactivity margin is computed with the effective multiplication factor ( $k\_{eff }$) at different stages of the fuel cycle defined by Equation. (7) [4]. At full power operation, the fuel rods experience a higher rate of burnup, while with flexible operation, depending on how flexibly or inflexibly the reactor operates, the burnup rate will vary, and experience a degradation of the reactivity margin that is proportional to the keff history of the fuel assembly. The parameter keff therefore begins at a specified initial value at the Beginning-of-Life (BOL) of the fuel assembly (which is proportional to the fuel enrichment). It then gradually decreases as fissile nuclei are consumed, ultimately reaching its minimum value at the End-of-Life (EOL) of the fuel.

This degradation in this study is modelled with a simple recursive relation, as shown in Equation. (8), where $k\_{eff,n}$ is the multiplication factor for day n, and $k\_{eff,n+1}$ is the multiplication factor on day n+1. $α\_{n}$ can be interpreted as the capacity factor for the reactor on day n and indicates how flexibly (<1) or inflexibly (~1) the reactor operated. $α\_{n}$ is used to scale the full power degradation rate *m* and update the $k\_{eff,n+1}$. This way, we can approximate the available reactivity margin based on how the reactor participates in the dispatch.

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| $$Δρ\_{marg,n }=\frac{k\_{eff,n }-1}{k\_{eff,n }}×10^{5}$$ | (7) |
| $$k\_{eff,n+1}=-m\*α\_{n}+k\_{eff,n}$$ | (8) |
| $$α\_{n}=\frac{\sum\_{i=1}^{24} P\_{i}}{\sum\_{i=1}^{24} P\_{max}}$$ | (9) |

At full power operation the Westinghouse AP1000 can operate for 18 months before needing refuelling, which becomes necessary when $k\_{eff}=1$[8]. With flexible operation, the refuelling timeline is extended consistent with our formalism (illustrated in Figure 1).



Figure 1. $k\_{eff}$ degradation at full power operation and flexible power operation (illustrative).

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| --- | --- |
| [a] | [b] |
| [c] | [d] |

Figure 2. Different ramp scenarios and subsequent Xe-135 and I-135 evolution. [a] Ramp down from 100% to 50% power at 20%/hr, [b] Ramp up from 50% to 100% power at 20%/hr, [c] Ramp down and up from 100% to 50% and back to 100% power at a ramp rate of 20%/hr, [d] Ramp up from 50% to 100% and back to 50% at 20%/hr.

## METHODS

Power plants have numerous technical constraints, such as minimum output levels, up and downtime, start-up and shutdown time, ramp-up/down rates, etc., which need to be taken into account before making a decision on commitment for generation. Unit Commitment (UC), a mixed integer linear programming (MILP) optimization model, is widely used for such scheduling [18]. UC coordinates the generation schedule of a set of power plants such that the objective is met at the lowest operation cost while all technical constraints are met. Power plant operators are provided with the commitment schedule ahead of time, and any uncertainty in demand or renewable generation are offset by including reserve margins on top of the generation commitments [19].

Traditionally, NPPs in energy system models include regulation-imposed operational constraints, start-up, shutdown costs, and variable costs [6]. This representation has often ignored the full range of flexibility for NPPs at BOL and the decreasing flexibility at the EOL. These observations motivate this present work, in which nuclear fuel burnup and the subsequent Xenon poisoning-induced minimum power level and deadtimes are added to the traditional UC model.

### NPP constraints

At BOL NPPs have considerable reactivity margin to overcome the peak *Xenon Defect*. As operational life goes on, the reactivity margin decreases, and certain ramp depths may induce deadtimes (where an increase in power output is not possible before a certain amount of Xe-135 has decayed out).To that end, if an NPP stays within the precomputed power range that avoids an unmanageable *Xenon Defect* that exceeds the available reactivity margin, it may operate flexibly without any Xe-135 poisoning induced deadtime. Conversely, if the reactivity margin has decreased due to the partial burnup of the fissile material within the fuel, power ramping transients can potentially induce sufficiently large Xe poisoning so as to prevent further reactor operation until the Xe poisoning transient has decayed sufficiently.

