Inertia Contribution of the Akkuyu NPP and Small Modular Reactors to Frequency Stability in the Turkish Power System

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***Abstract*—As Türkiye expands its renewable fleet, the rising share of power-electronic-interfaced generation is expected to reduce system inertia. This study provides a first-order, screening-level estimate of whether the synchronous inertia of the Akkuyu NPP and, in the longer term, of small modular reactors (SMRs) can keep the rate of change of frequency (RoCoF) within acceptable bounds. Following the prospective inertia-analysis approach developed for the Portuguese system, indicative RoCoF estimates are obtained for a 1,200 MW reference loss at three horizons (2025, 2035, 2050). The trajectory is non-monotonic: the initial RoCoF rises from about 0.32 Hz/s in 2025 to 0.41 Hz/s in 2035 as inverter-based capacity grows, then falls to 0.18 Hz/s by 2050 once the 20 GW nuclear fleet is in place. A without-Akkuyu counterfactual for 2035 (≈0.79 Hz/s) indicates that the plant acts as a stabilizing buffer through the most inertia-stressed years. On architecture, delivering 4,800 MW as a distributed SMR fleet (16×300 MW) rather than as large units (4×1,200 MW) reduces the post-contingency RoCoF by roughly 74% at essentially equal stored kinetic energy—an N-1 granularity effect. All figures are indicative and intended to reveal relative trends rather than absolute magnitudes.**

***Index Terms*—Akkuyu NPP, frequency stability, renewable integration, RoCoF, small modular reactor, system inertia, Turkish power grid.**

I. Introduction

System inertia is falling rapidly as more power-electronic-interfaced renewable generation comes online [1]. This reduction follows from the different grid-interface characteristics of synchronous and converter-based generation. A conventional synchronous generator stabilizes the grid by releasing the kinetic energy stored in its rotating mass whenever the frequency starts to drop [2], whereas wind turbines and PV plants connect through static converters and simply do not have this mechanism [1], [3]. As their share grows, RoCoF rises, the nadir deepens, and the margin for stable operation shrinks [4], [5]. The GB outage of 9 August 2019 is the relevant cautionary case: thin inertia margins combined with incorrect protection settings led to cascading losses and load shedding affecting roughly 1.1 million customers [6].

Türkiye is on this trajectory too. Its National Energy Plan sets a renewable share of installed capacity near 65% by 2035, with wind and solar together reaching 120 GW, of which 5 GW is offshore [7]. At the end of 2025 wind stood at about 14 GW and solar at about 25 GW [8], [9]. On the nuclear side, the first 1,200 MW unit of the 4,800 MW Akkuyu plant is due to commission in 2026 and the rest are expected to follow, with a national target of 20 GW of nuclear capacity by 2050 [10]. Taken together, these commitments will considerably reshape the generation mix, and Fig. 1 shows how the installed-capacity split is expected to evolve across the 2025, 2035, and 2050 horizons.

Against this backdrop, we look at what Akkuyu and SMR technologies can offer for grid stability, both from theory and from a set of scenarios, and we organize the discussion around two questions. One is about timing: across 2025–2050, when does the inertia margin actually become binding? The other is about design: once a certain amount of nuclear capacity is being built, how should it be deployed? On the second question we compare a small number of large units against an equivalent fleet of distributed SMRs on a like-for-like basis.

Within this scope, the contributions of this paper are as follows:

- The low-inertia risk of the Türkiye power system is assessed for 2025, 2035, and 2050 using a first-order, screening-level RoCoF calculation.
- The buffering effect of the Akkuyu NPP on system inertia during the 2035 transition period is illustrated through a without-Akkuyu counterfactual.
- For the same total nuclear capacity, a large-NPP architecture and a distributed-SMR architecture are compared from an N-1 contingency perspective.

- We show that the SMR advantage comes not from any extra kinetic energy but from the smaller contingency granularity of the distributed units.

