TESLA

Tesla Energy: The Role of Grid-Forming Inverters in Providing Inertia

August 2025

Executive Summary

The integration of renewable energy into Australia's power grid is shifting the landscape of grid stability and reliability. Grid-forming technology is transforming how we integrate renewable energy sources into the grid, offering a clean and adaptable alternative to traditional rotating machinery and providing a solution to the challenges of grid stability.

This white paper presents evidence that grid-forming batteries are technically capable of delivering reliable inertial responses in the National Electricity Market (NEM). It also advocates for performance-based technical assessments of advanced inverter-based technologies, rather than requiring replication of the physical characteristics of legacy synchronous machines, and provides policy and regulatory recommendations to facilitate the integration of these technologies into the NEM.

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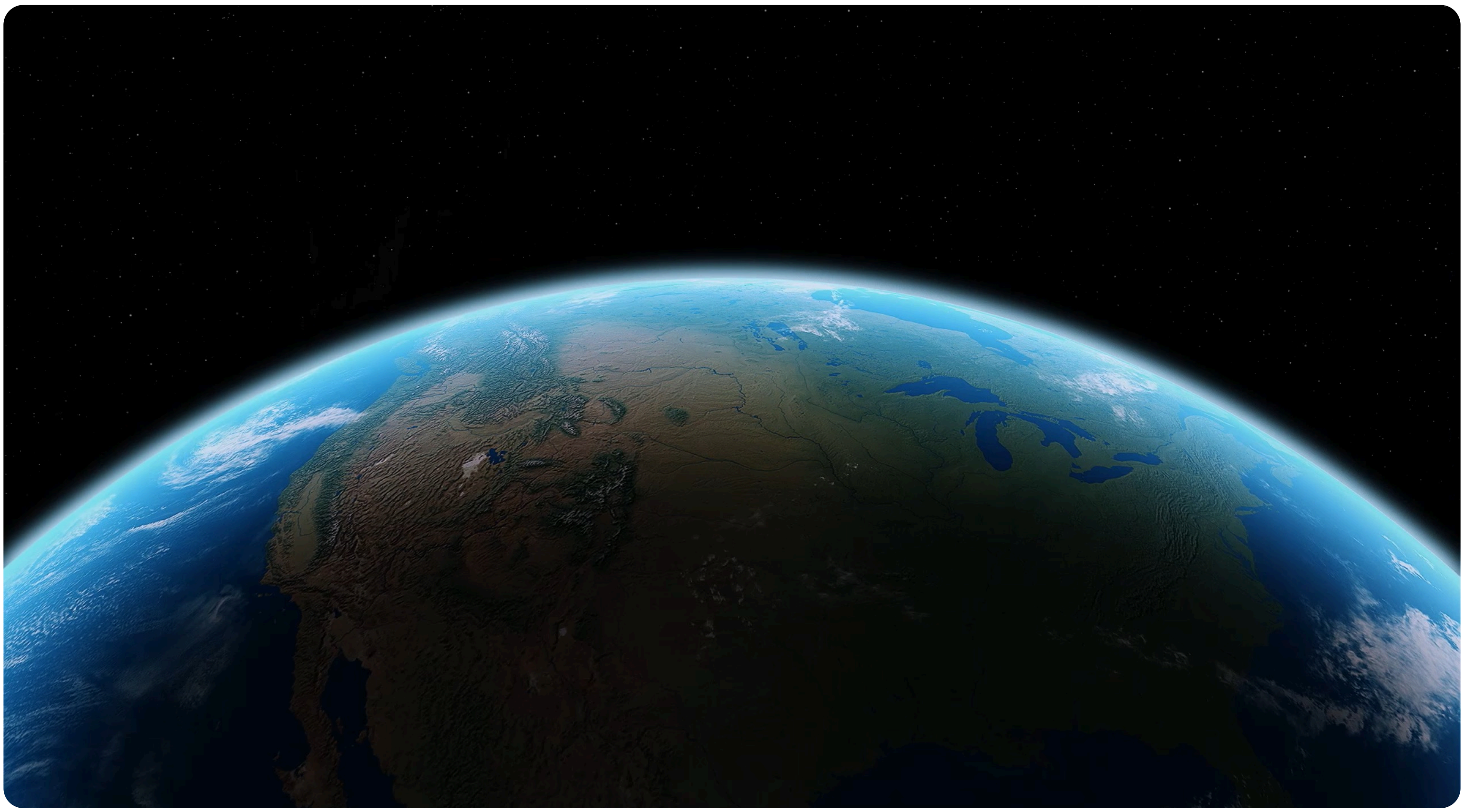
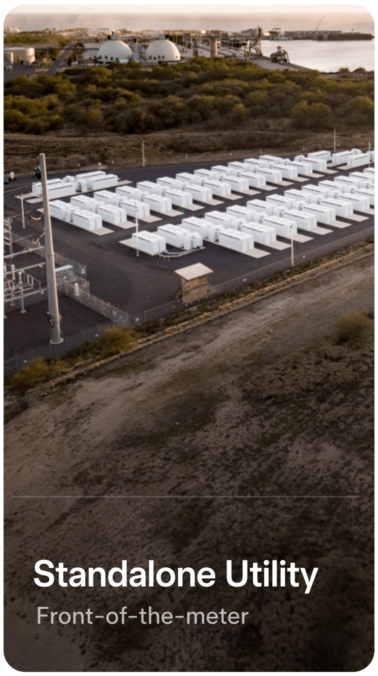
Our Mission Is to Accelerate the World's Transition to Sustainable Energy