This study does not include wear and tear of mechanical parts, nor does it take thermal reactivity feedback into account. A precise account of those would benefit in understanding flexibility more precisely. However, we assume that once a ramp event has ended a minimum stable time has to elapse before another ramp event is started and in no scenario minimum power level can go below 20% rated power. More details of our treatment of the reactivity-margin/*Xenon-defect* trade-offs are discussed below:

#### Minimum power level

The minimum power levels NPPs can ramp down to while avoiding Xe-135 poisoning-induced deadtimes are computed based on the state of the reactor as indicated by the $k\_{eff}$ value at any given time in the fuel lifetime. A table summarizing the ramp down from 100% power to $P\_{min}$ while keeping ramp rate constant at 20%/hr vs the peak *Xenon defect* ($ρ\_{Xe,max}\left(P\_{min}\right)$) value is then built. Before running the UC for each day, the minimum power levels are determined according to Equation. (*10*). If the reactor stays within this range of [$P\_{max}$, $P\_{min}$] values, it can ramp up and down without any deadtime since there is enough reactivity margin to override the resulting peak *Xenon defect*. Figure 3. shows the evolving $P\_{min}$ for AP1000 and AP300 from BOL to EOL, at full power operation.

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| $$argmin\_{P\_{min}}\left[Δρ\_{marg}\left(j\right)-ρ\_{Xe,max}\left(P\_{min}\right)>0 \& min\left(Δρ\_{marg}\left(j\right)-ρ\_{Xe,max}\left(P\_{min}\right)\right)\right]$$ | (10) |



Figure 3. Derived Minimum power table from BOL to EOL assuming full power operation for AP1000 (left) and AP300 (right).

#### Deadtime after shutdown

During reactor shut down, there is no Xe-135 sink from burnup or source from fission, only generation due to I-135 decay. Consequently, the peak *Xenon Defect* depends on the I-135 concentration which in turn depends on the power level before shutdown, illustrated in Figure 4 (right).During dispatch decisions, often for least cost dispatch, reactors may need to shut down. After such a shutdown decision, if the reactor needs to restart, then depending on the reactivity margin available, a minimum dead time is imposed before power can be ramped up. The deadtime is dependent on the $k\_{eff}$ value of the reactor and is computed as shown in Figure 4 (left).

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Figure 4. Deadtime after shutdown computation illustration (left). *Xenon Defect* $(ρ\_{Xe})$ evolution after shutdown from 100%, 80%, 50% and 10% power (right).

## SCENARIO DESCRIPTION

An energy mix consisting of solar, wind, nuclear, and storage is initiated to demonstrate the modified UC with the new NPP constraints. Dispatch is solved one day at a time, with reactor multiplication factor ($k\_{eff}$) transfer at the end of each day. The value of $k\_{eff}$ for each reactor on a given day determines the minimum power levels and the deadtime imposed after shutdown, as is updated daily to provide a constraint on the allowable level of Xe poisoning and associated deadtime. Demand data and solar and wind variability are obtained for ERCOT for the year 2020 from gridstatus.io [20]. Four separate scenarios are designed for flexibility analysis between GW class AP1000 reactors and the newly unveiled AP300 reactors. For the demonstration of our framework, demand is scaled down to 30% and hourly capacity factors for solar and wind are computed using annual generation and installed VRE capacities. The net nuclear capacity in all the scenarios is held fixed at 3000 MW, which translates to 3 AP1000s compared to 10 AP300s. Further, 4400 MW of Wind, 1100 MW of Solar, and 2750 MW of Storage with a 10-hour duration are kept constant in all scenarios. This VRE capacity mix is representative of the high wind capacity in ERCOT. Finally, we impose a 20%/hr ramp up/down rate for AP1000 and 40%/hr for AP300, a minimum downtime of 2 hours for Rankine cycle power transient, and constant Variable cost and Start-up cost across AP1000 and AP300 for comparison. In order to study the effect of initial fuel enrichment, we examine cases with keff (n=1) =1.1, and keff (n=1) =1.205. The four scenarios studied here then have:

* AP300 BOL: All 10 reactors start with $k\_{eff}=1.205$
* AP300 EOL: All 10 reactors start with $k\_{eff}=1.1$
* AP1000 BOL: All 3 reactors start with $k\_{eff}=1.205$
* AP1000 EOL: All 3 reactors start with $k\_{eff}=1.1$

## RESULTS

The UC results presented in this paper are derived from the simplified scenario explained above. A comprehensive journal article, which will provide detailed optimization methods, constraints, scenario design, and in-depth conclusions (beyond the scope of this work), will be published elsewhere. The modified UC was implemented on all 4-scenarios starting from day 1 to day 365, one day at a time with individual reactor $k\_{eff}$ value transferred from the previous day’s operational conditions. Table 1. summarizes the results over a one-year operation period. We observe that starting from the fresh fuel at BOL, both the AP1000 and AP300 reactors have sufficient flexibility to support high penetration of VRE. Even in this condition, the AP300 fleet results in smaller VRE curtailment, higher penetration of wind and solar power, and reduced nuclear generation compared to the AP1000. Further, the annual production cost for the AP300 scenario is lower, which is consistent with the lesser generation observed for AP300.