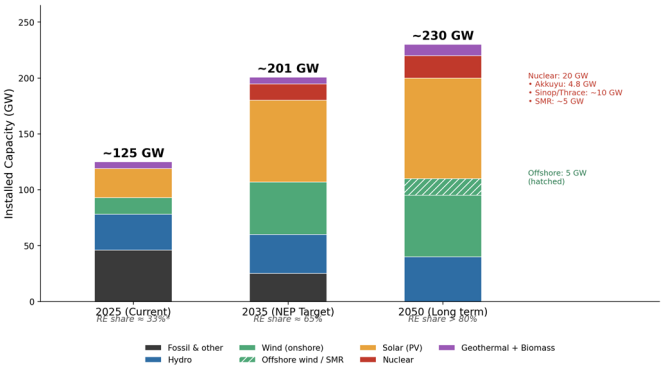

Fig. 1. Distribution of Türkiye's installed electricity capacity by source for 2025, 2035 (NEP target), and 2050 (long-term projection). *2025 RE share shown as the inverter-based (wind+solar) fraction (≈33%); including hydro the total renewable share is ≈63%. The 2050 values are compiled by the authors.

II. Theoretical Foundations

A. Swing Equation and System Inertia

Frequency dynamics are governed by the swing equation. For large imbalances, the initial RoCoF follows [4]:

$$\mathrm{RoCoF} = \Delta P \cdot f_0 / (2 \cdot E_{kin}) \quad (1)$$

where f_0 = 50 Hz and $E_{kin} = \Sigma\, H_i \cdot S_i$ (MW·s) is the kinetic energy held in the online synchronous machines; the larger E_{kin}, the more slowly the frequency moves. Synchronous generators sit at H ≈ 2–9 s, variable-speed wind can offer 2–6 s of "hidden" inertia, and PV is taken as H ≈ 0 [11]. The single-area frequency-control structure is given in Fig. 2, which separates the physical inertia of the NPP/SMR units from the virtual-inertia control loop.

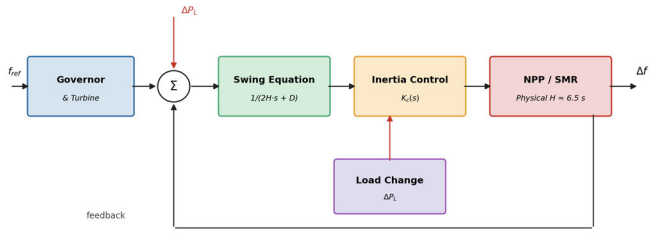

Fig. 2. Single-area frequency-control block diagram (physical NPP/SMR inertia and virtual-inertia control).

B. Frequency-Stability Indicators

We track three indicators. Maximum RoCoF governs protection and UFLS relay behavior; planning typically targets a 1 Hz/s limit for margin [4], [12]. Frequency nadir is the lowest frequency reached; a low nadir triggers under-frequency load shedding (UFLS) [1]. Steady-state deviation depends on the droop settings and the available primary reserve [13]. The Turkish grid code specifies a permissible frequency band of 47.5–51.5 Hz [14]. Fig. 3 traces how these indicators worsen as inertia falls, with a steeper RoCoF and a deeper nadir at lower inertia.

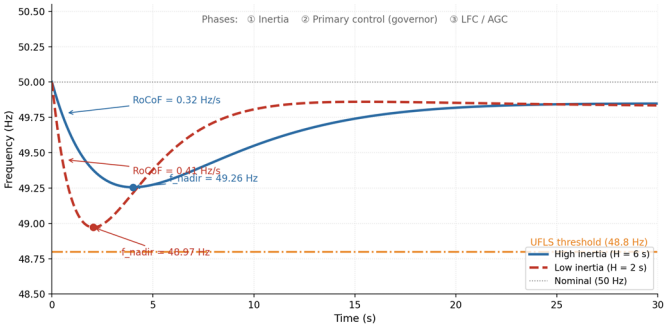

Fig. 3. Power-system frequency response for different inertia levels (illustrative; ΔP_L = 8%, R = 5% droop, f_0 = 50 Hz).

