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Essential System Services Reform

Australian Market Design for Renewable-Dominated Grids

IN 1863, A SINGLE ARC LAMP ON OBSERVATORY Hill in Sydney, Australia, was lit to celebrate the marriage of Prince Albert of Wales and Princess Alexandra of Denmark. It was the first use of electricity anywhere in the country. It took 25 years until Australia established its first permanent 240-V electrical grid, in the small country town of Tamworth, New South Wales, in 1888. Two 18-kW, dc, coal-fired generators were supplied by the plentiful Gunnedah black coal basin nearby, and in the same year, on the other side of the continent, C.J. Otte supplied electricity to the Western Australian Government House with a small, 15-kW dynamo. By 1899, a full three-phase 240-V ac grid had been built on the east coast, establishing the foundation of the future power system across the country.

Then, as today, synchronous coal generators provided the majority of system services to maintain security and reliability. These services include the inertia to maintain stable frequency, system strength to maintain stable voltage waveforms, and energy reserves to maintain the balance of supply

By Niraj Lal, Toby Price, Leon Kwek, Christopher Wilson, Farhad Billimoria, Trent Morrow, Matt Garbutt, and Dean Sharafi

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and demand, even with changing demand and unexpected contingency events. Under this arrangement, the provision of these services has been conveniently tied to the supply of electrical energy, with synchronous generators providing support simply by being synchronized with the electric grid. For more than a century, as the electricity infrastructure and trading systems grew, no separate mechanisms were developed to manage these "ancillary services" to the power system. Instead, grid connection standards implicitly regulated an equitable division of costs among facilities in rough proportion to their size. Operators could recover these "costs of doing business" as part of their energy revenue.

The generation mix around the globe is rapidly changing. In Australia, this is happening at a world-leading rate, from having the third-most carbon-intensive electricity generation in the world in 2010 to regularly receiving more than one-third of its power from renewables. One in five households has distributed photovoltaic (PV) systems (at an average of 600 W installed per person, growing at 250 W per person per year)—the highest rate of PV uptake anywhere. At times, more than 100% maximum instantaneous solar and wind penetration is achieved in some regions. Solar and wind generators connect to the ac grid via power electronics-based inverters, which do not provide traditional system services by default. This means that while inverter-based resources (IBRs) can replace the energy previously provided by synchronous coal and gas generation, the provision of system services is not replaced in proportion.

The remaining fleet of synchronous resources faces a growing burden of providing system support services, such as frequency and voltage control and spinning reserves, while revenues fall with electricity prices and reduced market share and energy generation. Left unchecked, this dynamic undermines the implicit stability that has historically supported the electricity system. In Australia's National Electricity Market (NEM), this has manifested in a 10-fold increase during the past five years in the number of occasions the system operator had to intervene outside normal market operations to maintain security and reliability [Figure 1(a)]. There has been a significant reduction in frequency control performance since 2007 [Figure 1(b)] due to the reduced provision of primary frequency control. Uncertainty and variability in net demand from increasing renewable penetration are expected to triple in the NEM through the coming five years [Figure 1(c)], as solar and wind are projected to regularly meet 100% of demand [Figure 1(d)].

As the generation mix has changed, a handful of events has catalyzed political interest and action. After a September 2016 statewide blackout in South Australia, the Australian government commissioned the report, "Review of the Future Security of the National Electricity Market," by the country's chief scientist, Alan Finkel. This led to the establishment of an overarching Energy Security Board (ESB) to implement a "long-term, fit-for-purpose market framework" to deliver a "secure, reliable, and lower-emissions electricity system at least cost" in the NEM. A key workstream of this reform program is to establish new markets and mechanisms for providing system support services. These were traditionally called *ancillary services* but are increasingly being referred to as *essential system services* (*ESSs*) in recognition of their changing value in grids with low levels of synchronous generation. There is a growing consensus that without market reform, the market operator's remit to "keep the lights on" will likely be accompanied by increased curtailment of renewables and greater complexity of operation. This trend is already being observed. In 2019–2020, renewables were curtailed, on average, 7% of the year in the NEM, due to ancillary service requirements, and operator interventions were in place more than 10% of the year.

This article presents the Australian approach to the challenge of providing ESSs in grids with a very high penetration of renewables, outlining first the physical and regulatory contexts of two comparative systems and markets—the NEM (with five regions across Australia's eastern and southern states) and Western Australia's wholesale electricity market (WEM)—and their concurrent programs of reform. The changing nature of ESSs in markets, principles of market design, the spectrum of opportunity for procurement of various new services, and the integration and congruency challenges of holistically addressing those services are discussed. Finally, we present the Australian pathway of reform and a vision for the future of ESSs, with the hope that it may prove helpful for other countries on similar decarbonization pathways (see "Essential System Services").

Context

Australia's electricity networks span vast distances across a continent roughly the area of the United States, but with less than one-tenth of the population. The energy industry, historically government owned, was deregulated in the 1990s to disaggregate the vertically integrated state utilities and support competition. This enabled cross-border electricity trading between states and territories. The NEM was established in 1998. The isolated nature of the Western Australia and Northern Territory electricity systems was a significant barrier to the continent-wide integration of infrastructure and policy. It was only in 2006 that Western Australia's WEM was established, covering the southwest region of the state and serviced by the South West Interconnected System, spanning an area roughly the size of the United Kingdom. The interconnected NEM power system is serviced by approximately 40,000 km of transmission network. The islanded South West system integrates approximately 7,800 km of transmission network.

The Australian Energy Markets

Arising from a period of widescale deregulation, the NEM was established with a strong commitment to market efficiency through real-time, 5-min dispatch intervals; no day-ahead capacity markets; and very high market price caps (currently AUD$–1,000–15,000/MWh). In 2021, the settlement time will reduce from 30 to 5 min to align with dispatch, further sharpening market efficiency in the continuous matching of electricity supply and demand. Along with providing efficient incentives for participants, real-time price mechanisms facilitate the possibility of contracts for difference and hedging to support long-term agreements and risk mitigation. This is extensively conducted in the NEM through hedging and swap contracts. NEM markets for system services were set up with a similar commitment to real-time pricing (for those services that were remunerated). The NEM has six frequency response markets (frequency control ancillary services): contingency frequency response raise and lower services for 6-s, 60-s, and 5-min response times and a causer-pays primary frequency response service. There are nonmarket services for network support and control, such as transient oscillation control, and system restarts.

Reflective of its smaller and more concentrated nature, the WEM balances market efficiency with greater structured procurement, including a capacity market (the reserve capacity mechanism), a day-ahead energy market, the short-term energy market, and a real-time energy market with 30-min dispatching (with lower market price caps, currently AUD$382–1,000/MWh). For system services, the WEM prioritizes structured procurement via a regulation market (load-following ancillary services) and other system services procured under contract, including frequency response (spinning reserve) and, like the NEM, similar nonmarket services for network control and system restarts.

The Post-2025 Program

In 2019, Australian federal and state and territory governments asked the ESB to advise on a long-term, fit-for-purpose market design for the NEM that could be applied starting in 2025 in response to the profound energy transformation occurring across the country. The initiative has

