Stability Has a Price: Grid-Forming Inverters after Synchronous Generation

A valuation and procurement framework for inertia, system strength and fault performance

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Abstract

Power systems have historically received inertia, voltage-source behaviour and fault current as physical characteristics of synchronous machines. As synchronous generation retires and inverter-based resources expand, those capabilities can become scarce, locational and commercially explicit. Grid-forming inverters can provide valuable responses, yet capability varies by control, hardware, energy source, network condition and operating envelope.

This paper develops the Grid-Forming Stability Value Framework. It separates inertia-like response, phase-jump power, protection-quality fault current, voltage support, damping, system strength and restoration. It compares grid-forming batteries, wind, solar, network devices, VSC-HVDC and synchronous condensers, then connects technical qualification to procurement, pricing, contracts, finance and valuation.

NESO states that grid-forming equipment can create voltage and frequency and identifies active RoCoF response, phase-jump power and fast fault-current injection in its requirements [1]. NESO has used competitive stability tenders and is developing enduring Stability Markets [1]-[3]. AEMO is testing methods to quantify grid-forming system-strength support and has initiated procurement for a protection-quality fault-current trial [4]-[5]. DOE, NREL and UNIFI identify modelling, validation, interoperability and standards as continuing priorities [6]-[9]. These sources support staged qualification; they do not establish universal performance or project economics.

The central conclusion is that stability should be purchased as measurable services under explicit operating conditions. Four tables and three figures translate the framework into an investment method. Numerical examples are hypothetical management assumptions used solely to demonstrate the method; they are not observations, forecasts, valuation conclusions or investment recommendations.

JEL Classification: G31, G32, L51, L94, O32, Q40, Q48

Keywords: grid-forming inverter, system stability, inertia, system strength, fault current, battery storage, stability market, energy transition

1. DEFINE THE INVESTMENT DECISION

System operators, networks and asset owners must decide how much grid-forming capability is required, where it is needed and whether it should be mandated, procured or co-optimised with energy and storage. The decision should connect measurable system need to qualified technical performance and financeable revenue.

The evidence package should reconcile system study, technical specification, validated model, site test, operating envelope and commercial obligation. Vendor claims and management estimates should remain distinguished from observed field performance.

A financeable service has measurable need, technology-neutral requirements, credible tests and predictable settlement. Procurement should preserve competition while recognising locational and first-of-a-kind constraints.

2. MAP THE CHANGING SYSTEM

Retiring synchronous generation reduces rotating mass, fault current and voltage-source behaviour while inverter-based resources grow. Planning should identify the operating conditions and locations where stability constraints become binding.

The valuation should separate required connection capability from incremental procured service. Dependable quantity, availability, location, energy headroom, opportunity cost and technology risk should be measured under common scenarios.

The board and system operator should see low-inertia, weak-grid, non-delivery, vendor-failure and market-reform cases. The preferred portfolio should remain secure and economically defensible across credible conditions.

3. SEPARATE STABILITY SERVICES

Inertia-like response, phase-jump power, fault current, voltage control, damping, system strength, island operation and restoration are distinct capabilities. A single grid-forming label should not substitute for product-specific performance.

The financing model should connect qualified performance to enforceable revenue and downside coverage. Accreditation, warranty, cyber, degradation and change-in-requirement risks should have accountable owners and contractual controls.

Implementation should translate the framework into planning, modelling, procurement, accreditation, operations and finance workstreams. Capital commitment should follow readiness gates and field evidence.

4. DEFINE THE COUNTERFACTUAL

The counterfactual may use synchronous generation, synchronous condensers, network reinforcement, operational constraints or curtailment. Value should be measured against the least-cost secure alternative.

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5. QUANTIFY INERTIA NEED

Frequency stability depends on credible loss, system inertia, primary response and load behaviour. Procurement should specify the response characteristic and operating envelope rather than an unsupported equivalent-inertia claim.

The valuation should separate required connection capability from incremental procured service. Dependable quantity, availability, location, energy headroom, opportunity cost and technology risk should be measured under common scenarios.

The board and system operator should see low-inertia, weak-grid, non-delivery, vendor-failure and market-reform cases. The preferred portfolio should remain secure and economically defensible across credible conditions.