C. Effects of Low Inertia

In the German system, the aggregate inertia constant is reported to fall from about 6 s to 3–4 s as RES expand [4], and EU-wide reviews estimate a roughly 20% decline over two decades [11]. The consequences extend beyond frequency: small-signal stability margins also weaken as converter-dominated behavior takes over [15], and inertia remains central to system flexibility under high penetration of variable renewables [16]. The Portuguese prospective study illustrates the severity: in its 2050 scenarios, without additional inertia sources, kinetic energy is insufficient to keep RoCoF below 1 Hz/s for most of the year [17]. Synchronous condensers with synthetic inertia mitigate the problem but do not eliminate it [18].

III. Current Status of the Turkish Power System

The Turkish transmission system operates at 400 kV and 154 kV and has been synchronized with ENTSO-E since 2010 via two lines to Bulgaria and one to Greece [14]. Generation reached roughly 360 TWh in 2025, split about 55% fossil and 45% renewable [8]. Two shares are easily conflated here. Renewables account for about 62% of installed capacity, but that figure is heavily weighted toward directly grid-coupled hydro, which is synchronous and provides inertia. What matters for inertia is the inverter-based wind and solar share alone, which was only about 33% of installed capacity at the end of 2025 (≈40 of 122.5 GW) [8] and is targeted to roughly triple to 120 GW by 2035 [7]. It is this rapid inverter-based build-out, not the headline renewable percentage, that drives the projected decline in inertia. The existing wind fleet is entirely onshore; a 5 GW offshore target for 2035 is set for sites along the Aegean and Marmara coasts [7]. Earlier simulations indicate the grid can withstand up to 1,800 MW of offshore additions, though the nadir deepens as wind penetration climbs [14]. Table I lists the permissible operating-frequency bands and their dwell times under the Turkish grid code.

TABLE I. FREQUENCY LIMITS OF THE TURKISH GRID [14]

Operating Frequency (Hz)	Permitted Duration
47.5–48.0	10 minutes
48.0–48.5	20 minutes
48.5–49.0	1 hour
49.0–50.5	Unlimited (nominal)
50.5–51.5	1 hour

IV. GRID-SUPPORTING SERVICES OF NUCLEAR TECHNOLOGIES

A. Synchronous Inertia of Nuclear Plants

Nuclear plants connect directly via synchronous turbogenerators, which provide natural inertia, short-circuit capacity, and reactive-power support [19]. A common value for their inertia constant is H ≈ 6.5 s [18], [19], which is well above the H ≈ 2 s of a synchronous condenser. For the 4,800 MW Akkuyu plant (≈5,330 MVA at a 0.9 power factor), the stored kinetic energy works out to $E_k = H \cdot S \approx 34{,}700$ MW·s. Because nuclear units operate at capacity factors above 90% [10], this contribution is steady and predictable rather than dependent on dispatch.

B. Advantages of Small Modular Reactors

Where large NPPs come in 1,000–1,200 MW blocks (Akkuyu's VVER-1200 units are rated at 1,200 MW [10], [20]), SMRs are built as smaller, distributed units of around 300 MW [19]. Three consequences follow:

- **N-1 security:** losing one small unit creates a far smaller power deficit, so by (1) a smaller ΔP directly implies lower RoCoF;
- **Distributed inertia:** units can be sited where the grid needs them, easing transmission constraints and improving regional dynamics;
- **Potential reduced SynCon need:** as synchronous machines, SMRs inherently provide reactive power and short-circuit current while generating active power, and — depending on the specific reactor design and the applicable licensing framework — may also be configured for black-start and island-mode operation [18], [19]; where such capabilities are realized, they could reduce the need for dedicated synchronous condensers in selected regions, subject to siting and regional grid constraints. Fig. 4 contrasts the grid-supporting services provided by a large NPP, a distributed SMR cluster, and a dedicated synchronous condenser.