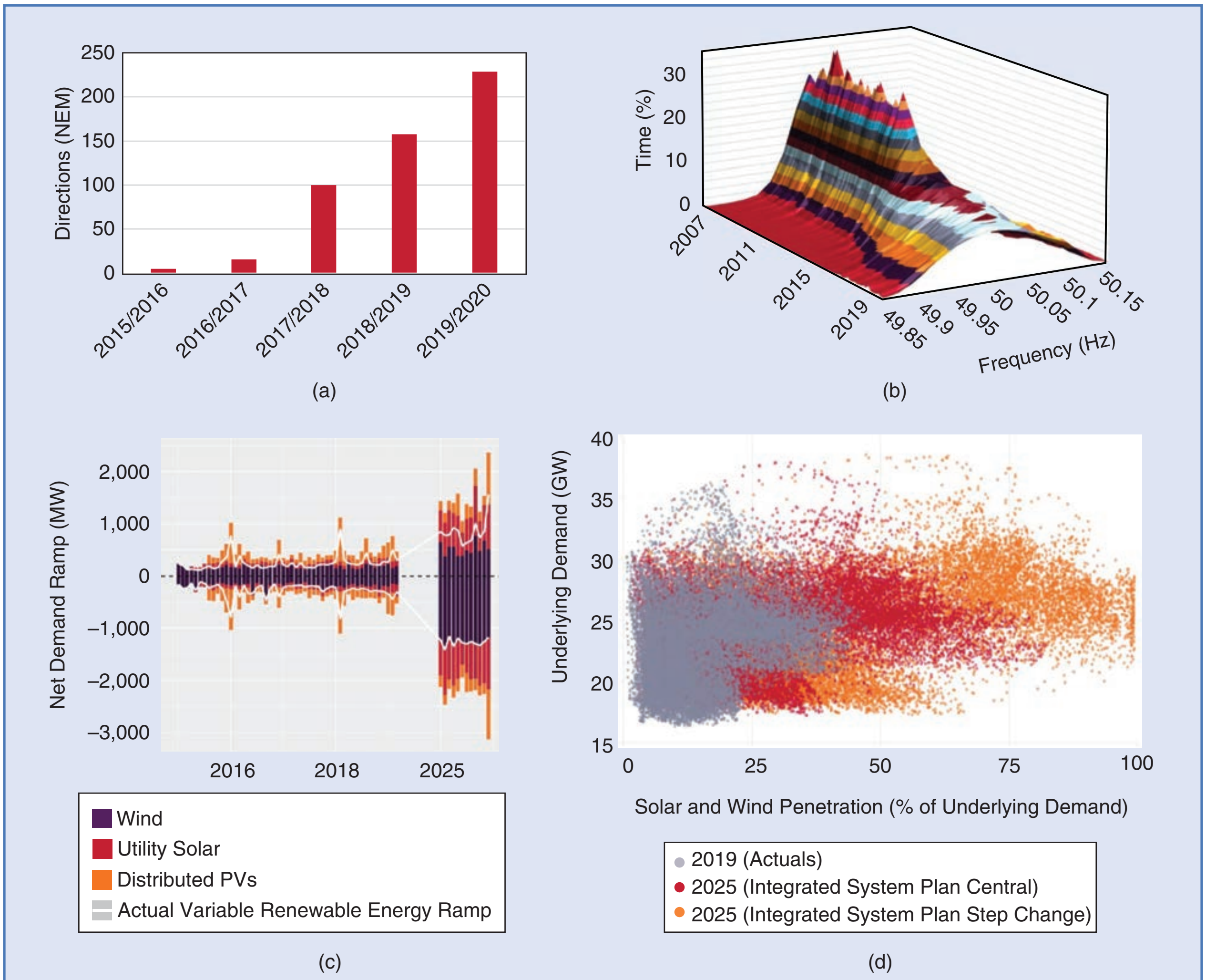

figure 1. (a) Operator directions in the NEM, showing that interventions are increasing. (b) A frequency distribution plot in the NEM to 2019, demonstrating frequency control declined as a result of reduced primary frequency control. (c) A butterfly plot of 5-min net demand ramps, historical and forecast (maximum 5-min ramp in 2025 > 1.5 GW, maximum 1-h ramp in 2025 > 6 GW), which shows that uncertainty is growing. (d) The forecast penetration of solar and wind as a percentage of underlying demand. They may meet 100% of Australia's power demand by 2025. [Source: Adapted with permission from Australian Energy Market Operator (AEMO) Renewable Integration Study, Stage 1, 2020, and AEMO Frequency and Time Monitoring Report, first quarter 2020.]

become known as the Post-2025 Market Design Project, focusing on the entire energy supply chain—from the wholesale energy market through transmission and distribution to behind-the-meter distributed energy resources. The ESB, resourced collaboratively by the Australian Energy Market Commission, Australian Energy Market Operator (AEMO) and Australian Energy Regulator, working with ESB staff, set up four workstreams to consider the issues and develop potential solutions, as in the following:

- ✔ resource adequacy through the transition
- ✔ ESSs and scheduling and ahead mechanisms
- ✔ demand-side participation
- ✔ access and transmission.

Industry and customer stakeholders have been extensively involved and consulted, and there is broad recognition that the individual workstreams are intrinsically interrelated and must be considered together for a coherent whole design. There is a wide range of views about each of the workstreams, but responses indicate that the reform of system service provision is the highest priority and most urgent. Such reform needs to occur before 2025 to address tighter frequency control, structured procurement for synchronous generation commitment (for system strength and inertia) potentially combined with an ahead mechanism to support scheduling, and the exploration of possible operating reserve and inertia spot markets.

The Western Australia 2022 Program

In 2019, the Western Australia government formed the energy transformation task force and charged it with making clear policy decisions through robust consultation to ensure coherent reform for a full overhaul of the market regulatory framework, to go live in 2022. The task force has an explicit focus on the assessment and redevelopment of a new ESS framework.

Principles for Procurement and Market Design

For the impending challenge of redesigning procurement frameworks for ESSs, it helps to first consider broad principles of market design alongside the intrinsic valuation of power system security. The objective of procurement frameworks should be to create efficient and effective economic mechanisms to deliver operational requirements. The operational requirements of power system security must focus on the management of the underlying physics of an electrical network, with sufficient redundancy and robustness in the face of uncertainty and risk.

Essential System Services

All power systems require a suite of system services, traditionally known as ancillary services but increasingly referred to as *essential system services* (*ESSs*), which are necessary for secure and reliable operation. Services can often perform the same function but vary in their names, implementation, competitiveness, and remuneration mechanisms across jurisdictions. Figure S1 and Table S1 summarize the various services that exist in Australia, with their wholesale electricity market and NEM implementations.

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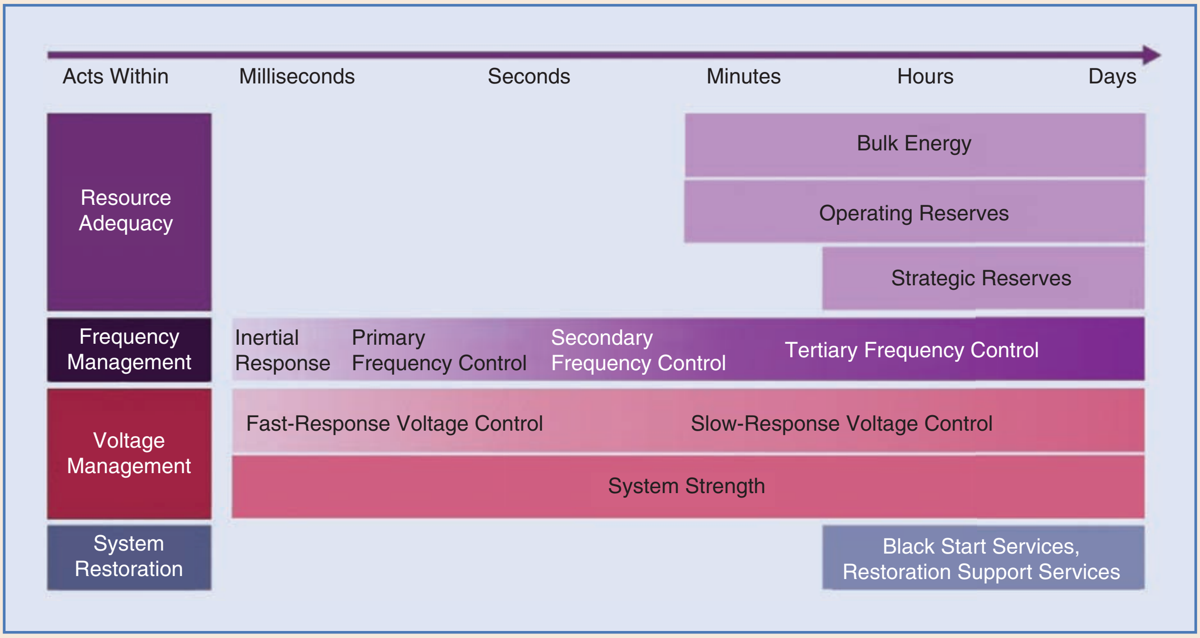

figure S1. Operation timescales and the categorization of certain ESSs. (Source: Australian Energy Market Operator Power System Requirements, 2020; used with permission.)

Market Design for ESSs

A recent report compiled by FTI Consulting for the ESB highlighted seven principles important to the design of effective procurement frameworks for ESSs (see Figure 2). These principles are fundamental in framing the design problem from a regulatory and market perspective. Alongside these principles is the recognition that any design process necessarily involves a compromise between elements to achieve an overall workable design. In particular, there is a natural tension between the idealized theoretical design of markets with assumptions of economically rational behavior and the physical reality of operation, which is complex, uncertain,

Essential System Services *(Continued)*

table S1. A summary of various ESSs in Australia and their implementations within the WEM and NEM.

Service	Description	NEM Equivalent	WEM Equivalent
Bulk energy	Power to meet demand (scheduled and unscheduled)	• Energy (5-m dispatch, 5-m settlement from 2021)	• Energy (30-min dispatch and settlement); moving to 5-min dispatch in 2022 and 5-min settlement in 2025
Regulation	Maintains frequency within the normal operating band, operating within seconds	• Regulation raise/lower	• Load-following ancillary service up/down market • Moving to co-optimized Regulation Service, 2022
Primary frequency response	Arrests and stabilizes frequency following an event that results in a sudden mismatch of demand and supply, operating within milliseconds	• Droop response and fast raise/lower (6 s) • Possible new fast-frequency response (<2 s) from 2022	• Droop response and spinning reserve • Moving to co-optimized contingency reserve real-time market in 2022
Secondary frequency response	Restores frequency to its normal operating band after an event, operating within seconds to minutes	• Slow raise/lower (60 s) and delayed raise/lower (5 m) • Possible combination of 6- and 60-s services from 2022	• Spinning reserve • Moving to co-optimized contingency reserve real-time market in 2022
Tertiary frequency response	Reschedules/unloads facilities that provide primary and secondary frequency response so that they are available to respond to new events	• Energy redispatch	• Energy redispatch and redispatch of government-owned energy assets • Moving to co-optimized contingency reserve real-time market in 2022
Inertia service	Physical inertia that reduces the rate of change of frequency (ROCOF) following a contingency event	• No existing service • Possible scheduling of synchronous resources through a unit commitment for security mechanism or synchronous services market • Possible future inertia spot market	• No existing service • Moving to a co-optimized ROCOF control service in 2022
Operating reserve	Balances the supply and demand of energy across a minute-to-hours horizon	• Possible new market for operating reserves and ramping availability from 2025	• No explicit service; managed by energy redispatch and self-commitment
System restart	Facility capability to restart a black system and to assist with reconstruction following a black system event	• System restart ancillary service	• System restart service • Provided as part of nonco-optimized essential systems services framework from 2022
Voltage support and system strength (discussed further in the text)	Stabilizes voltage in a location of a network	• Network support and control ancillary service • Possible scheduling of synchronous resources through a unit commitment for security mechanism or synchronous services market	• Network control service • Provided as part of nonco-optimized essential systems services framework from 2022
Capacity	Procurement of capacity (generation and demand-side management) to meet forecast peak demand on the yearly time horizon	• No explicit service except for reliability and emergency reserve trader function • Possible new market for operating reserves or ramping availability in the NEM	• Reserve capacity mechanism • Annually administered price mechanism for certified capacity

WEM: wholesale electricity market.

nonlinear, and failure prone. There are additional asymmetric costs of market efficiency and market failure. While designers may prefer complex, multilayered, and co-optimized markets, operators may desire conservative, expensive, and unoptimized solutions. Striking the right balance to develop efficient and robust economic solutions to technical challenges requires the rigorous and combined efforts of power system engineers and economists.

