Mapping the scales of instability in inverter-rich power systems

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Standfirst

Power-system security depends on interactions among controls, machines, networks and protection. Existing methods already describe these phenomena, but their assumptions and evidence can be difficult to connect across disciplines. We propose a scale-and-evidence framework that links a disturbance mechanism to an appropriate study request, illustrated through four documented events and a conventional boundary comparator. Its value must be tested against simpler presentations, not inferred from the appeal of a surface.

1. The missing link is between a mechanism and its next study

Inverter-rich electricity systems require careful choices about how to represent controls, network coupling and protection. The extended IEEE stability classification already recognizes converter-driven and resonance phenomena alongside rotor-angle, voltage and frequency stability [1]. Electromagnetic-transient (EMT) simulation, phasor-domain dynamics, impedance analysis and operational assessments are not competing universal explanations. Each answers particular questions under particular assumptions. A decision can fail when those assumptions disappear between the technical report and the commissioning of a study.

Aggregate inertia is useful for estimating the initial frequency response to an active-power deficit. It does not identify a turbine's repeated-fault counter, collection-system resonance, negative-sequence protection or current saturation. Conversely, a local converter disturbance does not necessarily become a system-wide instability. That consequence depends on the actual network configuration, operating point, controls and protection. Neither a universal inverter percentage nor a geographical footprint supplies those missing conditions.

We propose the Electrodynamic Stommel Map as an organizing layer, inspired by Stommel's oceanographic scale diagram [2]. The proposed contribution is not another stability category or a replacement solver. It is a reproducible chain: **mechanism → characteristic scale → evidence → model scope → next study**. Each link must remain inspectable. A reader should be able to distinguish an investigated cause from a model assumption and identify what additional information is needed before acting.

Figure 1 compares this contribution with established approaches. Stability classifications name phenomena; simulation tests represented trajectories; impedance and modal methods diagnose specified interactions; incident investigations establish chronology and causes. The map potentially adds a shared navigation between these products, especially for regulators and executives. It adds nothing where an existing report already answers the same question clearly. Novelty therefore concerns the workflow and its evaluation, not discovery of multiscale dynamics. A systematic prior-art review remains necessary before any claim of priority.