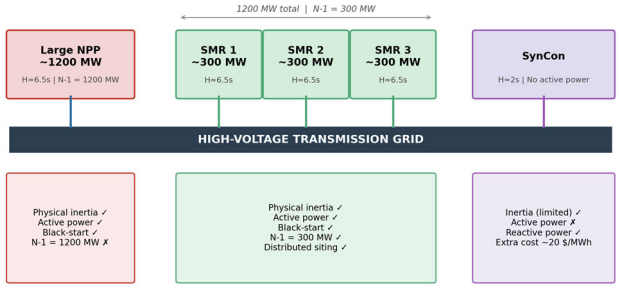

Fig. 4. Comparison of grid-supporting services: a large NPP, distributed SMR clusters, and a synchronous condenser.

C. Grid Integration of Akkuyu

Akkuyu sits at Büyükeceli in Mersin and consists of four Rosatom VVER-1200 reactors; its grid-connection agreement with TEİAŞ was signed in 2019 [20]. Six high-voltage lines tie it into the network, and the first unit should come online in 2026 [10]. The VVER-1200 design is load-following, but that only changes the active power output. The synchronous inertia is unaffected, since it is available for as long as the unit stays synchronized, regardless of how much power it happens to be exporting [10], [19].

V. SCENARIO-BASED COMPARATIVE ASSESSMENT

A. Framework

We build three scenarios for the Turkish system at 2025, 2035, and 2050 and compare them with first-order estimates drawn from recent literature and published targets [14], [17], applying the RoCoF relation (1) to each. The model is single-area (lumped) and deliberately ignores the inertia of the neighboring ENTSO-E system. This is conservative on two counts: the Continental Europe area is itself losing inertia [11], and the islanded (system-split) condition is the critical design case for protection settings, as the Portuguese reference also assumes [17]. Our figures are therefore a lower bound on inertia and an upper bound on RoCoF; under normal interconnected operation with Continental Europe the actual values would be considerably lower.

The inputs are representative low-synchronous operating points assembled from published installed-capacity figures, national targets, and literature inertia constants; the aim is to compare relative inertia trends and the effect of plant architecture under transparent assumptions, not to reproduce hourly TEİAŞ dispatch or a validated dynamic simulation.

B. Scenario Definitions

Scenario A—2025 (current): fossil synchronous units and hydro still dominate dispatch, wind and solar together sit at ≈40 GW [8], and Akkuyu is not yet contributing. Inertia is comparatively high.

Scenario B—2035 (NEP target): wind and solar reach 120 GW (5 GW of it offshore) [7] and the four Akkuyu units (≈4,800 MW) are online, adding ≈34,700 MW·s. This is where the system is most exposed. In the high-RES hours, the online synchronous fleet shrinks so far that, even with Akkuyu

running, inertia hits its lowest margin and RoCoF its highest. Akkuyu provides an inertia buffer in this period; on its own it does not fully restore the 2025 inertia margin.

Scenario C—2050 (long-term): Türkiye is closing on its 20 GW nuclear target (Akkuyu, Sinop, Thrace, plus ≈5 GW of distributed SMRs) [10] as coal comes off the system. This large nuclear inertia base undoes the 2035 dip, and the SMR fleet helps regional dynamics and N-1 security on top of that [19].

C. Transition-Period Considerations (2027–2029)

While Akkuyu is being phased in, two factors act against the system simultaneously: the single-contingency size grows toward ≈1,200 MW as each unit is commissioned, while the inertia buffer is not yet fully in place. The partial-commissioning period may therefore deserve separate operational attention, because the largest single-unit contingency increases before the full four-unit inertia contribution is available. Managing it requires coordinating the commissioning schedule with sufficient primary reserve and FFR.