Policy makers have a variety of regulatory and market instruments available to them. Options include technical standards and licenses, operational directions and interventions, regulatory delegations (including network monopolies and other central agencies), individual contracts with providers, ESS auctions, and tenders and short-term spot markets. Regulated approaches can provide greater comfort in the technical provision, especially given complex security services (such as system strength). While market approaches provide the opportunity for greater efficiency, there is potential for financial innovation to outcompete technological innovation. Market solutions can also optimize against the technical specification of a service, creating a lack of resilience.

A case in point is the design of contingency frequency response markets in the NEM, where technical specifications guided by normal operating frequency bounds resulted in wide frequency governor dead bands. In the face of uncertainty, this led to poor frequency performance and system fragility, only recently corrected by the reimplementation of stringent mandatory primary frequency response requirements. By contrast, the WEM complements a spot market for regulation services with an obligatory droop requirement, which has led to improvements in frequency management.

Tradeoffs abound for investment considerations, given commercial risk appetite. While spot markets, if appropriately designed, can provide efficient scarcity price signals, investment decisions on long-duration assets are typically made in the context of longer-term revenue and cash flow visibility. In the design of ESSs, it is relevant to consider the following:

- ✔ Framework flexibility is needed in managing current principles of provision (such as from synchronous generators and synchronous condensers) while accommodating future innovation (inverters providing "synthetic inertia" and grid-forming capability).
- ✔ The locational nature of service provision must be taken into account. For example, fault current and system strength are highly locational relative to inertial frequency response, which is system wide.
- ✔ The complexity of co-optimization in the context of uncertainty needs to be understood.

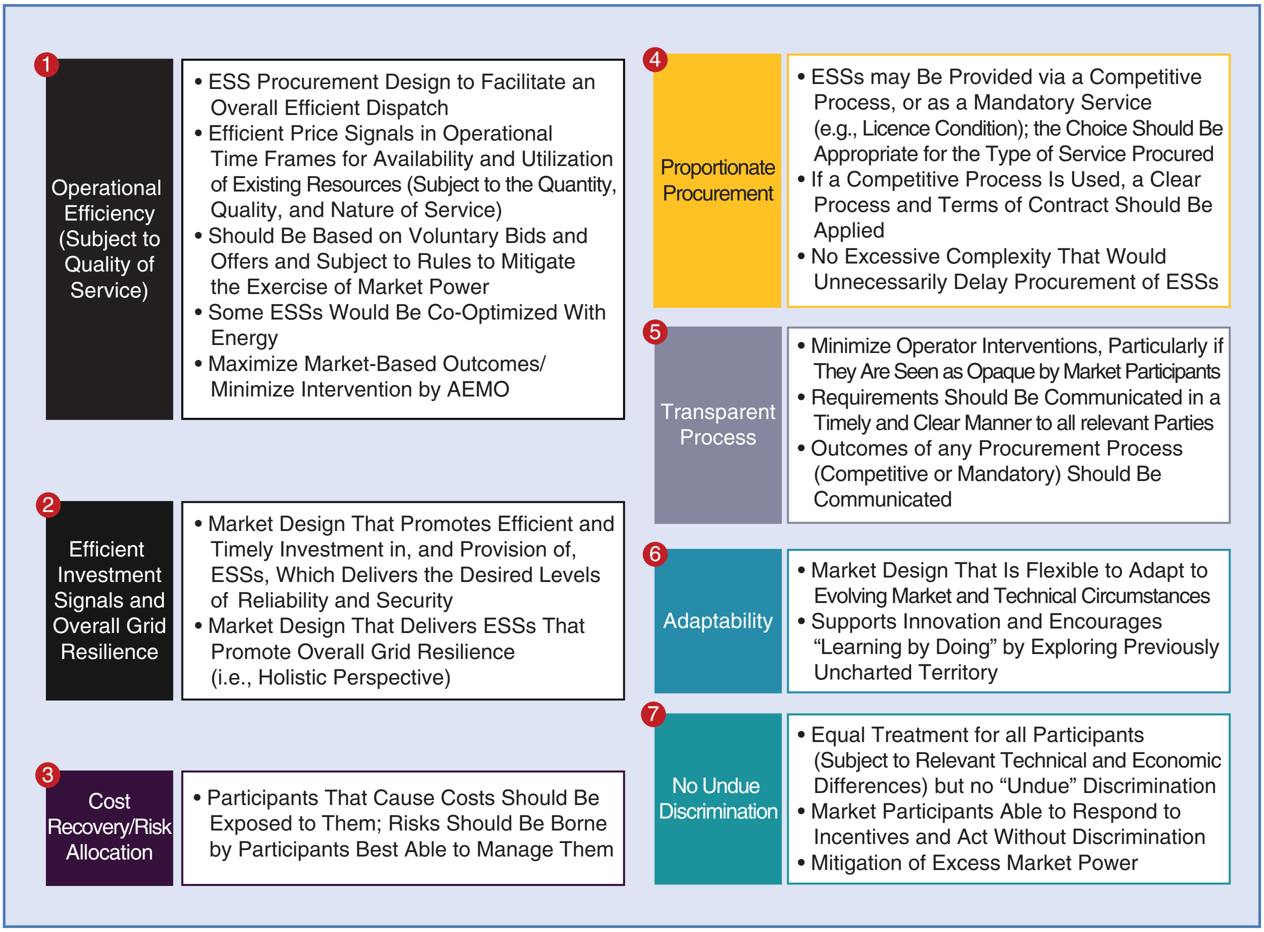

figure 2. Principles of market design for ESSs. (Source: Adapted from the 2020 FTI Consulting Report to the ESB.)

- ✔ The challenge of valuing ESSs and the consequent difficulty of allowing procurement quantities beyond minimum levels to provide additional robustness and resilience will have to be met.
- ✔ The tradeoffs of operational complexity and market sophistication are important: complex markets create more points of failure.

During this period of rapid change, adaptive governance and procurement approaches are helpful. For ESSs, a flexible contractual framework would support operators to mitigate fast-evolving system risks, potentially accompanied by an adaptive regulatory change process that supports participant decision making.

Other International Approaches

While Australia's power system finds itself in uncharted territory with the penetration of variable renewable energy (VRE) and distributed solar, there are pioneering advances in market design for system services being explored across the world. This section reviews some key developments in comparable systems in the United Kingdom and the United States. In the United Kingdom, electricity system operation and the procurement of system services are delegated to the National Grid Electricity System Operator (NGESO), a subsidiary of the for-profit, private National Grid UK, which also owns and operates the transmission network. This framework provides a comparatively high degree of flexibility in the approach to procurement, with the NGESO utilizing competitive tenders of varying duration and structure in procuring services.

Standardized system-wide frequency and reserve products have contributed to shorter-term, frequent contract auctions, while more individually tailored and longer-term contracts were used to secure requisite investment for services with locational requirements and smaller provider pools. A recent initiative is the stability pathfinder tender, which procures a combination of services, including fault levels and inertia. Reactive power, traditionally an obligatory service, is also increasingly obtained through competitive tender approaches.

The NGESO is subject to a unique financial incentive scheme with payments based on performance evaluated by the regulator Office of Gas and Electricity Markets through an annual scorecard assessment. The discretion provided to the Office of Gas and Electricity Markets has been particularly useful in a rapidly changing environment, providing flexibility to respond to evolving technical scarcities and to modify and adapt procurement on an ongoing basis. This has also left the NGESO to deal with the issue of supporting investment by initially procuring newer services via longer-term contracts (to underpin investment), moving toward shorter-term auctions as business models become established.

By contrast, regulatory regimes in the United States and Ontario, Canada, have delegated system services to independent system operators (ISOs), which are not-for-profit entities with relatively less discretion to make decisions about ESS procurement. Procurement approaches tend to be codified in regulations, with changes subject to detailed review, stakeholder engagement, market participant votes, and, in some cases, approval of the U.S. Federal Energy Regulatory Commission. Given the need for transparency, ESSs have tended to be obtained via either short-term spot markets (predominantly frequency and reserve products) or mandatory provision. Spot markets have provided transparency and price visibility, enabling financial markets to develop around services underpinning investment.