Table 1. Stability-service evidence map

Service	System need	Qualification evidence	Commercial unit	Principal risk
Inertia-like response	Limit frequency change after disturbance	Validated RoCoF response across operating envelope	MW response characteristic and availability	Headroom and saturation
Phase-jump power	Maintain stability after angle disturbance	EMT model and site test	Qualified capability and availability	Control interaction
Fault-current contribution	Operate protection and support voltage recovery	Sequence, magnitude, duration and waveform tests	Event capability and availability	Current limit and protection mismatch
Voltage and system strength	Support weak-grid operation	Frequency-domain and EMT studies	Locational capability	Network change and model error
Restoration	Energise and sustain islands	Black-start and load-pickup test	Availability and successful event	Auxiliary power and coordination

Exact requirements remain system-specific and require validated studies and tests.

6. QUANTIFY ROCOF RESPONSE

Active power response to rate of change of frequency can reduce frequency excursions. The model should capture measurement, delay, saturation, energy headroom and interactions with other controls.

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7. QUANTIFY PHASE-JUMP RESPONSE

A phase-angle disturbance can demand rapid active-power response. Capability should be demonstrated across credible network strength and operating conditions.

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8. QUANTIFY FAULT-CURRENT CONTRIBUTION

Protection-quality current requires adequate magnitude, duration, sequence content and waveform properties. AEMO's current trial illustrates the need for evidence before this service is relied upon at scale.

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9. QUANTIFY VOLTAGE SUPPORT

Grid-forming controls can establish voltage and support weak-grid operation. Reactive current limits, transformer impedance, network strength and recovery after faults determine useful performance.

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Implementation should translate the framework into planning, modelling, procurement, accreditation, operations and finance workstreams. Capital commitment should follow readiness gates and field evidence.

10. QUANTIFY OSCILLATION DAMPING

Controls can damp or amplify network and converter interactions. Small-signal and electromagnetic-transient studies should cover multiple vendors, operating points and credible contingencies.

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11. DEFINE BLACK-START CAPABILITY

Restoration requires energisation, voltage build-up, load pickup, island control, synchronisation and resilience. Grid-forming capability is necessary for some designs but does not alone prove a complete restoration service.

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12. COMPARE SYNCHRONOUS CONDENSERS

Synchronous condensers provide physical inertia, fault current, reactive power and familiar protection behaviour. Their capex, losses, maintenance, construction time and locational value should be compared with inverter options.

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13. COMPARE GRID-FORMING BATTERIES

Batteries can combine grid-forming controls with active-power headroom and energy services. Duration, state of charge, degradation and energy-market opportunity cost affect stability availability.

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14. COMPARE GRID-FORMING WIND

Wind converters can provide grid-forming behaviour subject to turbine, converter and resource constraints. Commercial value depends on available power, control mode, headroom and warranty.

The valuation should separate required connection capability from incremental procured service. Dependable quantity, availability, location, energy headroom, opportunity cost and technology risk should be measured under common scenarios.

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15. COMPARE GRID-FORMING SOLAR

Solar and co-located storage can provide voltage-source behaviour when irradiance, headroom and DC-energy support are adequate. Night-time and low-resource operation require explicit design.

The financing model should connect qualified performance to enforceable revenue and downside coverage. Accreditation, warranty, cyber, degradation and change-in-requirement risks should have accountable owners and contractual controls.

Implementation should translate the framework into planning, modelling, procurement, accreditation, operations and finance workstreams. Capital commitment should follow readiness gates and field evidence.

16. COMPARE STATCOM AND POWER-ELECTRONIC DEVICES

Converter-based network devices can provide rapid voltage and stability support. Active-power services require an energy source or stored energy beyond reactive capability.

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17. COMPARE VSC-HVDC CAPABILITY

Voltage-source converters can support connected AC systems and restoration under defined configurations. Contracting should separate mandatory link performance from incremental system services.

The valuation should separate required connection capability from incremental procured service. Dependable quantity, availability, location, energy headroom, opportunity cost and technology risk should be measured under common scenarios.

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18. BUILD A HYBRID PORTFOLIO

Synchronous condensers, grid-forming batteries, network devices and retained generation can cover different services and locations. Portfolio design should manage common-mode and vendor-control risk.