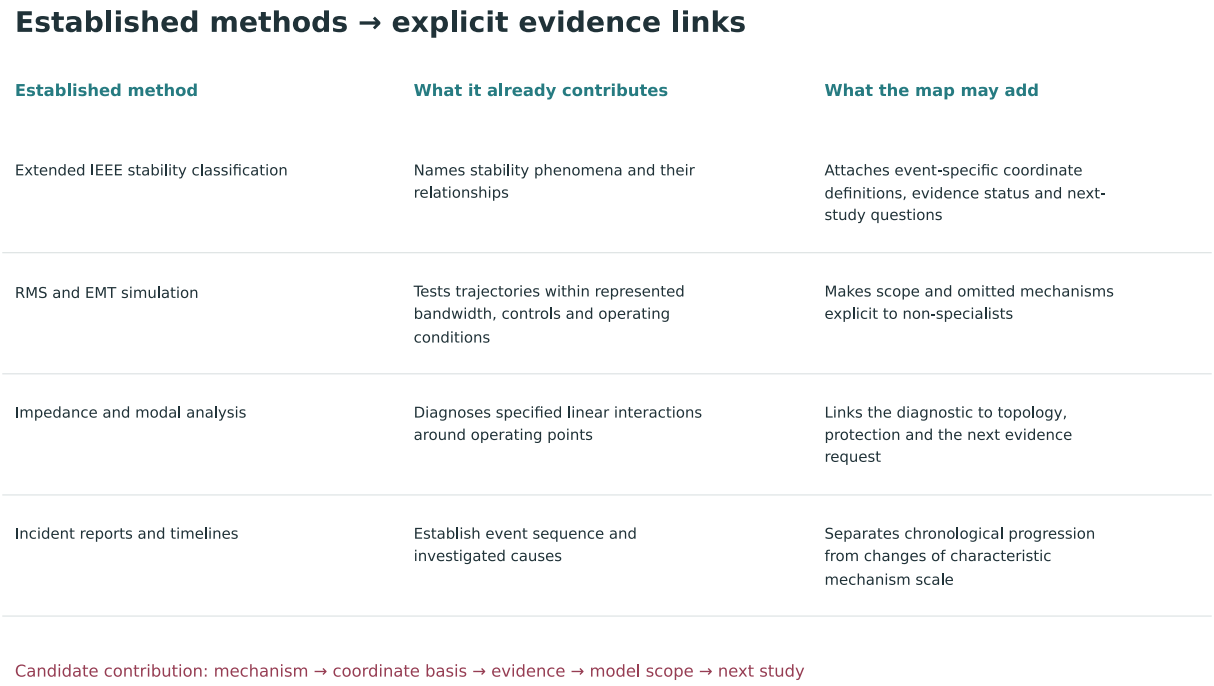


Figure 1 | An organizing workflow beside established methods. The proposed addition is explicit linkage among mechanism, coordinate definition, evidence and next study. Existing classifications and analysis methods remain authoritative within their scope. Source: conceptual synthesis of [1,2,9,10]; comparison is not a measured performance ranking.

2. Coordinates must reveal their assumptions

Characteristic time is not elapsed event time. Fault-clearing duration, a controller's oscillation period and the interval before a relay operates are different quantities. A chronology may advance while the active mechanism shifts to a shorter characteristic time. Such a transition is not backward propagation in time. The source must specify which quantity a mark represents, rather than converting every reported delay into an oscillation frequency.

Coupling extent is equally conditional. A turbine protection counter acts locally even if many turbines respond in parallel. A series-compensated circuit couples wind controls and network components; its line length is not automatically a mode's coherence extent. Geographic separation, effective-reactance distance and an assigned mechanism extent are different coordinates. They cannot be substituted without a declared convention. The current application assigns some process extents and provides a separate electrical-distance diagnostic; it is not a wholly derived electrical manifold.

A defensible mark therefore carries a coordinate type, provenance and uncertainty status. Where no event-specific period or electrical extent is publicly measured, a mechanism row without a numerical coordinate is preferable to false precision. Figure 2 uses causal sequences rather than inventing such coordinates. The existing South Australian machine-stage extent remains an interpretive placement, not an operator observation. The new SSCI illustration is source-led and has no calibrated dynamic replay.

The constructed scalar field, Ψ, is optional to this framework. It combines engineering-inspired Gaussian footprints and an unnormalized smooth maximum; it is neither a failure probability, conserved energy nor stability bound. Selected network diagnostics inform its amplitudes, but no Gaussian-to-resolvent theorem is established. An analytical companion separately evaluates balanced machine-pair power input and relative-frequency output:

$$G(\tau) = \left| C\left(\mathrm{i}\frac{2\pi}{\tau} I - A_E\right)^{-1} B \right|. \tag{1}$$

The gain is in Hz/GW for the declared retained operator and ports. It is not absolute grid frequency, nadir or a continuous length-dependent stability law. The supplement states projection, unsupported-state and numerical limitations. The framework must also work without this observable or any scalar surface: its essential unit is the evidence-bearing mechanism, not a visually dramatic aggregate.

3. Four events, not four versions of the same failure

The cases were selected for complementary study questions and public evidence, not statistical representativeness. They also overlap. Great Britain's event included a reported subsynchronous plant resonance, so it cannot be treated as purely a reserve-speed example distinct from all control interaction. The fourth case sharpens a different topology-and-equipment question rather than creating an artificial four-category taxonomy.

South Australia, 2016: settings and repeated disturbances. AEMO's investigation links storm-related faults, repeated voltage disturbances, wind control/protection responses, generation reduction, interconnector separation and collapse [4]. The useful question is whether installed ride-through counters, resets and protection settings tolerate the relevant sequence. Aggregate inertia alone cannot answer it. Required evidence includes the repeated-fault chronology and installed firmware settings, followed by appropriate plant and network dynamic studies. The application's prescribed losses do not independently predict turbine trips; its post-collapse frequency decline is scripted. Embedded numerical report inputs still await complete page-level audit.