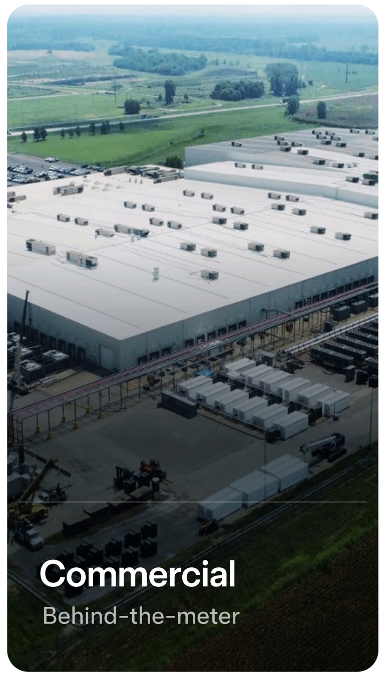


Market Segments and Applications

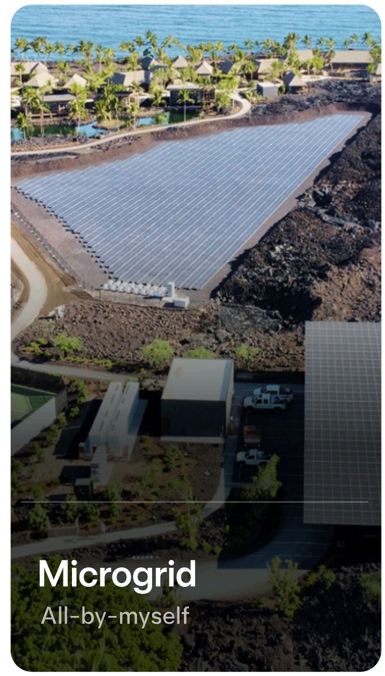


- Peaker replacement
- Capacity support
- Frequency support
- Voltage support
- Grid services

- Energy shifting
- Ramp rate control
- Forecast deviation
- Grid services
- Hybrid controls



- Solar self-consumption
- Peak shaving
- Load shifting
- Demand response



- Backup
- Off-grid
- Grid-tied

Tesla Has 4.5 GW+ / 12 GWh+ of Grid-Forming Batteries in the Pipeline Across Australia

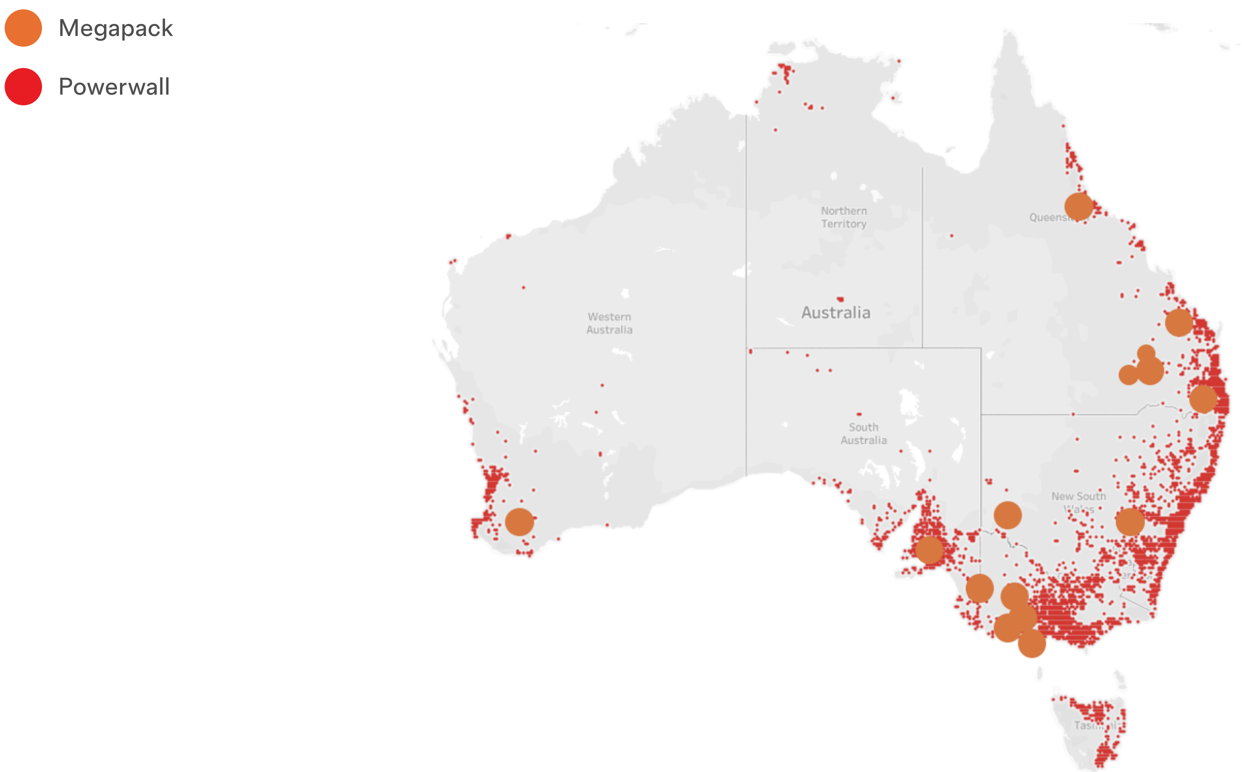


Figure 1: Tesla Battery Deployments in Australia

Tesla Grid-Forming Projects:

1.Hornsdale Power Reserve (Neoen): 150MW / 194 MWh | Jamestown, SA

2.Victoria Big Battery (HMC Capital)[1]: 300MW / 450 MWh | Geelong, VIC

3.Wallgrove Grid Battery (Lumea): 50 MW / 75MWh | Wallgrove, NSW

4.Riverina Energy Storage System (Edify): 150MW / 300MWh | Darlington Point, NSW

5.Greenbank (CS Energy) : 200 MW / 400 MWh | Greenbank, QLD

6.Western Downs Stage 1 & 2 (Neoen): 2 x 270MW / 540 MWh | Western Downs, QLD

7.Melbourne Renewable Energy Hub (Equis) : 600MW / 1,600MWh | Melbourne, VIC

8.Swanbank (Cleanco): 250MW / 500 MWh | Swanbank, QLD

9.Orana BESS (Akaysha): 415MW/ 1,660MWh | Wellington, NSW

10.Koorangie Energy Storage System (Edify): 185MW / 370MWh | Sandhill Lake, VIC

11.Tarong BESS (Stanwell): 300MW / 600MWh | Tarong, QLD

12.Stanwell BESS (Stanwell): 300MW / 1200MWh | Stanwell Power Station, QLD

13. Limondale BESS (RWE): 50MW / 400MWh | 8H | Balranald, NSW

14. Brendale BESS (Akaysha): 205MW / 410 MWh | Brendale, QLD

15. Elaine BESS (Akaysha): 311MW / 1244MWh | Elaine, VIC

16. Williamsdale (Eku): 250MW / 500MWh | Williamsdale, ACT

17. Calala (Equis): 300MW / 600MWh | Tamworth, NSW

Operational
In commissioning
Approved 5.3.4A (and public)

Note: Tesla's grid-forming batteries provide synthetic inertia using the rotor dynamics 'swing equation', responding to Rate of Change of Frequency (RoCoF). However, not all battery manufacturers with grid-forming capability are able to provide inertia.

[1] Operational, but still in grid-following. Grid-forming approved by AEMO.

Background
Role of Inertia in the NEM and Evolving Inertia Providers

Inertia Plays a Crucial Role in Stabilising the Grid and Controlling Frequency

In the NEM, system frequency must be maintained at 50 Hz to ensure stable and reliable power supply. Even small deviations can compromise system stability. When a major disturbance occurs, such as the sudden loss of a generator, frequency can drop rapidly, risking cascading failures and blackouts. To prevent Under-Frequency Load Shedding (UFLS), which is activated as the last resort to save the system, grid frequency must stay above the load shedding threshold. This requires large amounts of fast active power injection to arrest the frequency drop. Inertia offers an immediate energy response from connected assets, acting in under 5 milliseconds to changes in system frequency. In contrast, Primary Frequency Response (PFR) provides additional power by adjusting output in a controlled manner to help maintain the target frequency of 50 Hz. Together, these responses are critical to maintaining system security.

Response to Frequency Disturbances

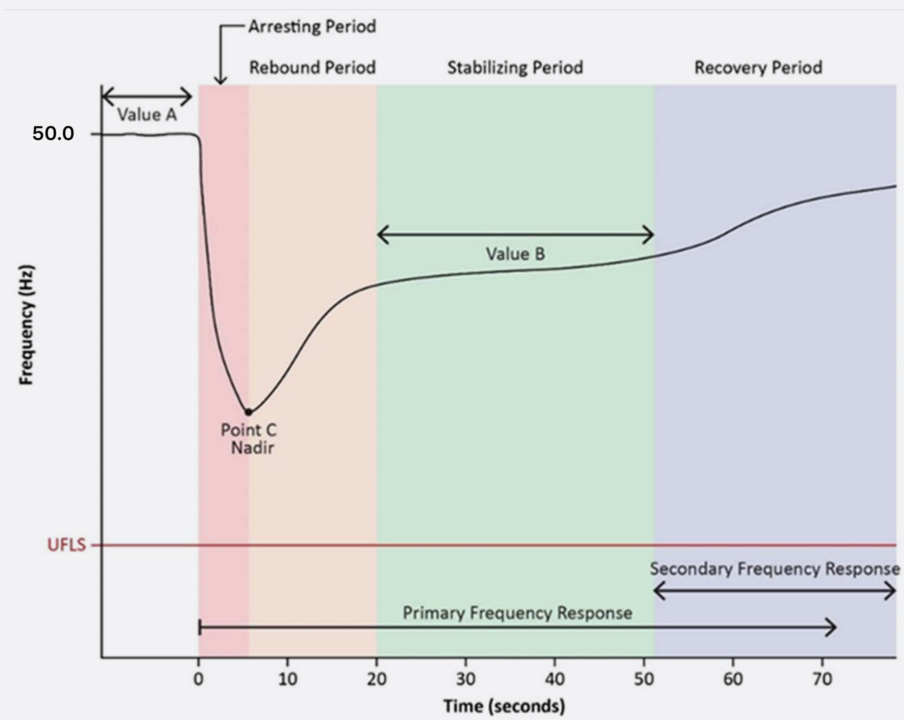
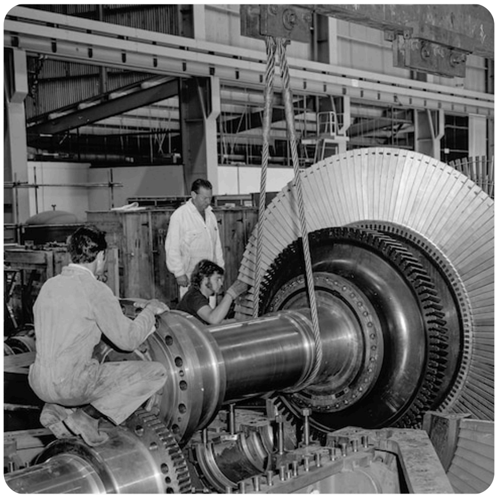