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Implementation should translate the framework into planning, modelling, procurement, accreditation, operations and finance workstreams. Capital commitment should follow readiness gates and field evidence.

19. SPECIFY THE OPERATING ENVELOPE

Performance should be defined across power, reactive output, state of charge, voltage, frequency, system strength and temperature. A narrow test point can overstate dependable capability.

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20. SET MINIMUM TECHNICAL REQUIREMENTS

Connection requirements establish a baseline, while procured services may demand higher performance. Mandates and markets should avoid paying twice for the same obligation.

The valuation should separate required connection capability from incremental procured service. Dependable quantity, availability, location, energy headroom, opportunity cost and technology risk should be measured under common scenarios.

The board and system operator should see low-inertia, weak-grid, non-delivery, vendor-failure and market-reform cases. The preferred portfolio should remain secure and economically defensible across credible conditions.

Figure 1. Grid-forming stability value chain

Commercial value requires evidence from system need through qualified settlement.

21. DESIGN MODEL VALIDATION

RMS, positive-sequence, frequency-domain and electromagnetic-transient models serve different questions. Validation should reconcile simulation, hardware tests, site commissioning and field events.

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Implementation should translate the framework into planning, modelling, procurement, accreditation, operations and finance workstreams. Capital commitment should follow readiness gates and field evidence.

22. TEST INTEROPERABILITY

Multiple grid-forming and grid-following controls can interact. System studies should include vendor diversity, communication failure, protection, current limits and mode transitions.

The evidence package should reconcile system study, technical specification, validated model, site test, operating envelope and commercial obligation. Vendor claims and management estimates should remain distinguished from observed field performance.

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23. REDESIGN PROTECTION WHERE NEEDED

Lower or controlled fault current can challenge legacy relays. Protection changes, communications and fault-current products should be planned with the stability portfolio.

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24. MANAGE ENERGY HEADROOM

Active-power response requires upward or downward headroom and sufficient energy. Reservation reduces energy-market revenue and should be included in service cost.

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25. MODEL CURRENT SATURATION

Inverter current limits can force trade-offs between active and reactive response during faults. Control priorities should be specified and tested under credible disturbances.

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26. DEFINE RESPONSE DURATION

Sub-cycle response, seconds of inertia-like support and longer balancing energy address different system needs. Payment and testing should match the required duration.

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27. VALUE LOCATIONAL NEED

System strength and voltage stability are often local or regional. Procurement zones should follow electrical need and should be reviewed as the network changes.

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Implementation should translate the framework into planning, modelling, procurement, accreditation, operations and finance workstreams. Capital commitment should follow readiness gates and field evidence.

28. BUILD THE STABILITY REQUIREMENT FORECAST

Forecasts should combine generation retirements, inverter connections, network outages, demand, interconnectors and operating patterns. Uncertainty supports staged procurement and periodic recalibration.

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29. SET THE PROCUREMENT PRODUCT

The product should define capability, availability, location, tests, telemetry, dispatch, outages and penalties. Technology-neutral specifications improve competition where equivalence can be demonstrated.

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30. USE COMPETITIVE TENDERS

Tenders can reveal cost and bring forward new assets when requirements and contract tenure are clear. Bid assessment should compare service portfolios, dependencies and total system cost.

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Implementation should translate the framework into planning, modelling, procurement, accreditation, operations and finance workstreams. Capital commitment should follow readiness gates and field evidence.

Table 2. Technology and commercial comparison

Option	Stability capability	Energy source	Revenue profile	Key diligence
Synchronous condenser	Physical inertia, fault current and reactive support	Grid losses and auxiliaries	Long-term availability	Location, losses and outage
Grid-forming battery	Fast active and reactive response	Stored energy	Availability plus stacked markets	State of charge, degradation and controls
Grid-forming wind or solar	Converter response with resource constraints	Renewable resource and headroom	Energy plus incremental service	Warranty, headroom and night operation
Power-electronic network device	Voltage and control support	DC link or limited stored energy	Regulated or contracted availability	Active-power duration and interoperability
Hybrid portfolio	Complementary physical and inverter services	Multiple	Diversified contracted and market	Coordination and common-mode risk

Ratings are qualitative and project-specific; detailed engineering remains necessary.