However, given regulatory structures, incentive mechanisms for U.S. ISOs have proven to be challenging due to narrow incentive thresholds and forecasted delivery targets. In practice, these obstacles, combined with the regulatory processes, have limited the ability of ISOs to develop new products expediently. While many jurisdictions are adapting technical standards for inverters, there has been less emphasis in international jurisdictions on service procurement concerning system strength. The meshed nature of North American grids means system strength and the provision of fault current is of less concern from a technical perspective, and as a result, it is not explicitly defined as a system service for many regions, including New York ISO, Midcontinent ISO, and Ontario Independent Electricity System Operator.

Australian market designs have strong parallels with security-constrained gross power pool models common across markets in North America, apart from procedures for centralized unit commitment and two-settlement market clearings, which are not part of the NEM. However, given the extent of VRE penetration and the unique operational phenomena observed in Australian grids, the networks will likely have to forge novel approaches to procure these complex and multifaceted technical services. These approaches will also have to work alongside the broader challenge of a 5-min spot market framework without ahead and capacity markets.

Spectrum of Opportunity

Procurement Frameworks

Having identified a case for change and reviewed the principles of market design for ESSs, the challenge progresses to canvasing the "spectrum of opportunity" in resolving the missing services that arise as IBRs replace synchronous generators. There are many options to procure ESSs, but frameworks can be broadly categorized along an axis of market efficiency, as follows (see Figure 3):

1) *market operator interventions and the self-provision of services* without market-based remuneration (currently used for system strength, inertia, and operating reserves)
2) *structured procurement* via nonspot market mechanisms (currently used for emergency out-of-market reserves, voltage control, and network support/control)
3) *spot market-based* provision of services (currently employed for energy, regulation, and contingency frequency control).

Although there is a preference for real-time signaling, not all system services are suited for market-based procurement. The market design assessment for each service includes

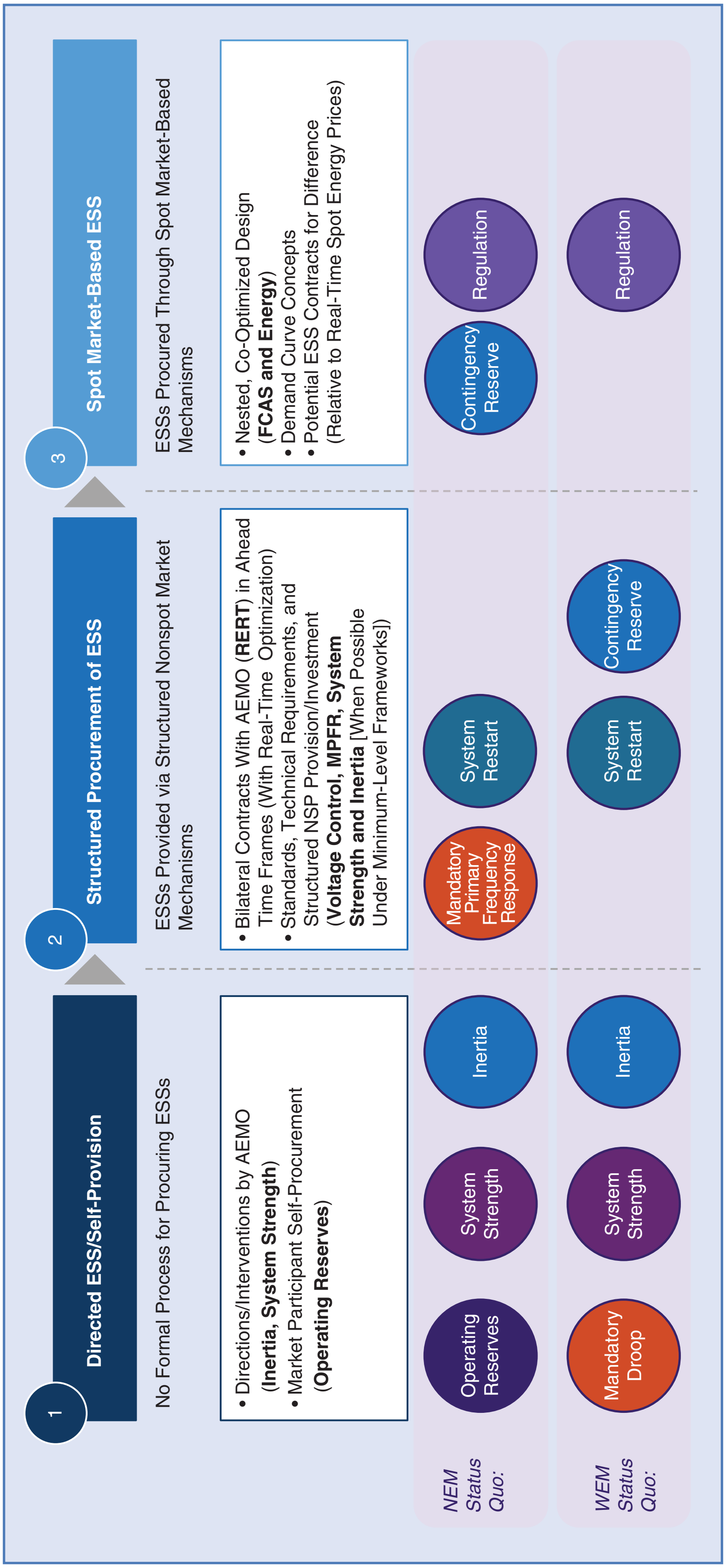

figure 3. The spectrum of opportunity for ESS in the NEM and the WEM, indicating the status of current ESS market mechanisms, with an implicit axis of "greater market efficiency" toward the right. RERT: reliability and emergency reserve trader; NSP: network service provider; MPFR: mandatory primary frequency response; FCAS: frequency control ancillary services. (Source: Adapted from the 2020 FTI Consulting Report to the ESB.)

factors such as the measurability/fungibility of a product, the competition and co-optimization scope, complexity and simplicity, and locationality. This section introduces various options for market designs for each ESS stream under consideration, namely, operating reserves, frequency management, synchronous services, and inertia.

Operating Reserves

Energy markets must maintain supply and demand in instantaneous balance with prices set through a spot market. Market participants often have separate contracts across their portfolios to manage the risk around the energy spot price. The market operator, however, typically does not see these contracts. Instead, it must rely on faith that participants will display economically rational behavior and take advantage of high prices at times of supply scarcity. This trust is increasingly being tested by the changing nature of generation, with the "invisibility" of behind-the-meter distributed PV generation and the variability and uncertainty of large-scale wind and solar [Figure 4(a)]. The likely result is the system operator managing the system more conservatively, leading to greater VRE curtailment as risk becomes excessively high. The possible design of an operating reserve or the ramping availability service that is under current consideration may help address this challenge in the NEM.

There are several market options to procure operating reserves, including 1) obtaining firm availability in the dispatch interval 30 min ahead [Figure 4(c)], 2) holding a certain level of spinning callable reserve to be triggered to dispatch as energy, and 3) securing operating reserve headroom in the coming 5 min to dispatch as energy. With each option, the use of a demand curve constructed from historical forecast errors may inform the efficient level of reserve and firm the availability to acquire it [Figure 4(b)]. These options are being developed for possible NEM implementation in the next two years. Decisions on a final preferable new market will be based on tradeoffs between operator confidence, market efficiencies, and potential adverse impacts on the energy spot market.

Frequency Management

This class of services encompasses the need to schedule reserves of energy capacity that respond to unexpected changes in the load–generation balance (in addition to synchronous inertia, which will be discussed). There are two broad categories to consider:

1) *regulation reserves*: responding to ongoing and smaller imbalances, primarily due to variations in demand and generation from intermittent sources
2) *contingency reserves*: responding to sudden and very large disturbances, such as the loss of a major generation unit.

Under assumptions of reasonable connectivity and system strength, frequency management can be sourced from any network location. Much like the case of standard energy supply, this global pool of resources lends itself to procurement via a centralized, co-optimized spot market (energy dispatch can be considered a very slow class of frequency control). However, the desire for a universal and highly optimized market design must be carefully weighed against the complexities and irregularities this can create in a physical system.