Great Britain, 2019: plant interaction and containment of compound loss. ESO's investigation and the Ørsted account distinguish Hornsea's response from the wider frequency event [5,14]. Appendix D describes an insufficiently damped electrical resonance in the subsynchronous range, collection-system voltage depression and protection-driven de-loading. The reported de-loading interval is 107 ms: several 50-Hz cycles, not a subcycle event. RoCoF was not the reported Hornsea de-loading trigger; loss-of-mains responses of embedded generation are a separate part of the account. The study chain requires plant control/protection assessment and frequency-response/LFDD coordination for the combined deficit. The existing reconstruction narrowly remains above its LFDD threshold and fails to trigger the observed action. That disagreement must remain visible: a small nadir residual need not imply the correct protection outcome.

Odessa, 2021: model adequacy is mechanism-specific. NERC and Texas RE report several inverter and plant responses, including PLL loss of synchronism, momentary cessation and protection behaviour [6]. A PLL trip does not establish a sustained SSCI oscillation or one common cause for the generation reduction. Table 2.1 identifies limitations of conventional positive-sequence representation for particular mechanisms while marking phase-jump tripping as representable. The defensible question is whether the chosen models include the relevant bandwidth, controls and protection. Validated vendor-specific EMT studies are needed for the fast mechanisms that require them; EMT software alone does not supply missing protection logic. The application's simplified sequence screen and prescribed loss do not reproduce the actual fleet response, and its double-line-to-ground initiating convention is not source-validated.

ERCOT, October 2009: topology can create a control interaction. NERC explicitly identifies SSCI after a normally cleared fault left Type-3 wind generation connected through series compensation [11,12]. Its lesson learned reports two plants with 485 MW capacity, a single 80-mile 345-kV line with 50% series compensation, damaging oscillation growth within 200 ms and capacitor bypass 1.5 s after the initiating line trip. These are source-specific equipment and timing quantities, not an inferred oscillation period or coherence radius. The account includes induction-machine/series-capacitor resonance, crowbar behaviour and converter controls contributing negative damping; it is not a pure PLL diagnosis. The next studies examine credible radializing outages, impedance assumptions, Type-3 electrical/control dynamics and protection. The generic app converter is not a replica of that installation.