31. USE ENDURING MARKETS

Regular markets can adapt volumes and prices as need changes. Participation rules, accreditation, clearing and performance monitoring require sufficient liquidity and standardisation.

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32. USE BILATERAL CONTRACTS SELECTIVELY

Bilateral procurement can support first-of-a-kind or location-specific solutions. Price discovery and change control need governance where competition is limited.

The valuation should separate required connection capability from incremental procured service. Dependable quantity, availability, location, energy headroom, opportunity cost and technology risk should be measured under common scenarios.

The board and system operator should see low-inertia, weak-grid, non-delivery, vendor-failure and market-reform cases. The preferred portfolio should remain secure and economically defensible across credible conditions.

33. CHOOSE AVAILABILITY PAYMENTS

Grid-forming services may be delivered continuously when an asset is connected, as NESO notes for grid-forming batteries. Availability payment can align with this service when performance is independently verified.

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Implementation should translate the framework into planning, modelling, procurement, accreditation, operations and finance workstreams. Capital commitment should follow readiness gates and field evidence.

34. DEFINE UTILISATION PAYMENTS

Some services require instruction or measurable activation. Utilisation payment should avoid duplicating availability revenue and should reflect incremental energy, degradation and opportunity cost.

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35. SET PERFORMANCE DEDUCTIONS

Deductions should reflect unavailable capability, failed tests, outages and non-delivery. Caps and cure rights should preserve proportionality while protecting system security.

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36. BUILD THE CAPEX MODEL

Capex includes converters, controls, storage, transformers, connection, protection, modelling, testing, cyber and owner cost. Incremental grid-forming cost should be separated from the host asset.

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37. BUILD THE OPERATING-COST MODEL

Software, maintenance, testing, monitoring, insurance, warranties, energy losses and specialist support create lifecycle cost. Vendor licence and upgrade terms should remain visible.

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38. MEASURE AVOIDED SYSTEM COST

Benefits can include reduced must-run generation, fewer synchronous condensers, lower curtailment, faster connections, improved restoration and deferred reinforcement. Each benefit needs an attributable counterfactual.

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39. CO-OPTIMISE ENERGY AND STABILITY

Energy, frequency, reserve, capacity and stability commitments share converter, current and energy limits. Dispatch and valuation should prevent double counting.

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40. STACK REVENUES WITH CONTROLS

Revenue stacking can improve financeability when service obligations are compatible. Contract priority, availability windows, dispatch rights and default consequences should be explicit.

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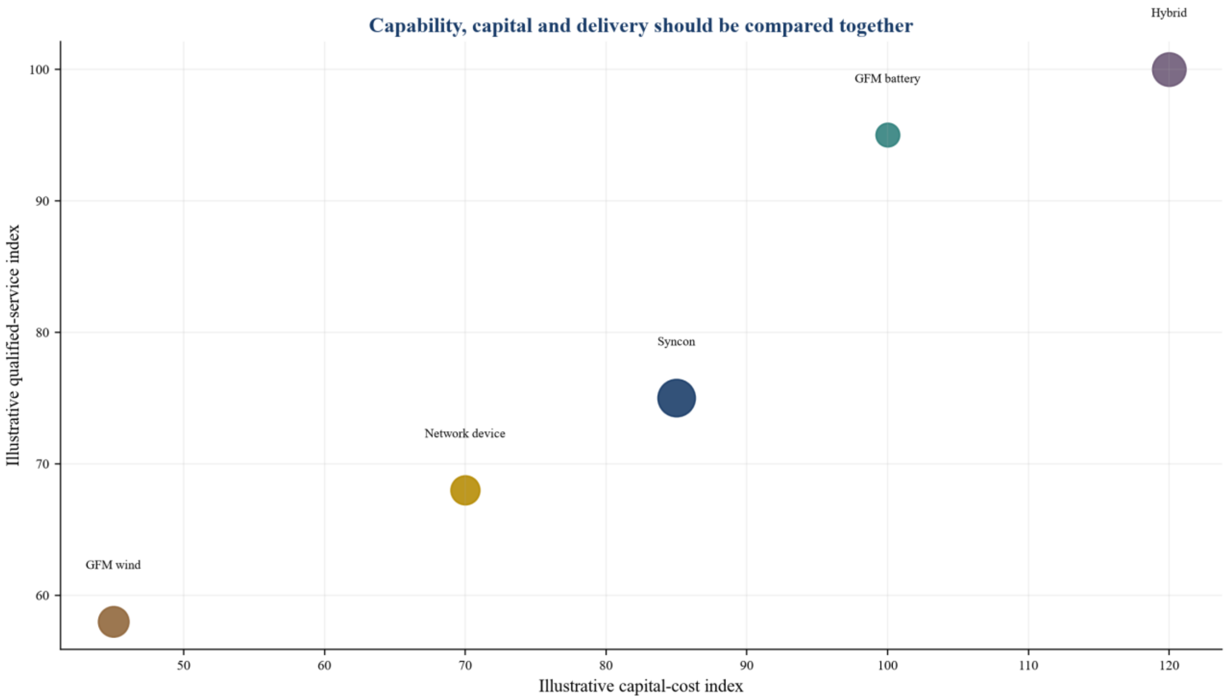