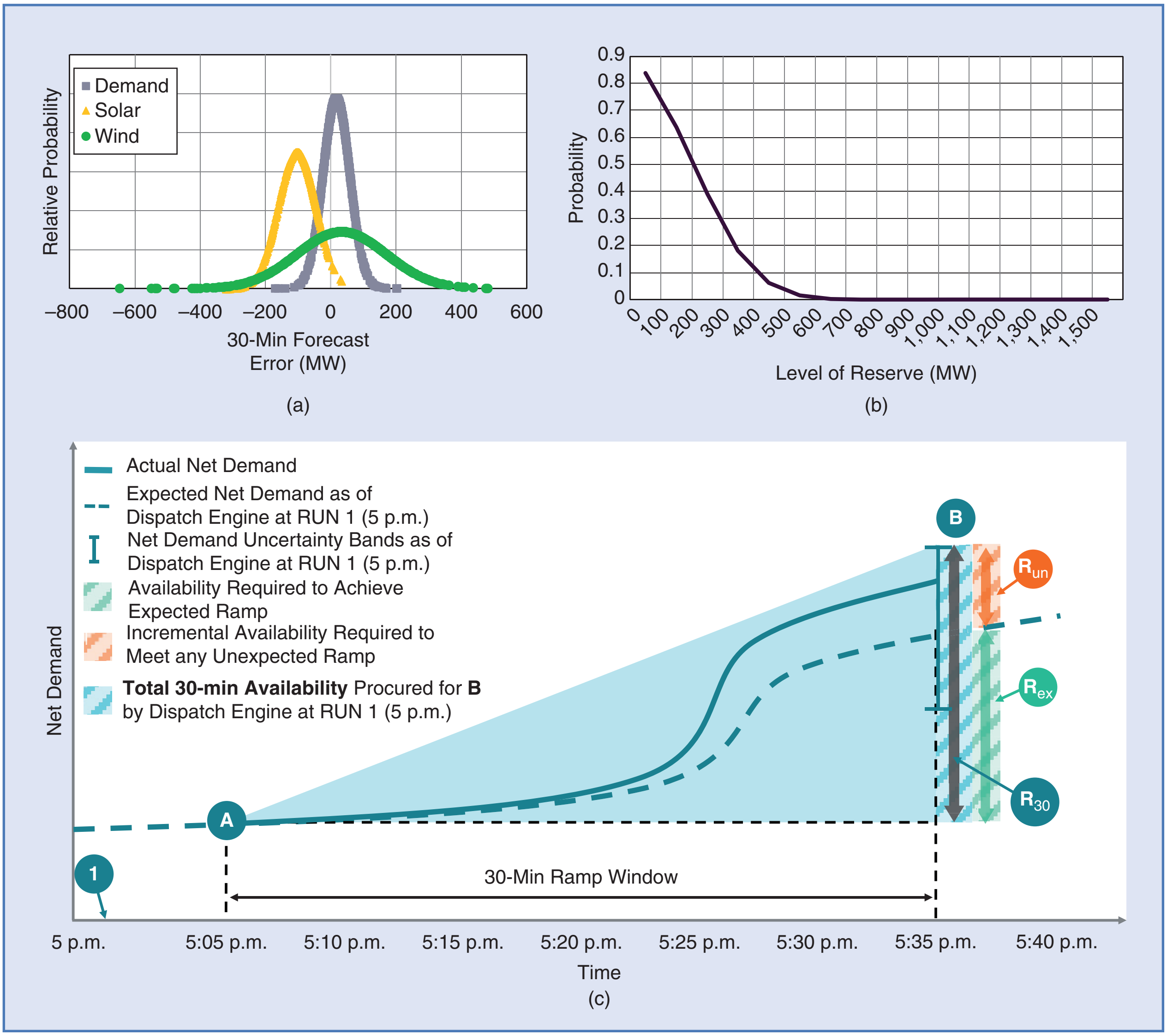

figure 4. (a) The probability distribution of 30-min forecast errors for South Australia, summer 2019–2020, 2–6 p.m. (b) The probability that the 30-min forecast error is higher than any particular reserve level, which may inform an efficient reserve demand curve. (c) An example 30-min ramping "availability" product to address unexpected ramps across a 30-min time horizon. (Source: adapted from Brattle Consulting Report to AEMO, 2020.)

Figure 5 illustrates this consideration through a system operations abstraction of frequency management for contingency response services. In this view, the physical response of the entire generation fleet is aggregated and considered according to different performance requirements for the deployment and sustainability of power output into inertial, primary, secondary, and tertiary response. These distinctions are not fundamental but reflect control structures formed around physical properties and useful tradeoffs optimized in the allocation of power system resources.

Three critical security limits must be managed following a generation contingency (Table 1). Exact operating limits vary due to jurisdictional norms and reliability standards. However, these standards ultimately reflect the physical tolerances of an electrical plant. Inverter-based facilities, for example, generally have a higher tolerance to the rate of change of frequency (ROCOF) than rotating machinery. The ideal procurement model also incorporates incentives to reward tolerances. It reduces overall service requirements in addition to the procurement of suppliers. The NEM reform program is reviewing the feasibility of including additional fast-frequency contingency response (with reaction times shorter than 1 s) alongside mechanisms to support the efficient provision of (currently mandated) primary frequency response within the normal operating frequency band.

Inertia and System Strength

The procurement of synchronous services, namely, system strength and inertia, is particularly complex to transition from the traditional provision as a by-product of generation from synchronous generators. Options to replace this include the network operator building additional synchronous resources (for example, synchronous condensers with flywheels) and creating incentives for the provision of services through advanced power electronics (see "Australia's Big Battery"). There is an opportunity to procure inertia as a separate service, an option being implemented as part of the market reform in Western Australia through the ROCOF Control Service (see "Western Australia Rate of Change of Frequency Control Service").

System strength is an emerging concept broadly defined as the strength of a power system's voltage waveform. It is closely associated with inertia and fault current levels but does not solely consist of either. The ability to maintain a stable waveform is decreasing as IBRs connect to the system. The appropriate procurement mix for system strength may incorporate elements of various frameworks, with challenges for

table 1. Frequency limits to be managed following a generation contingency.

Limit	Description	Management
ROCOF	Maximum ROCOF in the first 1–2 s	Synchronous inertia and potentially "virtual inertia" from power electronics resources
Nadir	Absolute minimum frequency, typically reached around 6 s	Primary response of local generation control systems
Settling frequency	A "quasi-steady-state" frequency maintained while the system is restored to normal operating conditions	Secondary response directed by central generation control schemes

Australia's Big Battery

Following an 8-h statewide system blackout in South Australia in 2016, there was an intense period of government effort to ensure ongoing security for the approaching summer. Following a series of tweets between billionaires Elon Musk, chief executive officer of Tesla, and Mike Cannon-Brooks, chief executive of Atlassian, Tesla offered to build a 100-MW battery within 100 days of signing a contract or the battery would be "free." The South Australian government accepted the offer, subsidizing the initial development cost, expediting planning approvals, and negotiating an ongoing contract for the government to use the battery as an emergency reserve, which French developer Neoen would own. In 2017, the Hornsdale Power Reserve (HPR) was commissioned and connected to the grid, becoming the world's largest grid-scale battery, at 100 MW/129 MWh. The battery has been a resounding commercial success for South Australia customers and Neoen, delivering an estimated AUD$150 million in electricity cost savings to consumers in its first two years—AUD$116 million alone from frequency control costs in a two-week period in 2019, when South Australia was islanded from the rest of the grid.

The facility has demonstrated the potential of future ESS provision through inverter-connected equipment. The precision with which batteries follow automatic generator control set points while providing frequency control ancillary services as compared to a traditional thermal generator is striking (see Figure S2). At present, there is no extra remuneration for facilities that exceed the market ancillary service specification in the NEM. The performance of the battery (typically subsecond) has provided an impetus for the consideration of a fast-frequency response service, which is critical for maintaining security in the power system as inertia levels continue to decrease.

In December 2019, HPR was expanded by 50 MW/64.5 MWh (to 150 MW/193.5 MWh) with grants and financial support from multiple state and federal initiatives.

policy and regulation in appropriately allocating risks, costs, and benefits to customers, system operators, and network service providers.

A possible approach to procurement is to mandate threshold levels at all nodes across the network (via the specification of a minimum fault current level and short circuit current ratios) and allocate maintaining these levels to the transmission network service provider. As regulated entities, there is some incentive for providers to procure capital equipment to include in their regulated asset base. This may discourage the provision of synchronous services from smaller, nimbler, and more efficient technologies in the medium to long term. Australia's NEM experienced the "gold plating" of its network during the first decade of the millennium, with overinvestment in capital infrastructure in network providers' regulated asset bases. There is caution toward enacting regulation to revisit this through the overprocurement of system strength and synchronous

The upgrade is being delivered by Neoen in collaboration with Tesla, the AEMO, and the network service provider ElectraNet to demonstrate the capability of inverter-connected generation to deliver a service equivalent to one from a synchronously connected generator, which is typically achieved by modeling and implementing the theoretical response of a synchronously connected generator at high speed to govern the response of the facility to power system conditions. Tesla expects to show a system functional inertial capability equivalent to 3,000 MW. Such a capacity has not been demonstrated at grid scale but may represent a pathway to displacing synchronous generation for the provision of these services in the future.

HPR enjoyed first-mover advantages as the initial grid-scale connected battery in Australia. At the time, it was expected to prevent support for additional (*n*th of a kind) battery investment, under the assumption that it had taken the majority of the available funding. This has not been the case. At the time of writing, 209 MW of grid-scale battery storage are operating. A further 900 MW are expected for delivery by 2024, and 7 GW are in the proposal phase in addition to several gigawatts of pumped-hydro investments slated across the country.