Figure 2: NERC, "East Interconnection Frequency Response Assessment with Inverter Based Resources", July 2018

Provision of Inertia Has Evolved From Synchronous to Inverter Based



Historical sources of inertia:

Traditionally, inertia in the power system has been provided by large synchronous generators, which store kinetic energy in their rotating masses. During a disturbance, this stored energy is released almost instantly, slowing the rate of frequency decline Rate of Change of Frequency (RoCoF) and giving PFR and other Frequency Control Ancillary Services (FCAS) time to respond. As the NEM shifts to renewable energy, fewer synchronous generators are online, which reduces the system's inherent inertia and increases the risk of rapid frequency changes that could lead to instability.

Non-generating sources of inertia:

As synchronous generators are displaced by renewable energy sources, grid operators are turning to alternative equipment to help stabilise the frequency. Synchronous condensers, also known as syncons, which replicate the rotating mass and magnetic field of traditional generators, provide physical inertia to resist sudden changes in frequency. Although they do not generate power, they offer a hardware-based solution to support grid stability during disturbances.

New inverter-based sources of inertia:

Grid-forming batteries are playing an increasingly important role in maintaining power system stability as traditional sources of inertia decline. These advanced inverter-based resources can establish and regulate grid voltage and frequency, a function once provided by synchronous generators. A key feature of grid-forming operation is the ability to provide synthetic inertia, where active power is rapidly injected in response to frequency changes. This fast response helps limit the frequency nadir following disturbances, enhancing stability in low-inertia conditions. Tesla's grid-forming batteries can provide controllable, instantaneous active power through emulated inertia responses to constrain frequency nadir in a power system with fewer synchronous generators.[2]

[2] However, not all battery manufacturers with grid-forming capability are able to provide inertia.

Grid-Forming Inverters Are Gaining Acceptance by Grid Operators Around the World

Adopted by grid operators globally, grid-forming batteries are hailed for their unique capability to stabilise weak networks, accelerate renewable integration, and safeguard against cascading failures.

"The inertial response provided by the Hornsdale Power Reserve grid-forming battery is comparable to a typical inertial response provided by a synchronous machine. During a frequency event, the grid-forming battery provided its response to the rate of change of frequency like a synchronous machine."

Source: "Australian Landscape of Grid-Forming Batteries," ESIG, August 29, 2023

"Industry research has indicated system stability can be achieved at very high levels of instantaneous Inverter-based resources penetration if dynamic stability constraints are addressed. While large systems offer additional challenges, community microgrids served by 100% IBRs, including grid-forming storage, are in operation today, demonstrating GFM as a solution in a real-world application."

Source: "MISO Grid-Forming Battery Energy Storage Capabilities, Performance, and Simulation Test Requirements Proposal", MISO, June 2024

"New inverter-based energy storage resources will be required to provide advanced grid support… inverter-based energy storage resources are commercially available today to provide advanced grid support…ERCOT's preliminary assessments have identified the improvement of system stability performance and the benefits to the generic transmission constraints."

Source: "Advanced Grid Support Inverter-based Energy Storage System Assessment and Adoption Discussion," ERCOT, July 12, 2024

"Grid-forming inverters are a critical enabler for operating a low-inertia system securely… The ability of batteries to provide synthetic inertia ensures we can maintain frequency stability even as synchronous generation decreases."

Source: "Delivering a Secure Sustainable Electricity System (DS3 Programme)," EirGrid Group, 2022 Annual Report

"Through our trials, grid-forming batteries have shown they can deliver inertia at a fraction of the time it takes synchronous machines, paving the way for a more resilient and renewable-led energy system."

Source: "System Stability: The Role of Grid-Forming Technology," National Grid ESO webinar transcript, June 2022

"It's the first time a battery has been used by a major utility to balance the grid: providing fast frequency response, synthetic inertia, and black start. This project [in reference to Project Kapolei Energy Storage] is a postcard from the future — batteries will soon be providing these services, at scale, on the mainland."

Source: "Hawaii home to 'world's most advanced grid-scale battery'", Energy Source & Distribution, January 17, 2024

In Australia, AEMO Recognises Grid-Forming Inverters as a Critical Technology to Support the NEM's Transition

Inertia is defined in the National Electricity Rules (NER) as the 'contribution to the capability of the power system to resist changes in frequency by means of an inertial response from a generating unit, bidirectional unit, network element or other equipment'.[3]

Following extensive studies and demonstration trials, AEMO recognises grid-forming batteries as a critical technology for maintaining grid stability as Australia transitions to a renewable-dominated energy system. Grid-forming batteries are highlighted for their ability to provide inertia, system strength, and fast frequency response.