Figure 2. Hypothetical stability-portfolio comparison

Values are hypothetical management assumptions used solely to demonstrate trade-offs.

41. PRICE OPPORTUNITY COST

Providing headroom or maintaining state of charge may displace energy and ancillary-service earnings. Bids should include the foregone margin under expected and stressed conditions.

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42. MODEL BATTERY DEGRADATION

Stability services can cause cycling, high-power events and calendar exposure. Degradation should be linked to duty cycle, warranty and augmentation rather than assumed negligible.

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43. CREATE REVENUE CERTAINTY

Long-term tenders can support financing while short markets adapt to need. A blended structure can combine contracted base revenue with merchant upside and periodic volume review.

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44. SET CONTRACT TENOR

Tenor should reflect asset life, technology maturity, forecast confidence and financing need. Short contracts can underwrite little capex, while long contracts require reopeners and performance evolution.

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The board and system operator should see low-inertia, weak-grid, non-delivery, vendor-failure and market-reform cases. The preferred portfolio should remain secure and economically defensible across credible conditions.

45. ALLOCATE TECHNOLOGY RISK

The asset owner generally bears design and performance risk, while the system operator specifies need and tests. First-of-a-kind uncertainty may justify pilots, staged acceptance and shared learning.

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46. MANAGE VENDOR CONCENTRATION

Proprietary controls, models and service tools can create dependency. Source-code escrow, model access, data rights, spare capability and transition support should be considered.

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A financeable service has measurable need, technology-neutral requirements, credible tests and predictable settlement. Procurement should preserve competition while recognising locational and first-of-a-kind constraints.

47. PROTECT CYBERSECURITY

Grid-forming controls and remote access are critical operational systems. Security design should cover identity, firmware, logging, incident response, recovery and supply-chain assurance.

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48. ALIGN WARRANTIES AND MARKET OBLIGATIONS

OEM warranties may restrict control modes, current, cycling or field changes. Service contracts should not require operation that invalidates equipment support.

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Implementation should translate the framework into planning, modelling, procurement, accreditation, operations and finance workstreams. Capital commitment should follow readiness gates and field evidence.

49. USE GREAT BRITAIN EVIDENCE

NESO has procured stability through competitive tenders and moved toward enduring Stability Markets. Its requirements distinguish connection-code obligations from higher commercial performance.

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A financeable service has measurable need, technology-neutral requirements, credible tests and predictable settlement. Procurement should preserve competition while recognising locational and first-of-a-kind constraints.

50. USE AUSTRALIAN EVIDENCE

AEMO is developing methods to quantify grid-forming system-strength support and is procuring a fault-current trial. The evidence supports staged qualification and service-specific valuation.

The valuation should separate required connection capability from incremental procured service. Dependable quantity, availability, location, energy headroom, opportunity cost and technology risk should be measured under common scenarios.