D. First-Order Quantitative Estimate

Hourly unit-commitment and dispatch data for the future Turkish system are not in the public domain, so the online synchronous capacities in Table II are built as screening assumptions for stressed high-RES conditions. They represent representative minimum-inertia operating points, not annual averages or official TEİAŞ forecasts; the derivation of each value is given below.

TABLE II. SCENARIO INPUT ASSUMPTIONS AND DATA SOURCES

Parameter	2025	2035	2050	Source / assumption
Wind + solar capacity	≈40 GW	120 GW (5 GW offshore)	—	[7], [8]
Online synchronous (MVA)	23,000	14,830	29,230	Author assumption (stressed high-RES dispatch point; derivation in Sec. V-D)
Nuclear capacity online	0	4,800 MW	≈20 GW	[10]
H fossil / hydro	≈2–6 s	≈2–6 s	≈2–6 s	Literature [18], [19]
H nuclear	6.5 s	6.5 s	6.5 s	Literature [18], [19]
Contingency size (ΔP)	1,200 MW*	1,200 MW	1,200 MW	Standardized screening basis (ENTSO-E reference)

*In 2025 the physical largest contingency is smaller (~800 MW); the 1,200 MW basis is applied uniformly across all horizons as a deliberately conservative screening assumption.

For each horizon we take a representative high-RES, low-synchronous operating point, since it is the minimum-inertia hours that set the binding RoCoF. Only machines directly coupled to the grid are counted, and the hidden inertia of wind is left out as a conservative measure. The operating points are constructed as follows, following the minimum-inertia screening logic of the Portuguese prospective study [17]. In A, an hour of strong combined wind and solar output (≈12–15 GW from the ≈40 GW installed fleet [8]) coinciding with moderate demand (≈33–35 GW) leaves roughly 20–21 GW of residual demand and reserve duty to be carried by synchronous gas, coal/lignite, and hydro units — ≈23,000 MVA at a 0.9 power factor. In B, with installed wind and solar tripled to 120 GW [7], the same construction yields stressed-hour inverter outputs that compress the dispatchable synchronous fleet toward a low-synchronous screening level, represented here by regulating hydro and a limited set of gas units retained for voltage and reserve support, and taken as ≈9,500 MVA; the four always-on Akkuyu units (4,800 MW at 0.9 power factor) add ≈5,330 MVA, giving 14,830 MVA. In C, the ≈20 GW nuclear fleet (≈15 GW of large units plus a 5 GW SMR fleet) runs as must-run baseload — ≈22,200 MVA at a 0.9 power factor — and, with coal retired, a residual ≈7,000 MVA of flexible hydro and gas is assumed to remain online, giving ≈29,230 MVA. The same 1,200 MW single-unit loss — about the size of the ENTSO-E reference incident — is applied across all three for a clean comparison. From Scenario B on, that is also the genuine binding contingency, namely one Akkuyu unit; in A the real largest contingency is smaller (~800 MW), so using 1,200 MW there is conservative by design. The per-technology inertia constants come from the literature (fossil/hydro H ≈ 2–6 s, nuclear H ≈ 6.5 s [18], [19]). Weighting these by the online synchronous mix of each horizon gives the average constants in Table III — ≈4.1, ≈4.9, and ≈5.6 s for A, B, and C — the rise reflecting the growing nuclear share. Table II collects the full set of inputs and their sources.