In 2022, AEMO confirmed that the Hornsdale Power Reserve (150 MW / 194 MWh), following its 2020 grid-forming upgrade, could deliver approximately 2,000 MW-seconds of inertia,[4] validating grid-forming batteries as a viable replacement for mechanical inertia in the NEM.

AEMO views grid-forming batteries as a strategic investment to ensure stability as coal retires (14 GW by 2030) and renewables reach 100% instantaneous penetration in parts of the NEM, like South Australia.[5]

Multiple AEMO reports[6] reference grid-forming batteries as "anchors" that offer a scalable, cost-effective path to the energy transition in Australia.

Application of Advanced Grid-Scale Inverters in the NEM

Service/capability	Grid-following inverter system	Grid-forming inverter system	Synchronous machines
Can contribute to system strength		✓	✓[A]
Can have positive disturbance withstand (active power oscillation damping)		✓	✓
Can have positive disturbance withstand (fault ride-through capability)	✓	✓	✓
Can contribute to system inertia		✓[B]	✓
Can contribute to FFR	✓	✓	
Can contribute to primary frequency response	✓	✓	✓
Can support a power system island with supply balancing and secondary frequency response	✓	✓	✓
Can initiate or support system restoration	✓[C]	✓	✓

A. Synchronous machines can usually contribute to system strength much more than IBR due to their higher overload capacity.
B. A grid-forming inverter system requires energy storage to deliver inertia.
C. Grid-following inverters can support but not initiate system restoration.

Figure 3: AEMO, "Application of Advanced Grid Scale Inverters in the NEM", August 2021

[3] AEMO, "Amendments to the Inertia Requirements Methodology", November 2024
[4] ARENA, "Neoen Hornsdale Project Summary Report – Full Inertia Trial", December 2023
[5] AEMO, "2024 Transition Plan for System Security", December 2024
[6] AEMO, "Analysis and modelling of a gridforming battery energy storage system during a system incident", December 2024

Grid-Forming Batteries Have Proven and Mature Technology and Commercial Levels

Based on the Australian Renewable Energy Agency (ARENA)'s guidelines for Technology Readiness Levels for Renewable Energy Sectors, the Commercial Readiness index "extends to when the technology or application is being commercially deployed and has become a bankable asset class".

Technology Readiness Level (TRL) 9

Requirements: Actual system proven through successful operations: Fully integrated with operational hardware/software systems.

There are already multiple successful operating grid-forming assets in the NEM, with Hornsdale producing a knowledge-sharing after completing its inertia trial.[7]

Commercial Readiness Index (CRI) 5-6

Requirements: Regulatory, planning and permitting challenges are understood and under review, yet some remain unresolved and becoming critical as penetration grows. Multiple data sets discoverable on commercial projects operating in range of operating environments.

Market bodies have made significant progress in incorporating grid-forming technology through the connection process and NER, including AEMO's review of the inertia methodology[8] for synthetic inertia and voluntary spec for grid-forming inverters.[9]

Tesla's grid-forming batteries are viewed as a bankable asset by leading Australian banks and developers as well as major financial institutions across Asia, Europe, the United States and the United Kingdom.