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Table 3. Hypothetical revenue and debt sensitivity

Case	Contracted availability revenue	Merchant revenue share	Qualified availability	Minimum debt-service coverage	Decision implication
Base contract	70%	30%	96%	1.55x	Financeable with tested performance
Accreditation delay	45%	30%	80%	1.08x	Needs equity and delayed draw
Lower merchant prices	70%	15%	96%	1.37x	Contracted base protects coverage
Higher opportunity cost	70%	30%	90%	1.24x	Reprice headroom commitment
Blended long and short contracts	82%	18%	96%	1.68x	Stronger coverage with reopeners

All values are hypothetical management assumptions and do not represent an actual asset, market or forecast.

51. USE US RESEARCH EVIDENCE

DOE, NREL and the UNIFI consortium identify modelling, validation, standards, interoperability and commercialisation as central to deployment. Research maturity does not remove project-specific diligence.

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Implementation should translate the framework into planning, modelling, procurement, accreditation, operations and finance workstreams. Capital commitment should follow readiness gates and field evidence.

52. ADDRESS GCC CONDITIONS

Rapid renewable, battery and data-centre growth can create weak-grid and stability needs in specific areas. High temperature, network structure, operating practice and procurement rules should inform design.

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53. VALUE THE ASSET

Valuation should separate host energy cash flow, contracted stability revenue, merchant upside, incremental capex, degradation, technology risk and terminal obligations.

The valuation should separate required connection capability from incremental procured service. Dependable quantity, availability, location, energy headroom, opportunity cost and technology risk should be measured under common scenarios.

The board and system operator should see low-inertia, weak-grid, non-delivery, vendor-failure and market-reform cases. The preferred portfolio should remain secure and economically defensible across credible conditions.

54. STRUCTURE DEBT

Debt sizing should rely on enforceable availability revenue, tested performance, warranty alignment and downside coverage. Merchant stability prices and unaccredited services should receive conservative credit.

The financing model should connect qualified performance to enforceable revenue and downside coverage. Accreditation, warranty, cyber, degradation and change-in-requirement risks should have accountable owners and contractual controls.

Implementation should translate the framework into planning, modelling, procurement, accreditation, operations and finance workstreams. Capital commitment should follow readiness gates and field evidence.

55. STRUCTURE EQUITY

Equity absorbs development, accreditation, technology, merchant and residual-value risk. Return analysis should include opportunity cost and potential changes in mandatory requirements.

The evidence package should reconcile system study, technical specification, validated model, site test, operating envelope and commercial obligation. Vendor claims and management estimates should remain distinguished from observed field performance.

A financeable service has measurable need, technology-neutral requirements, credible tests and predictable settlement. Procurement should preserve competition while recognising locational and first-of-a-kind constraints.

56. BUILD THE RISK-ALLOCATION MATRIX

The matrix should assign specification, model, commissioning, availability, market, cyber, warranty and change-in-law risk to parties with control and balance-sheet capacity.

The valuation should separate required connection capability from incremental procured service. Dependable quantity, availability, location, energy headroom, opportunity cost and technology risk should be measured under common scenarios.

The board and system operator should see low-inertia, weak-grid, non-delivery, vendor-failure and market-reform cases. The preferred portfolio should remain secure and economically defensible across credible conditions.

57. CREATE THE CONTRACT SUITE

Connection agreements, stability contracts, energy-market terms, OEM warranties, LTSA, finance documents and data licences should align. Conflicting dispatch and performance obligations require resolution before close.

The financing model should connect qualified performance to enforceable revenue and downside coverage. Accreditation, warranty, cyber, degradation and change-in-requirement risks should have accountable owners and contractual controls.

Implementation should translate the framework into planning, modelling, procurement, accreditation, operations and finance workstreams. Capital commitment should follow readiness gates and field evidence.

58. CREATE THE LENDER-GRADE DATA ROOM

The data room should contain system need, studies, models, tests, contracts, warranties, capex, operating plan, cyber controls and financial cases. Each assumption needs a source and owner.

The evidence package should reconcile system study, technical specification, validated model, site test, operating envelope and commercial obligation. Vendor claims and management estimates should remain distinguished from observed field performance.

A financeable service has measurable need, technology-neutral requirements, credible tests and predictable settlement. Procurement should preserve competition while recognising locational and first-of-a-kind constraints.