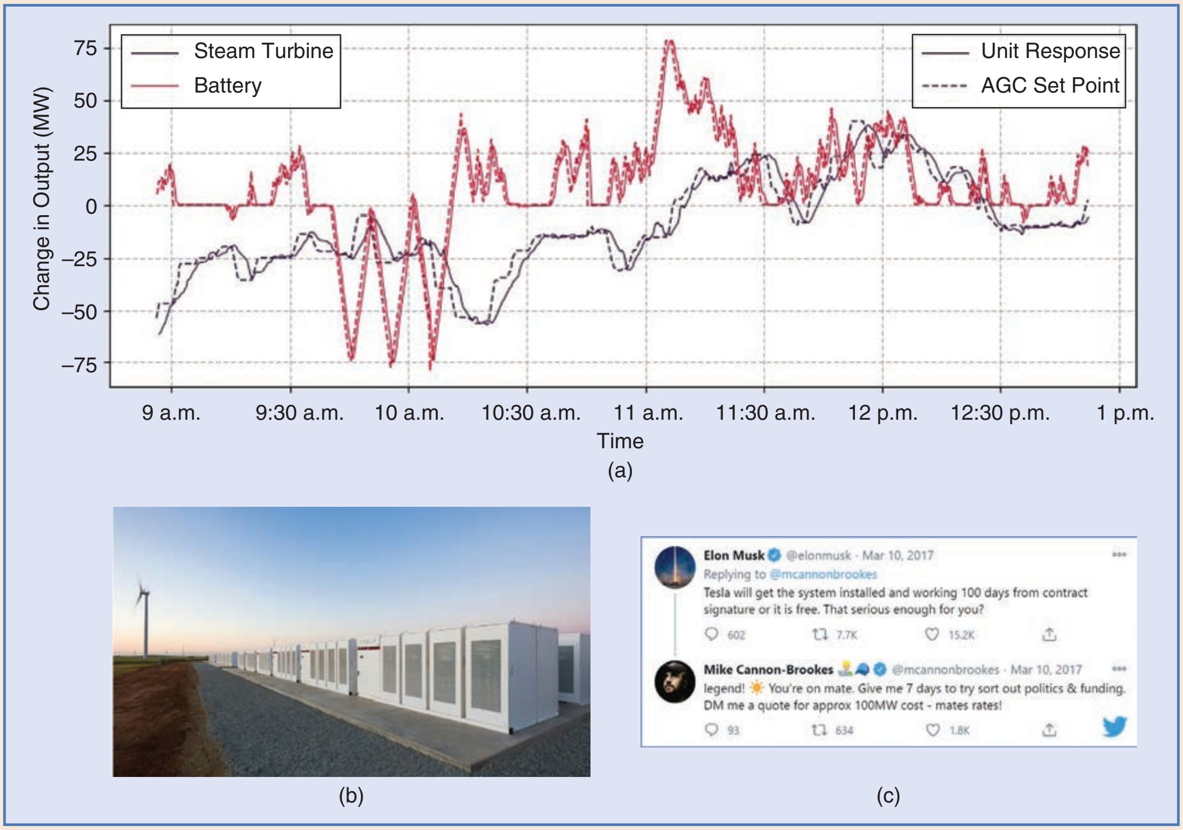

figure S2. (a) A comparison of the regulation frequency response capabilities of HPR compared to a steam turbine. (b) HPR. (c) An extract of the Twitter conversation between Mike Cannon-Brookes and Elon Musk that formed the genesis of the battery. AGC: automatic generation control. (Source: Twitter.)

services. The challenge will be in allocating risk and cost appropriately while enabling operator confidence and flexibility within the system to adapt without causing inefficient overprocurement.

A parallel option includes a unit commitment for security or synchronous services market mechanism that enables an operator to schedule synchronous units to minimum levels for safe operation. The mechanism could then support additional VRE penetration through competitive provision from uncontracted resources. This could also be potentially supported with a "nomogram" (a diagram that facilitates calculation through geometrical construction), a precursor of which is the example transfer limit advice table for strength in South Australia (Figure 6). While not exhaustive, this example indicates the various combination of synchronous (gas) units that support different levels of nonsynchronous (renewable) generation.

The computational complexity of modeling to construct a table such as this is significant. Additional difficulty arises from the inclusion of economic considerations to support efficient decisions in allowing or curtailing renewable energy. When this economic analysis can be combined with such a table, it may provide a pathway toward a complete nomogram to support the greater economic integration of renewables in the short to medium term. It is not clear how these various approaches may be married, nor is it evident how to manage the risks and costs of over- and underprocurement to customers via network service providers and the system operator. The emerging capabilities of grid-forming inverters (see "Australia's Big Battery") will likely play a part in any future mechanism, requiring review and revision during the transition.

Interdependencies

Thermal power stations (largely coal fueled) are forecast to retire at pace in the next two decades from the NEM and WEM (Figure 7). A key pillar of reform is the consideration of resource adequacy mechanisms to drive investment in capacity to ensure that the reliability standard is met through the transition. However, the power system will also need investment in resources capable of meeting its ESSs. If these requirements are not considered when investing in new generation (or demand-side) capacity, the overall cost of delivering secure and reliable energy to consumers is likely to be higher. Investment in system service capability may take the form of incremental capital expenditures to new entrant generation, retrofitting existing generators, and new stand-alone merchant resources with system service capabilities. A resource adequacy mechanism (e.g., a capacity market) could be extended to incorporate investment in system service capabilities by placing an obligation on consumers (or retailers) to procure additional capabilities.

These interdependencies present a significant challenge to the overall coordination of reform and market participation across investment horizons. Historically, grid-scale power systems have required large investments in equipment to be economical. In smaller systems and jurisdictions, this has meant that a single provider may be the most economically

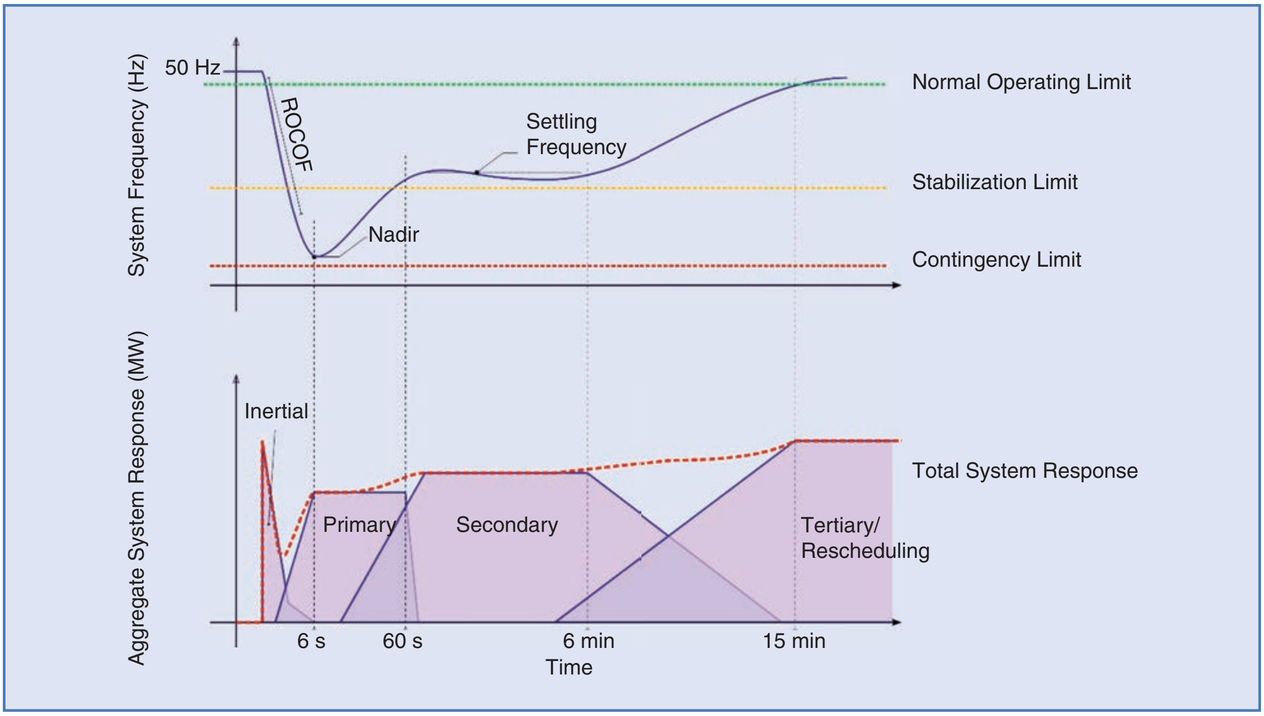

figure 5. (a) The system frequency appropriately managed after a contingency event. (b) Frequency management mechanisms to support the restoration of system frequency following a contingency event. ROCOF: rate of change of frequency.

Western Australia Rate of Change of Frequency Control Service

In August 2019, a Western Australia energy transformation task force found that a real-time co-optimization of all frequency control services, including inertia, was most appropriate for the future WEM, driven by a mixture of physical, operational, and market considerations. Historically, the WEM relied on an empirically derived rule of thumb: 70% of the largest generation contingency (in megawatts) was allocated as headroom across a set of designated facilities. An analysis and comparison of this approach identified that the combination of isolation and relatively small size resulted in the WEM being run close to its technical limits.

The transition to the greater penetration of renewables has necessitated a more sophisticated market design and led to a preference for a real-time spot market to optimize system inertia and primary response speed. In this context, initial design options focused on the correct balance of service definition "segmentation," for example, adding 1-, 2-, and 3-s services to complement the co-optimized 6- and 60-s markets, as done in the NEM. With system requirements abstracted to fundamental quantities (i.e., generic megawatt specifications), the optimal delivery of these services would be by market dynamics, irrespective of the underlying technology.