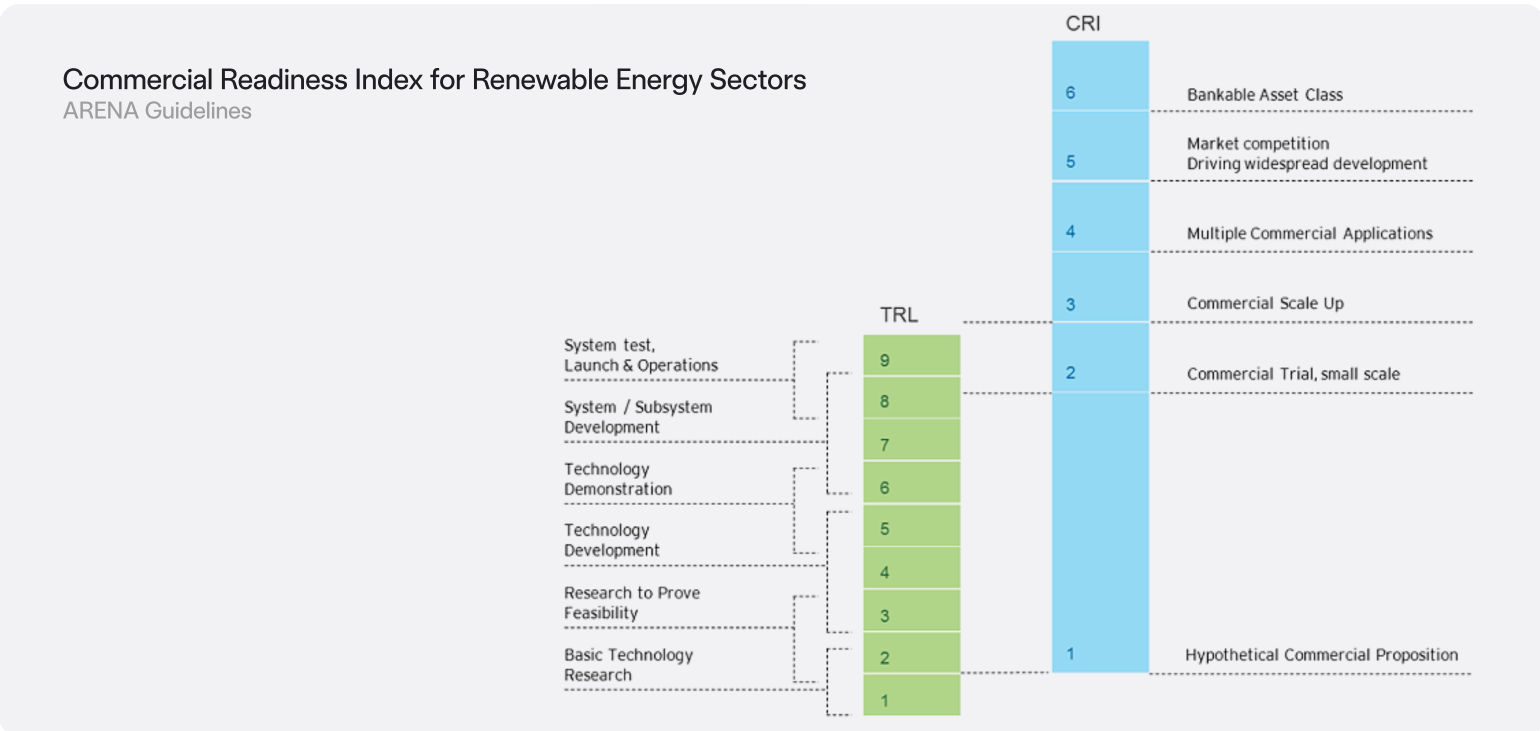


Figure 4: ARENA, "Commercial Readiness Index for Renewable Energy Sectors ", February 2014

[7] ARENA, "Neoen Hornsdale Project Summary Report – Full Inertia Trial", December 2023
[8] AEMO, "Amendments to the Inertia Requirements Methodology", November 2024
[9] AEMO, "Voluntary Specification for Grid-forming Inverters". May 2023

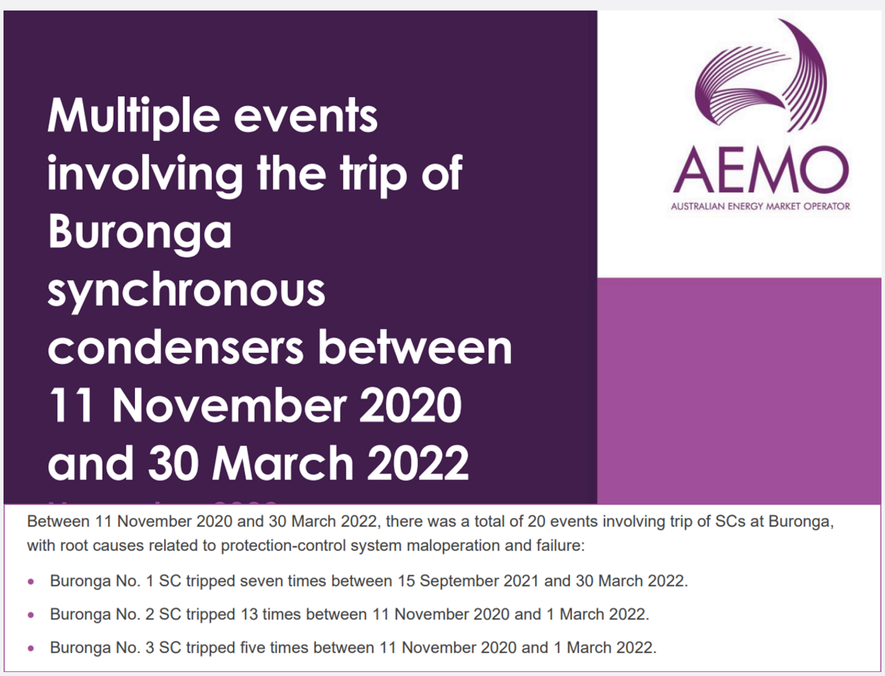
Reliability Benefits of Grid-Forming Batteries

Grid-forming batteries provide a more reliable and resilient source of synthetic inertia than synchronous condensers, which rely on mechanical components and can experience a total loss if taken offline for maintenance due to even minor faults. The modular architecture of batteries allow them to continue operating even when individual units fail, maintaining inertia provision without disruption. Tesla's batteries also feature remote diagnostics, which can reduce downtime and maintenance costs.

As the NEM transitions to higher proportion of variable renewable energy, the flexibility, scalability, and rapid response of batteries make them a more suitable solution for grid stability, with the average availability rate of batteries exceeding 99%.[10]

AEMO outlines in the report (Figure 5): "Inadvertent trips of synchronous condensers could present an increasing risk as progressively more synchronous condensers (SC) are installed across the NEM to manage system strength requirements." Root causes of the multiple trips included faulty logic in the Programmable Logic Controller (PLC) and maloperation of the stator differential protection and vibration protection, as well as some trips with root causes yet to be determined.