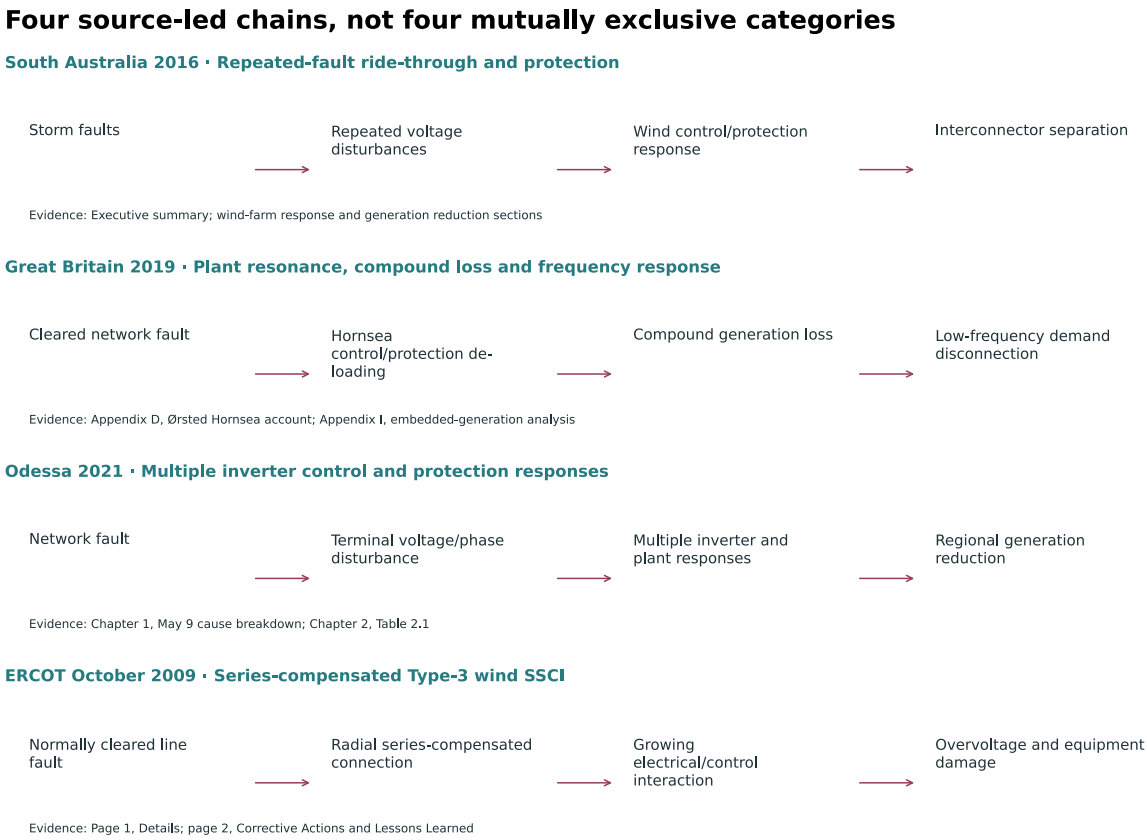


Figure 2 | Four causal chains produce different study requests. The sequences are source-led interpretations, not inferred propagation trajectories or new recordings. GB also involves reported plant resonance; case diversity does not imply mutually exclusive mechanisms. Source: AEMO [4], ESO/Ørsted [5,14], NERC/Texas RE [6] and NERC [11].

4. A boundary comparator prevents converter exceptionalism

The Continental European synchronous-area separation of 8 January 2021 provides an explicit counter-case [13]. Conventional network configuration, power flows, protection and wide-area separation demonstrate that local-to-system consequences are not uniquely inverter-driven. The appropriate study request starts with the actual busbar topology, transit flows and protection sequence, followed by relevant angular and frequency analyses. It would be a mistake to invoke converter firmware solely because the event spans large distances.

The map should help distinguish this counter-case, not absorb it into a generic converter-cascade narrative. Figure 3 links each case to a study question, minimum evidence and a prohibited inference. A useful framework narrows the requested study and exposes unknowns. If it merely attaches a generic demand for more EMT simulation to every event, it has not demonstrated a distinctive benefit.

Model choice cannot be read directly from a temporal band. RMS models can include appropriately represented control and protection dynamics; EMT models can still omit installed logic. Impedance analysis is powerful around declared conditions but does not alone settle a switching sequence. Modal analysis describes specified linearized dynamics without predicting every protection transition. Cross-method agreement matters only after operating points, controllers, ports and observables have been matched. The supplement retains separate non-normal, current-limit and numerical analyses without promoting them into a universal map theory.