TABLE III. KINETIC ENERGY AND INITIAL ROCOF (ΔP = 1,200 MW)

Parameter	A 2025	B 2035	C 2050
Online sync. (MVA)	23,000	14,830	29,230
Avg. H (s)	≈4.1	≈4.9	≈5.6
E_kin (MW·s)	≈94,000	≈72,700	≈163,600
Initial RoCoF (Hz/s)	**≈0.32**	**≈0.41**	**≈0.18**

The trajectory that emerges from this is *non-monotonic*. Between 2025 and 2035 the inverter-based build-out pushes so much synchronous generation off the system that the initial RoCoF deteriorates from 0.32 to 0.41 Hz/s even with Akkuyu in place. The plant's contribution becomes clear in the without-Akkuyu counterfactual for 2035: removing the four units, E_{kin} falls to ≈38,000 MW·s and RoCoF rises to ≈0.79 Hz/s, close to the 1 Hz/s limit. This does not imply the system would actually operate at that RoCoF; it isolates Akkuyu's inertia contribution under the same stressed operating point. On this basis Akkuyu reduces the 2035 RoCoF by about 48% and keeps the worst horizon within the margin. By 2050 the 20 GW fleet brings the figure down to ≈0.18 Hz/s. Every horizon remains under 1 Hz/s at the representative operating point, although the margin narrows in the lowest-synchronous hours, particularly in 2035. Since the 2035 figure depends on the assumed dispatch, a ±10% variation in the online synchronous capacity shifts the calculated RoCoF by roughly

±0.04 Hz/s; the non-monotonic shape is therefore robust to the dispatch assumption even though the absolute values remain indicative. The nadir is governed by fast frequency response and governor dynamics rather than inertia alone, and its credible estimation requires a time-domain treatment beyond the first-order scope adopted here. Fig. 5 plots the trajectory across the three horizons: panel (a) the total kinetic energy, panel (b) the resulting initial RoCoF.

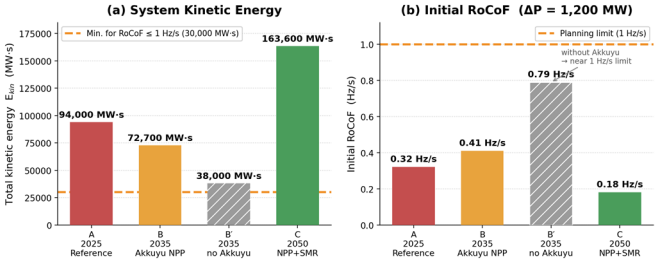

Fig. 5. Scenario-based comparison for the Turkish grid: (a) total kinetic energy and (b) initial RoCoF (first-order estimate, f_0 = 50 Hz, ΔP = 1,200 MW).

E. Architectural Choice: Large NPP vs. Distributed SMR

A second related question arises regarding the build-out: for a fixed amount of nuclear capacity, does the way it is split into units change the response? To isolate that, we place the same 4,800 MW block on a common small high-RES base (9,000 MVA) and hold everything else equal. *Architecture A* delivers it as four 1,200 MW units backed by dedicated synchronous condensers (≈1,500 MVA), so its largest contingency is a single 1,200 MW unit. *Architecture B* delivers the same 4,800 MW as sixteen 300 MW SMRs sited near load; its largest contingency is one 300 MW unit, four times smaller, and the SMRs may take some of the pressure off the dedicated condensers depending on local grid needs. The SMR units are assigned the same inertia constant as the large nuclear units (H ≈ 6.5 s [18], [19]); smaller turbogenerators may in practice sit somewhat below this, which would slightly reduce Architecture B's kinetic energy without altering the granularity conclusion. The stored kinetic energy is almost the same in both. Table IV presents the unit configuration, kinetic energy, largest contingency, and initial RoCoF for each unit.