Figure 5. Generation stackplot for all scenarios in the final 400 hours

When all reactors start from EOL, we observe that the generation from both AP300 and AP1000 units become increasingly inflexible and, during some hours, nuclear energy is curtailed on top of curtailing all the VRE that could have been utilized. AP300, however, still exhibits fleet-level flexibility even though individual units have become inflexible. Towards EOL, reactors operate either at full power or need to be shut down. Due to smaller unit sizes, AP300 reactors are shut more frequently while still meeting optimum UC dispatch. However, the AP1000 units, if shut down, will face longer deadtimes and may not be able to come online as fast as needed, hence they stay online even while over-generating. Figure 5 highlights the dispatch for all scenarios and all generators, including storage charging and discharging for the last 400 hours of the year in all scenarios.

Table 1. Summary table for annual dispatch for all 4 scenarios

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| --- | --- | --- |
| **High-Wind Scenario** | **Beginning of Life (BOL)** | **End of Life (EOL)** |
| **AP300** | **AP1000** | **AP300** | **AP1000** |
| **Production Cost (Mn$)** | 46.14 | 47.54 | 52.03 | 57.59 |
| **Nuclear (TWh)** | 5.78 | 6.01 | 6.51 | 7.21 |
| **Solar (TWh)** | 2.71 | 2.68 | 2.61 | 2.51 |
| **Wind (TWh)** | 13.38 | 13.1 | 13.92 | 12.04 |
| **Curtailment (TWh)** | 1.03 | 1.14 | 1.61 | 2.19 |

## CONCLUSION

In conclusion, this study captures the evolving constrained operational space for flexibly operating nuclear reactors from the Beginning of Life (BOL) and End of Life (EOL), considering burnup, enrichment, ramp limits, declining reactivity, Xenon poisoning-induced deadtimes, and minimum power levels in a modified Unit Commitment (UC) model. The analysis shows that Small Modular Reactors (SMRs) achieved the least cost dispatch in all scenarios due to their smaller unit sizes and greater inherent flexibility compared to gigawatt-scale reactors (GW-reactors). Additionally, replacing GW reactors with SMRs facilitates higher penetration of variable renewable energy (VRE) in dispatch. SMRs also dispatch reactors in their fleet efficiently, operating some reactors as must-run and others more flexibly to cumulatively result in higher fleet flexibility. These results highlight SMRs' ability to integrate more flexibly in high renewable future grids. Consequently, in both the BOL and EOL stages, the deployment of SMRs resulted in reduced VRE curtailment, demonstrating their effectiveness in supporting a more sustainable and efficient zero-carbon energy system.

**NOMENCLATURE:**

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| $$λ\_{I}$$ | Iodine decay constant (hr-1) |
| $$λ\_{Xe}$$ | Xenon decay constant (hr-1) |
| $$\overbar{Σ}\_{f}$$ | Macroscopic fission cross section (cm-1) |
| $$γ\_{Xe}$$ | Xenon effective yield |
| $$γ\_{I}$$ | Iodine effective yield |
| $$σ\_{abs}^{Xe}$$ | Xenon microscopic thermal absorption cross section (cm2) |
| $$ϕ\_{0}$$ | Average neutron flux (n/cm2·hr) |
| $$ϕ(t)$$ | Single energy group neutron flux (n/cm2·hr) |
| $$P\left(t\right)$$ | Nuclear unit power output (MW) |
| I(t) | Number density of I-135 (at/cm3) |
| Xe(t) | Number density of Xe-135 (at/cm3) |
| $$P\_{max}$$ | Maximum nuclear unit technical rating (MW) |
| $$P\_{min}$$ | Minimum allowable power level (MW) |
| $$v$$ | Average number of emitted neutrons during fissions |
| $$ρ\_{Xe}(t)$$ | Xenon defect (pcm) |
| $$Δρ\_{marg }$$ | Reactivity margin (pcm) |
| $$k\_{eff}$$ | Effective multiplication factor |
| $$α\_{n}$$ | Capacity factor for reactor on day n |
| $$m$$ | $k\_{eff}$ degradation rate at full power operation |

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