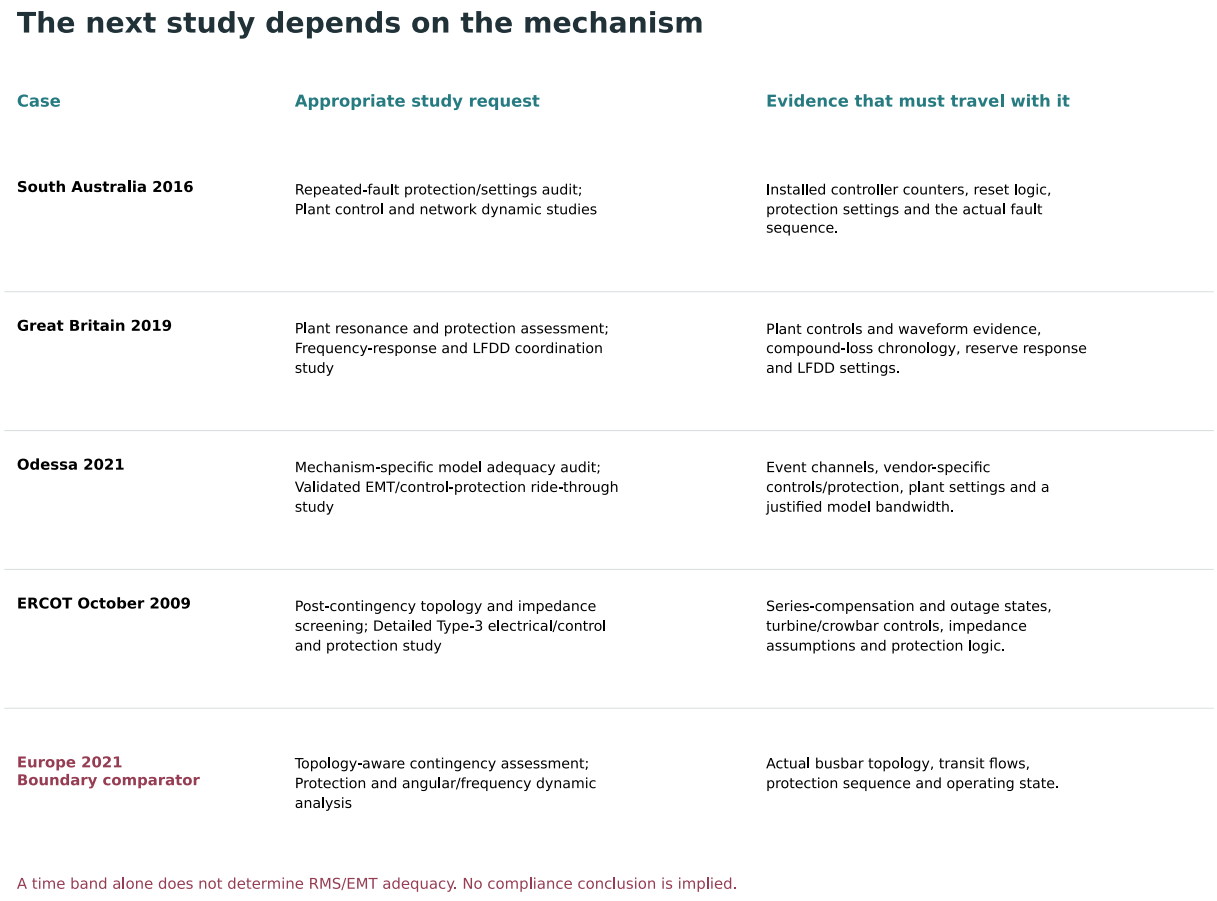


Figure 3 | Study selection requires evidence, not just a time band. Four cases and a conventional boundary comparator specify appropriate questions and required inputs. Tools are complementary; listed studies are scoping guidance, not compliance determinations. Source: conceptual interpretation of [4–6,11,13,14].

5. Test whether the map improves decisions—or remove it

The immediate policy application is an auditable study request, not autonomous dispatch, a stability market price or automatically released connection capacity. A dossier can preserve the operating point, source record, intervention, uncertain criterion and missing evidence. A bounded pilot would additionally specify authority, monitoring, stop conditions, sunset and liabilities. The application can assemble a draft, but no dossier grants a derogation or certifies compliance. Conditional economic arithmetic remains supplementary and cannot establish calibrated welfare or a benefit multiplier.

A complementary operating-region view translates selected diagnostics into conditional margins. Physical kinetic energy is $E_k = \sum_i H_i S_i$, with H_i in seconds and E_k in MW·s; under the aggregate swing approximation, $| \dot{f}(0^+) | = f_0 \mid \Delta P \mid / (2E_k)$. Inertia and initial RoCoF are therefore not independent coordinates for a fixed deficit. Inverter fraction must use a declared denominator and a linear axis if zero is included. Converter synchronism additionally depends on impedance, operating point, controls and protection [9,10], not one universal inertia or SCR threshold. The console samples generalised strength and IBR share while varying generic GFM support and condenser capacity, reporting physical energy separately from equivalent virtual support. Its intersection of frequency, strength and damping screens is neither a universal phase-lock frontier nor certified dispatch: voltage, fault-current limits and credible contingencies require further studies. This view scopes those studies without deriving a stability law from Ψ.

Scientific readiness and document maturity are separate. Four independent SciPy reconstructions check the same reduced equations; an executed ANDES full IEEE39 run is unmatched to the application and retains growing modes and warnings. All twenty matched physical benchmark gates remain pending. These experiments document implementation and limits, not validation of historical trip predictions. A licensed proprietary solver is not intrinsically necessary for a conceptual Perspective, but claims of physical accuracy require adequate matched evidence regardless of software license.

The framework's central claim needs a different evaluation. Compare conventional reports/classification, a scale-and-evidence map without Ψ, and the full display. Keep case information equivalent across arms and preregister correct mechanism identification, next-study selection, evidence-limit recognition and false confidence. Recruit engineers, regulators and executives separately; use a pilot-informed power analysis rather than inventing a sample size or expected improvement. Randomized allocation and blinded scoring should limit familiarity and presentation effects. No practitioner evaluation has yet been conducted.