More broadly, synchronous condenser asset life is likely shorter than expected due to equipment obsolescence and limited vendor maintenance support, and requiring periodic major refurbishments to maintain functionality and impacting ability to meet annual availability targets closer to end of life.[11]


Multiple events involving the trip of Buronga synchronous condensers between 11 November 2020 and 30 March 2022

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Between 11 November 2020 and 30 March 2022, there was a total of 20 events involving trip of SCs at Buronga, with root causes related to protection-control system maloperation and failure:

- Buronga No. 1 SC tripped seven times between 15 September 2021 and 30 March 2022.
- Buronga No. 2 SC tripped 13 times between 11 November 2020 and 1 March 2022.
- Buronga No. 3 SC tripped five times between 11 November 2020 and 1 March 2022.

Figure 5: AEMO "Operating Incident Report" , November 2022

10 Tesla's industrial energy fleet performed at an average annual guaranteed availability of 99.4% for the period from 1 July 2024 to 30 June 2025
11 GHD Advisory, "Economic life for ElectraNet synchronous condensers", June 2019

Simulation Modeling

Comparisons of Inertial Responses Modelled on Inverter and Synchronous Sources

Through Appropriate Tuning, Grid-Forming Batteries Provide Greater Inertia Responses to Syncons

Simulation-based analysis shows that grid-forming batteries can deliver inertia responses that are comparable to, or greater than, those of an equivalently sized synchronous condenser, when site is appropriately configured.

In Tesla's experience, projects in Australia are often asked by AEMO or the Network Service Providers (NSPs) to reduce inertia settings to meet specific plant behaviour expectations. These expectations are shaped by how AEMO and NSPs interpret clauses in the NER, such as active power recovery time and the ability to ride through high RoCoF events with a clean response. The standards grid-forming batteries are assessed against were originally developed around grid-following technologies, which typically require extremely low inertia settings to produce the prescribed behaviour.

Figure 6 presents a comparison of inertial responses during a frequency event with a RoCoF of 0.5 Hz/s. It includes a typical Australian site using low inertia settings (orange line), a synchronous condenser (black line), and a site using Tesla's recommended grid-forming settings (red line). The results highlight how appropriate tuning can significantly improve performance.

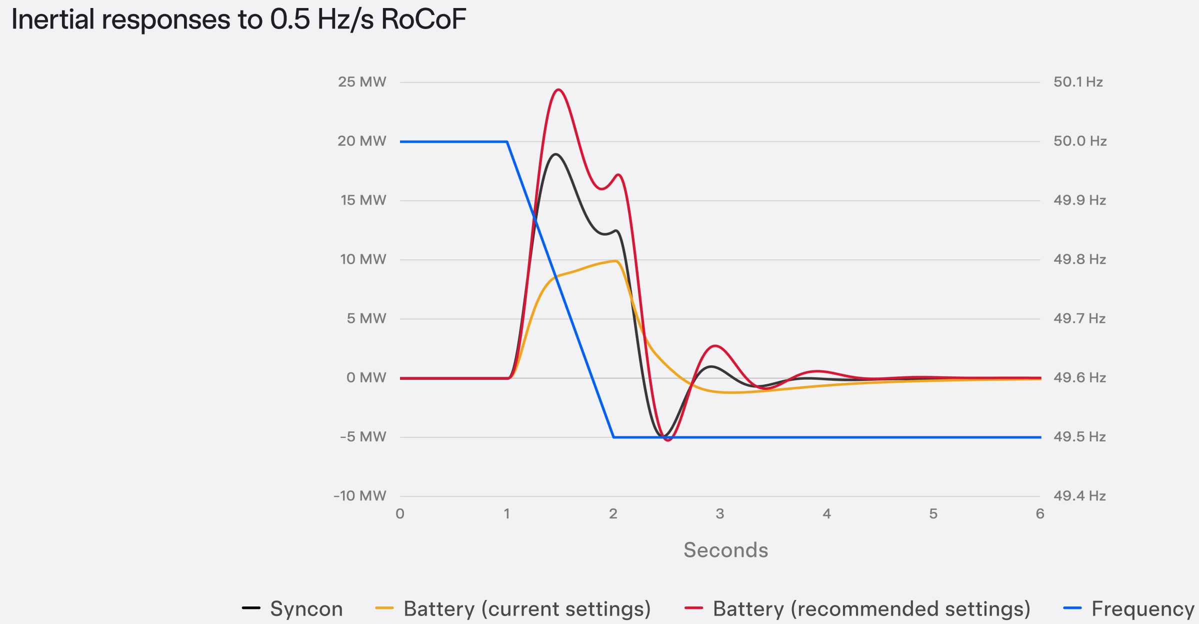


Figure 6: Simulation based inertia response of syncon, existing grid-forming battery, and modified settings battery under RoCoF of 0.5 Hz/s

Experimental Design: Comparing Grid-Forming Responses for Three PSCAD Models

Tesla undertook simulation modelling for a specific site in the NEM to assess grid-forming performance under the appropriate inertia settings.

During the generator alteration application process (from grid-following to grid-forming), there were limitations due to specific requirements of the GPS negotiation framework.

To test different tuning outcomes, Tesla created three datasets in PSCAD.
The battery models were tested at P=0 MW to provide a like-for-like comparison with the syncon model.

The testing was performed using Single Machine Infinite Bus (SMIB) model with grid modelled as voltage source behind the impedance (short circuit ratio= 13, reactance to resistance ratio= 3).