TABLE IV. LARGE-NPP VS. DISTRIBUTED-SMR (EQUAL 4,800 MW)

Parameter	A: 4×1,200 + SynCon	B: 16×300 SMR
Unit config.	4×1,200 MW	16×300 MW
Dedicated SynCon	≈1,500 MVA	None
E_kin (MW·s)	≈73,700	≈70,700
Largest ΔP (MW)	1,200	300
Initial RoCoF (Hz/s)	**≈0.41**	**≈0.11**

For kinetic energy that differs by only about 4%, the distributed-SMR architecture settles at ≈0.11 Hz/s, compared with ≈0.41 Hz/s, a drop of roughly 74%. This indicates that this is an *N-1 granularity* effect, not an inertia effect: applying the same 1,200 MW loss to Architecture B yields ≈0.42 Hz/s, essentially the same as A. With inertia held fixed, the four-fold smaller contingency (1,200→300 MW) produces a four-fold lower RoCoF, exactly as (1) predicts. Three considerations qualify this result. It is a first-order initial-RoCoF estimate only; the granularity benefit assumes single-unit losses, so a site-level common-cause outage of several co-located SMRs would re-create a larger contingency; and commercial SMRs are still in licensing and first-of-a-kind construction, with their own siting, cooling, and cost challenges. The comparison, therefore, measures the stability value of granularity, conditional on those hurdles being cleared.

F. Comparison with Virtual Inertia

Energy-storage-backed virtual synchronous generators (VSG/VSM) imitate inertial behavior in control software and can improve both RoCoF and nadir [2], [3], and virtual-inertia scheduling folds them into the economic dispatch [21]. However, they involve storage cost and control delay, and large-scale deployment and standardization of grid-forming inverter controls are still evolving [19], [22]. A nuclear plant provides physical rotational inertia with no software or storage layer in between, which is most significant in the first 0–500 ms of a large disturbance. A full cost–benefit comparison is beyond the scope of this paper; as a single reference point, the levelized cost of providing equivalent support via a synchronous condenser has been estimated at about 20 $/MWh of inverter-based energy enabled [19].

VI. CONCLUSIONS

(1) Across the three horizons, the estimated inertia margin does not change monotonically: the initial RoCoF increases from 2025 to 2035 despite Akkuyu's contribution, and then decreases by 2050 as the larger nuclear fleet is assumed to be online. The computed value still stays inside 1 Hz/s, but the without-Akkuyu counterfactual (≈0.79 Hz/s) shows that, under our assumptions, the plant provides a substantial share of the inertia margin to keep it there.

(2) At full output Akkuyu holds about 34,700 MW·s, which makes it a significant source of synchronous inertia. But it all sits at a single point on the coast, so it cannot meet the system's distributed-inertia needs on its own, and regional support will still be needed elsewhere.

(3) Virtual inertia and synchronous condensers each have their place [18], [21], but large-scale deployment and standardization of the grid-forming controls behind them are still evolving. In the near to medium term, then, the physical inertia of nuclear plant can carry a meaningful part of the system-support role.

(4) How the nuclear capacity is configured is shown to be as relevant as how much there is. For an equal 4,800 MW block on an equal-inertia base, a distributed-SMR layout (16×300 MW) brings the initial RoCoF down to ≈0.11 Hz/s, compared with ≈0.41 Hz/s for the large units. That ~74% improvement is fundamentally an N-1 granularity result. Within the initial RoCoF and single-unit N-1 framework adopted here — and setting aside cost, licensing, siting,

network topology, and common-cause outage risk, none of which enter the comparison — these results suggest that, as Türkiye works toward its 20 GW target, a distributed-SMR build-out may offer additional frequency-stability value per megawatt relative to further large units. Whether this advantage holds in practice depends on those excluded factors and remains to be established. Akkuyu remains a useful near-term buffer through the 2035 inertia trough.

Limitations: The estimates are first-order and rest on a single representative high-RES, low-synchronous operating point per horizon, built from scenario assumptions rather than hourly TEİAŞ dispatch or a validated dynamic model; the numerical RoCoF values are therefore indicative screening results. The contribution is the relative comparison — the shape of the inertia trajectory and the N-1 granularity effect — not an operational forecast. The nadir is left unquantified because it depends on fast frequency response, governor dynamics, load damping, and protection settings beyond the initial RoCoF formulation. A time-domain treatment, inter-area effects, and annual kinetic-energy duration curves are left to a journal extension.

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