Figure 4 makes the potential failure outcomes explicit. If the map increases confidence without improving correct study selection, it is harmful. If removing Ψ preserves comprehension and reduces errors, the simpler map is preferable. If a conventional matrix performs equally well at lower effort, the contribution should be narrowed to the contexts where navigation adds value. Professional uptake would require evidence of more precise, auditable requests and safer pilot boundaries, not satisfaction scores alone.

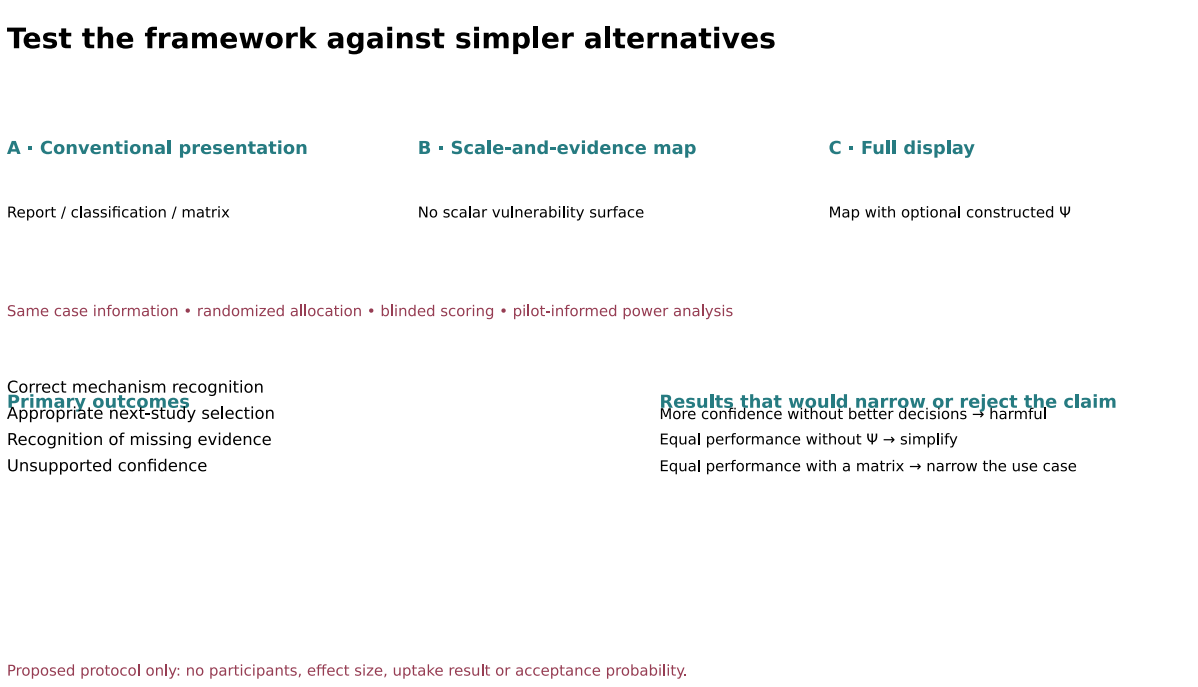


Figure 4 | A falsifiable evaluation, not a promised benefit. Three equivalent-information presentation arms test mechanism recognition, next-study choice and unsupported confidence. No participants, effect size or acceptance probability is asserted. Source: proposed study design; not observed results.

The ambition is a transparent boundary object between engineering evidence and decisions. Its maximum defensible contribution is to show which question a model answers, which assumptions support that answer and which study is needed next. That contribution remains a hypothesis until comparative evaluation. A polished representation is useful only if it makes those boundaries harder—not easier—to overlook.

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Submission declarations

Data availability: Shared-model snapshots, frozen parameters, independent SciPy comparisons, ANDES input deck, rotor-frequency/voltage traces, state matrices, eigenvalues, warnings and regeneration scripts accompany this draft. No original operator recordings or independent EMT results are included. Repository/archival DOI to be added after licensing and deposit.

Code availability: Current shared TypeScript engine and offline publication tooling are in the project repository. Public repository URL, license and versioned DOI require author approval.

Author contributions (CRediT): Rolf Bastiaanssen: Conceptualization; Methodology; Software; Writing – original draft; Writing – review & editing. This attribution does not claim independent external validation.

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