Unfortunately, investigations and analysis revealed issues with the multisegment approach from the following physical and market perspectives:

- Physical
  - Each segment adds complexity and increases the degree of "fantasy" space in which the commercial abstraction diverges from physical reality. In practice, there is no clean, linear separation of megawatts into convenient buckets.
  - Inertia is only superficially the same as primary response. True rotating machinery has a fundamentally instantaneous reaction, while power electronics suffer from an electronic detection delay on the same order (<1 s) of the critical ROCOF period.
- Market
  - Each segment adds complexity, resulting in additional infrastructure/systems overhead plus an opportunity to game/manipulate market systems.
  - Especially in a relatively "shallow" market (pool of suppliers), more complexity increases the chances of a participant effectively exercising power over a market.

The task force decided that a single segment was most appropriate. While multiple segments facilitate more service differentiation, in practice, such gains were marginal, while the downsides were guaranteed. The implementation of this direction required a fundamental change in the perspective of service definitions. Rather than split physical responses across multiple segments, the entire response profile is characterized in reference to a perfect exponential response (see Figure S3) chosen to approximate the output of a physical turbine. The response factor is then converted into a multiplier that incentivizes speed. Inertia is split from the primary response in recognition of the underlying physical differences, while inverter-based generation is credited through very high-performance multipliers. The task force, however, noted the ongoing research and development of inverter-based technology, and named the inertial service ROCOF Control in recognition that future developments may open this segment to power electronic devices.

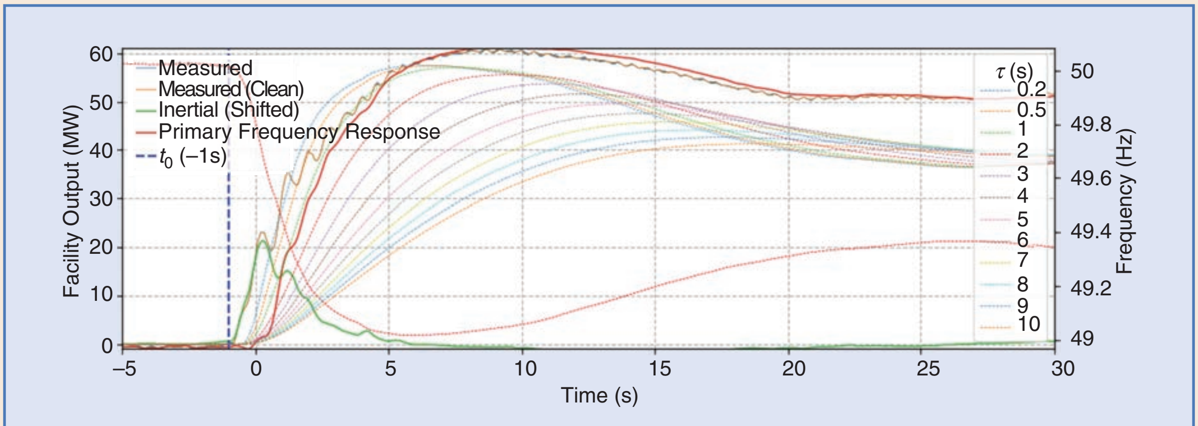

figure S3. The physical response of a gas turbine is measured and compared against an array of hypothetical "perfect exponential" responses of different speeds.

efficient approach for providing a certain service. Even with rapid distributed energy resource (DER) emergence, it may still hold that a single regulated ESS provider is a more economical solution than open-market provision. To facilitate investment, the markets for procuring services need to be stable and have clear participation requirements. In theory, markets with sufficient competitive tension will drive efficient investment and retirement decisions, ensuring that suitable

Combination	Nonsynchronous Generation Level	Torrens Island A				Torrens Island B				Pelican Point			Osborne		Quarantine or Dry Creek*
		Ax	Ax	Ax	Ax	Bx	Bx	Bx	Bx	GTx	GTx	ST18	GT	ST	
LOW_2	≤1,300 MW					■	■			■		■			
LOW_3	≤1,700 MW					■	■						■	■	■
LOW_4	≤1,450 MW									■		■	■	■	■
LOW_5B	≤1,700 MW	■	■			■	■	■							
LOW_6	≤1,700 MW					■				■	■	■			
LOW_7	≤1,700 MW	■	■							■		■			■
LOW_8	≤1,600 MW	■				■				■		■	■	■	
LOW_10	≤1,750 MW	■	■			■	■						■	■	
LOW_11	≤1,700 MW	■								■	■	■			
LOW_13	≤1,700 MW	■				■	■	■					■	■	
LOW_14	≤1,300 MW	■	■			■				■		■			
LOW_15	≤1,300 MW	■				■				■		■			■
LOW_18B	≤1,700 MW	■				■	■	■							■

figure 6. An excerpt of the AEMO's 2020 transfer limit advice for South Australia, indicating the combinations of synchronous units (green squares) at low levels of system strength that may support various levels of nonsynchronous (renewable) generation (column 2). Ax, Bx, and so on represent different generating units of the power stations.

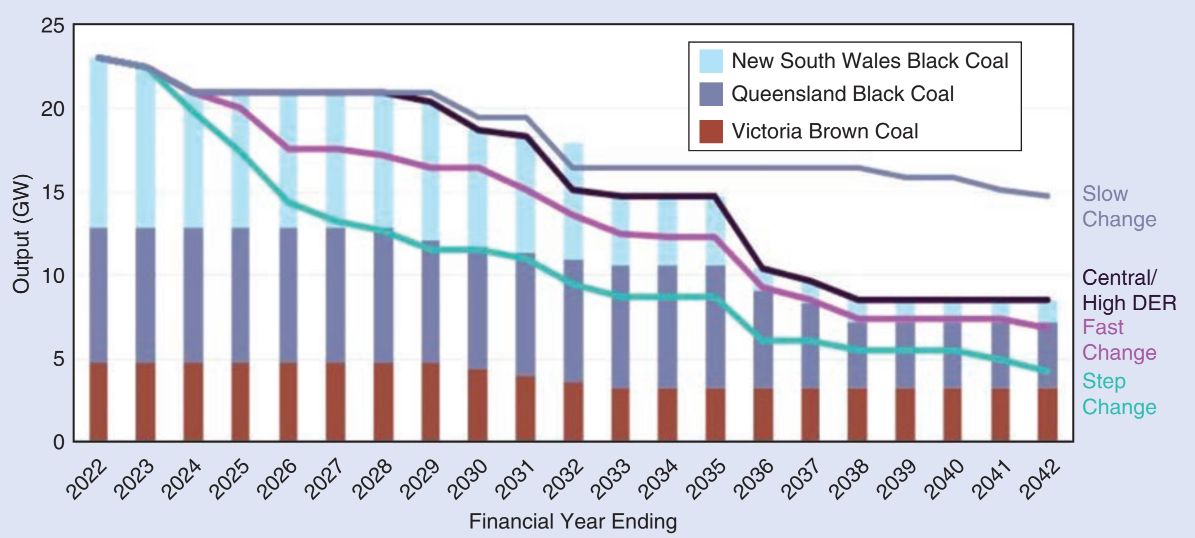

figure 7. A forecast for coal generation retirements in three Australian states. DER: distributed energy resource. (Source: 2020 AEMO integrated system plan.)

quantities of each ESS are available. For power systems that lack competitive tension due to either a small size or market concentration, a nonmarket procurement mechanism may be more appropriate. In either case, without appropriately defined services and compensation mechanisms, gaps are likely to appear in the market due to insufficient new investment. Such voids will not be filled without government or other external intervention.

In particular, DERs and demand-side management can likely provide ESSs on a cost-competitive basis with traditional and new grid-scale resources. DERs can be scaled in a more granular fashion than grid-scale resources once the appropriate rules and initial participation infrastructure are established. This may make them an effective option for augmenting the availability of ESSs on multiple time horizons. Thus, it is vital that, when revising market arrangements, DERs are designed to be part of the solution. If they are not explicitly designed for, there is a real risk that DERs will not be able to participate. The approach needs to balance the requirements of visibility for system operation, distribution-level operation requirements, and the implementation cost of any control and communications systems required to facilitate market access. Explicitly considering how DERs participate in ESSs will enable proponents to build a clear business case and "value stack" alongside other services to bring the required systems and solutions to market. Without such, mechanisms could drive separate capital investments to meet each of the power system requirements, increasing costs to consumers.

The Australian Approach and the Future of ESSs

Australia's electricity system is rapidly transitioning from a generation fleet dominated by coal and gas to accommodating the world's highest penetration of residential solar PVs (22% of all stand-alone houses), with the regular instantaneous provision of a 100% renewable supply likely within five years. This will occur on the east coast, with a grid covering more than three times the area of Texas and in southwestern Australia across an area the size of the United Kingdom. Catalyzed by the rapid pace of change and through a handful of significant system security events, Australian governments have instigated sweeping market reforms to support the transition to higher VRE penetration. A key focus is on ESSs, with the recognition of services once provided by synchronous generators as a byproduct of energy generation and not yet replaced by inverter-based technologies.