59. RUN IMPLEMENTATION GOVERNANCE

System planning, operations, markets, engineering, procurement, cyber, legal and finance require shared decisions. A controlled baseline should govern service definition, tests, costs and change.

The valuation should separate required connection capability from incremental procured service. Dependable quantity, availability, location, energy headroom, opportunity cost and technology risk should be measured under common scenarios.

The board and system operator should see low-inertia, weak-grid, non-delivery, vendor-failure and market-reform cases. The preferred portfolio should remain secure and economically defensible across credible conditions.

60. ADOPT THE SCORECARD AND 90-DAY PLAN

The final record should state need, services, portfolio, procurement, economics, finance, risks and readiness gates. The first 90 days should close evidence gaps that could change investment.

The financing model should connect qualified performance to enforceable revenue and downside coverage. Accreditation, warranty, cyber, degradation and change-in-requirement risks should have accountable owners and contractual controls.

Implementation should translate the framework into planning, modelling, procurement, accreditation, operations and finance workstreams. Capital commitment should follow readiness gates and field evidence.

Table 4. Illustrative 90-day stability-investment programme

Period	Workstream	Core actions	Decision output	Accountable owner
Days 1-15	Need and services	Confirm system conditions, locations and product definitions	Approved need statement	System planner
Days 16-30	Models and options	Validate models, operating envelopes and technology portfolio	Feasible option set	Stability engineer
Days 31-45	Tests and accreditation	Define factory, site and field evidence	Qualification plan	System operator
Days 46-60	Economics and markets	Model capex, opportunity cost, degradation and revenue	Risk-adjusted value model	Commercial lead
Days 61-75	Contracts and finance	Align service, warranty, security, covenants and downside	Financeable term sheet	Corporate-finance adviser
Days 76-90	Approval and governance	Close risks, owners, KPIs and implementation gates	Authorised investment plan	Board and system operator

Timing is indicative and should be adapted to system and transaction governance.

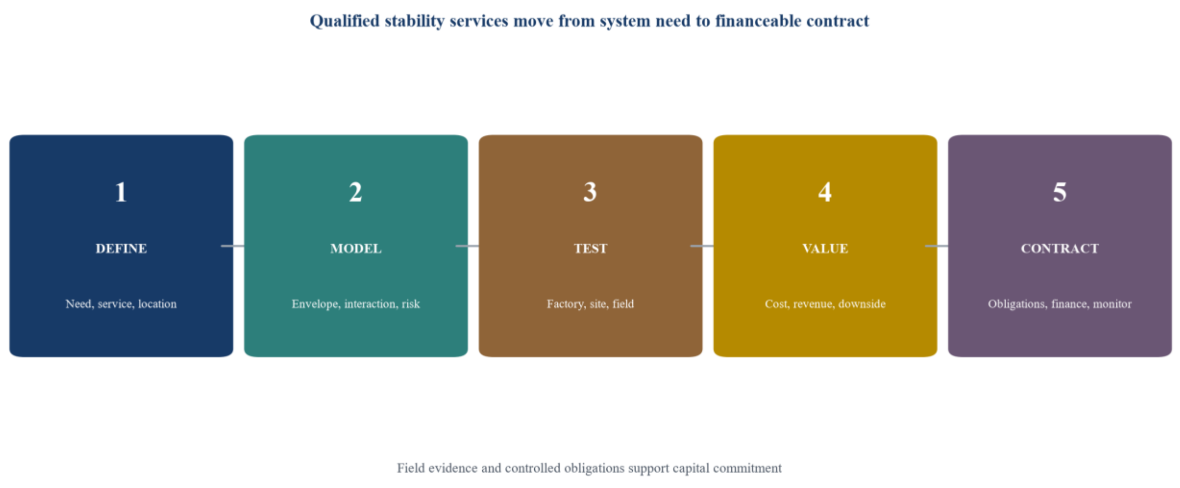

Figure 3. Five gates for grid-forming stability investment

Each gate requires documented evidence before the next capital commitment.

The framework converts an emerging control capability into measurable stability products and financeable obligations. It preserves traceability from system need through field evidence to revenue and downside protection.

Investment should proceed through staged qualification. Market design, warranties, cyber controls and operating experience should evolve with the technical evidence.

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