Although there are regulatory and physical differences between the west and east coast markets, the philosophical and economic principles established during the markets' conception have been maintained. Included are the importance of efficient price signals in operational time frames based on voluntary bids and offers, facilitating overall dispatching while maximizing market-based outcomes and minimizing interventions. Regarding the reform of specific system services, Figure 8 outlines a graphical road map indicating the pathways for reform in both markets. For the NEM, this involves the possible implementation of the following:

- ✔ a new operating reserve spot market likely based on a 5- or 30-min ramping availability product procuring either the total ramp or holding reserve out of the market through a separate call mechanism
- ✔ a new fast-frequency response market (sub-2s) to encourage and reward the provision of rapid frequency control from batteries and the refinement of the mandatory requirement for primary frequency control (recently enacted and already delivering market improvements to systemwide frequency performance)
- ✔ a new framework for system strength, where the system operator sets minimum/efficient levels (via a short circuit current ratio) at all nodes of the network, and the network service provider is obliged to maintain those levels. There will likely be a mechanism to schedule synchronous resources in operational time frames to provide inertia and system strength with support for the longer-term consideration of an inertia spot market.

For the WEM, the reform pathway includes the following:

- ✔ a new spot market for regulation frequency management and the transformation of the current contingency frequency control framework to spot markets similar to the NEM
- ✔ the implementation of a ROCOF control service spot market to pay for inertia in operational time frames—the first such market we are aware of anywhere in the world.

For all new services, there is an explicit awareness of the importance of setting technical requirements to support and encourage emerging technologies and, in particular, possible future DER capabilities and demand-side participation. Both the NEM and WEM reform programs are ongoing. Development to date has required robust collaboration across market operators, regulators, and government agencies and extensive engagement with market participants, including generators, retailers, DER aggregators, consumer representatives, and network operators.

The rapid pace of change has been catalyzed by legislated net-zero emission targets from states and territories toward 2050, although a national target has not yet been set. Australia is the world's largest exporter of coal and natural gas. Ensuring the impact of measures to address climate change generates significant political debate with extensive business lobbying. This may, in part, explain why Australia has struggled during the past two decades to navigate a middle path through the electricity transition with bipartisan support. But even with uncertain support at a federal level, and perhaps, in part, because of it, Australian households have embraced rooftop solar at world-leading levels, and industrial buildings are

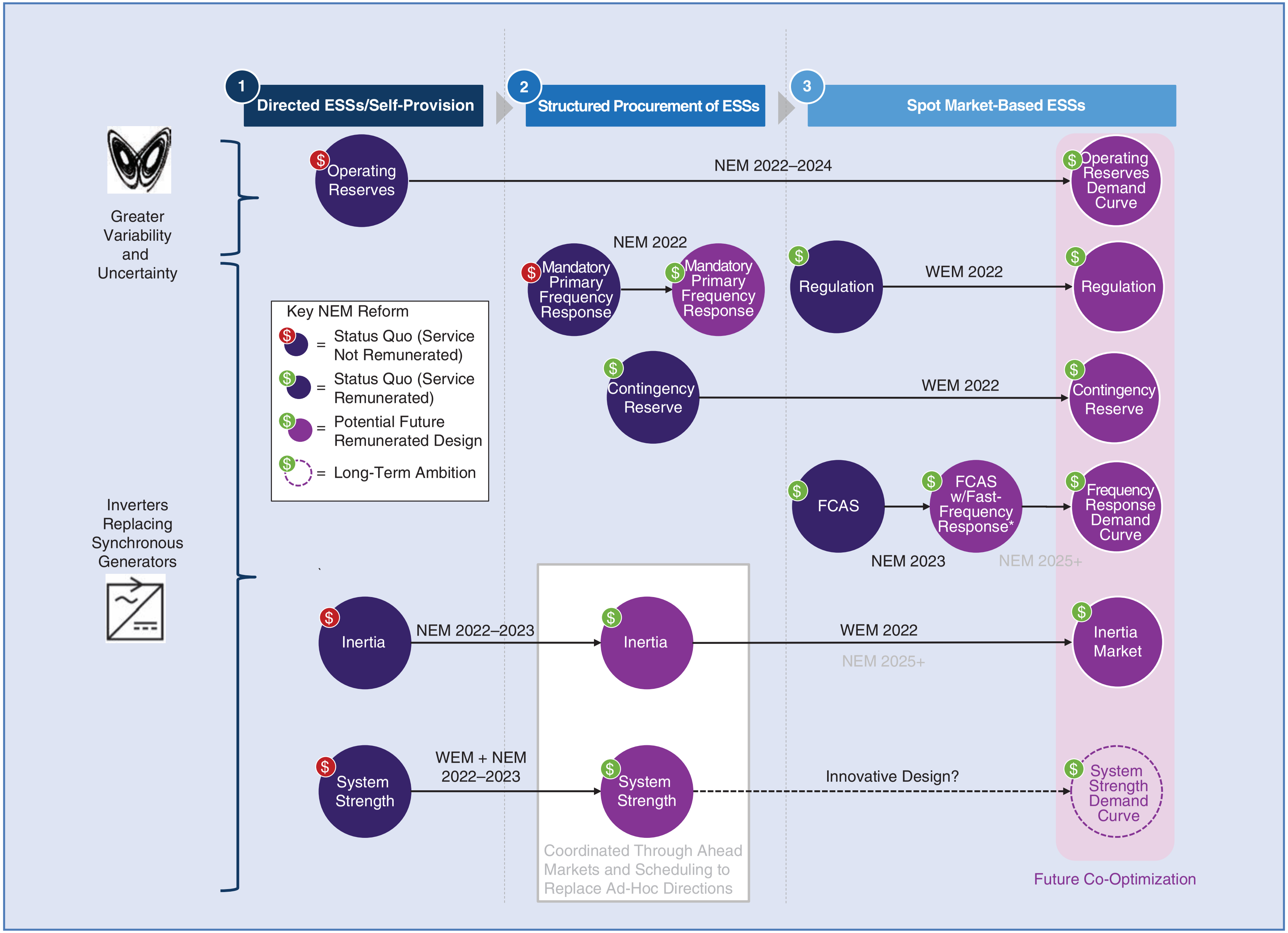

figure 8. A possible road map for ESSs in Australia (the NEM and WEM) to 2025 and beyond, indicating an evolution toward spot market-based mechanisms, where possible. (Source: adapted from FTI Consulting's 2020 Report to the ESB.)

now following. Spurred by broad political support at the state level for net-zero targets, state and territory governments are heavily investing in renewable generation through reverse auctions and power purchase agreements. They are making investments in transmission designs flagged by the system operator as essential to support emerging renewable energy zones. These zones are discussed in another article in this issue, "Planning at System Level, Renewable Energy Zones."

Reform programs are underway but with significant work still to be completed. For the NEM and the WEM, the detailed work of market design, technical qualification, compliance, and regulatory frameworks has yet to be finalized. Each will have a significant impact on market participant behavior and system outcomes, and there is a growing recognition of the value in allowing flexibility to those involved in the transition. Australia is likely to continue on its reform pathway for the coming decade, due to the rapid pace of change in both supply and demand.

The current reform of ESSs predominantly addresses challenges arising from the inverter-based replacement of synchronous generation, with early steps focusing on the emerging variability and uncertainty of supply. Future essential services will likely be needed to 1) mitigate minimum demand (already a pressing security concern for some regions, 2) provide individual components of system strength (where fungible), and 3) provide a broader provision of system restart services to support greater resilience and islandability in the event of bushfires and extreme weather events. All future reforms will need to interact fairly with DERs, recognizing that the advanced grid-forming technological capabilities of new battery technologies, such as the Hornsdale Power Reserve, will likely be eventually translated to the power electronics of smaller inverters at the household scale. To support customer participation and fairness, this may be facilitated through a broadly accepted "DER Bill of Rights" with principles that could include 1) the allowance of the near-unimpeded self-consumption of self-generated electricity (even if exports may be curtailed), 2) the fair imposition of technical requirements to support grid security, and 3) remuneration for energy and system services proportional to that received by large-scale resources.

As the electrification of transportation proceeds at pace alongside the increased sophistication of demand-side participation, there will likely be new system service needs and opportunities for provision from emerging resources, such as electric cars. This will need to be accompanied by a redefinition of roles for network service providers. As the energy transition gathers momentum through the millennium, Australia finds itself rapidly departing from the paradigm first enacted in 1899 of default system service provision from synchronous resources. It is moving toward new market frameworks that remunerate the provision of distinct services in real time from technology unimaginable 100 years ago. How Australia addresses this change has the potential to help inform the global energy transition in the coming century for the urgent decarbonization journeys all countries across the world are now navigating.

For Further Reading

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Biographies

Niraj Lal is with the Australian Energy Market Operator, Melbourne, 3000, Australia, and Australian National University, Canberra, 2000, Australia.

Toby Price is with the Australian Energy Market Operator, Melbourne, 6000, Australia.

Leon Kwek is with the Australian Energy Market Operator, Melbourne, 6000, Australia.

Christopher Wilson is with the Australian Energy Market Operator, Melbourne, Australia.

Farhad Billimoria is with the Australian Energy Market Operator, Melbourne, 3000, Australia, and the University of Oxford, Oxford, OX2 6FA, United Kingdom.

Trent Morrow is with the Australian Energy Market Operator, Melbourne, 4000, Australia.

Matt Garbutt is with the Energy Security Board, Canberra, 2000, Australia.

Dean Sharafi is with the Australian Energy Market Operator, Melbourne, 6000, Australia.