Model	Function	Inertia constant	Damping	Reactance	Proportional band
Synchronous condenser	Uses a PSCAD generic library model based on the Davenport synchronous condenser parameters, scaled down to 77.16 MVA to match the size of compared battery.	8.655	0.0 damping based on ElectraNet's publication via the OPDMS case	N/A	N/A
Grid-forming battery with settings from an operational asset	The specific customer requested Tesla to reduce the grid-forming inertia as much as possible, requiring these settings.	1.0	0.9	0.2	0.5 Hz
Grid-forming battery with high inertia settings	For comparison, the same plant was modelled with adjusted grid-forming settings.	5.0	2.0	0.04	0.8 Hz

Figure 7: Simulation based inertia response of syncon, existing grid-forming battery, and modified settings battery under RoCoF of 0.5 Hz/s

Experimental Design: Comparing Grid-Forming Responses Under a Range of RoCoF Conditions

The three PSCAD datasets are compared across the range of RoCoFs outlined in the Reliability Panel's 2023 Frequency Operating Standard (FOS):

0.1 Hz/s RoCoF lasts 1 s and grid frequency settles at 49.9 Hz

0.5 Hz/s RoCoF lasts 1 s and grid frequency settles at 49.5 Hz

1 Hz/s RoCoF lasts 1 s and grid frequency settles at 49 Hz

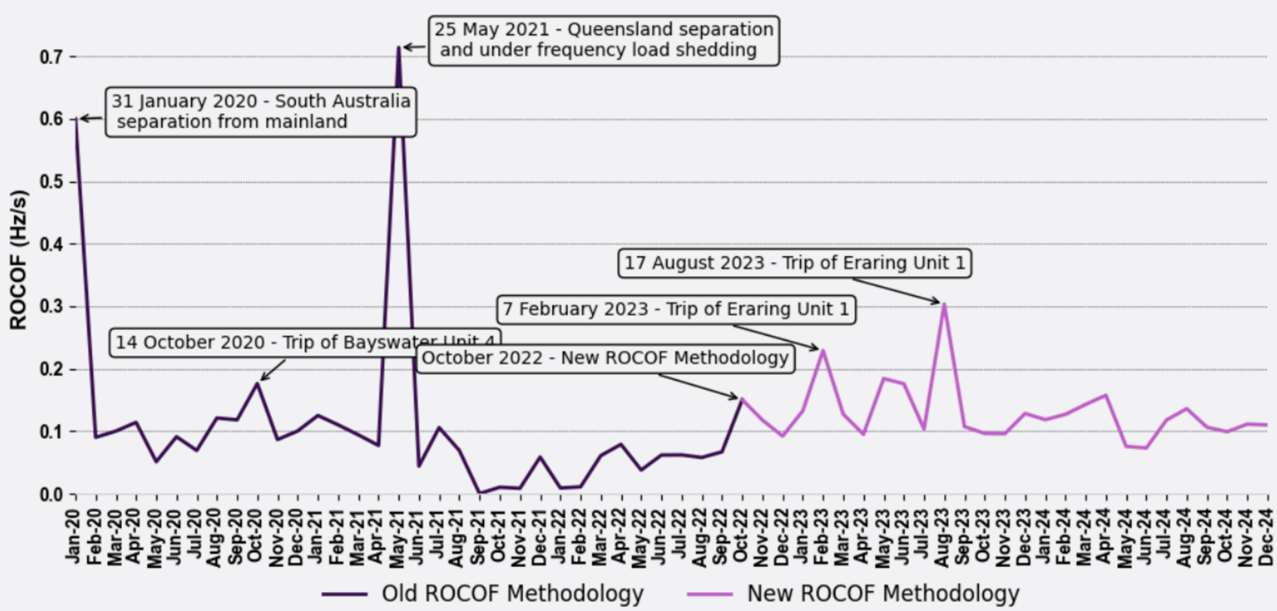
2 Hz/s RoCoF lasts 1 s and grid frequency settles at 48 Hz

3 Hz/s RoCoF lasts 1 s and grid frequency settles at 47 Hz

4 Hz/s RoCoF lasts 0.25 s and grid frequency settles at 49 Hz

While the FOS covers a range of RoCoF conditions that are explored in this modelling, AEMO's Frequency Monitoring Reports show that there have been no RoCoF events at greater than 1 Hz/s since 2020 (see figure 8).

Monthly Maximum RoCoF recorded since 2020



Note: 31 January 2020 RoCoF as measured in South Australia and 25 May 2021 RoCoF as measured in Queensland. New ROCOF calculation methodology used as of October 2022.

Figure 8: AEMO "Monthly Maximum RoCoF recorded in any mainland region since 2020", January 2025

For RoCoF Events ≤ 1 Hz/s, Grid-Forming Batteries Provide Comparable Inertia Responses if Appropriately Tuned

The results demonstrate that the plant can be tuned to match the power ramping speed of the baseline synchronous condenser and provide an even larger inertia response for a RoCoF between 0.1 Hz/s and 1 Hz/s. The magnitude and speed of the inertia response from a Tesla grid-forming battery can be tuned to emulate different inertia quantities and sub-transient reactance of synchronous machines, subject to over current capability.

Figure 9 shows the inertial response of a syncon (black line), grid-forming battery in existing low inertia settings (orange line), and the same battery with a less rigid GPS requirement (red line), following frequency events with RoCoF 0.1 Hz/s, 0.5 Hz/s, and 1.0 Hz/s (blue line).

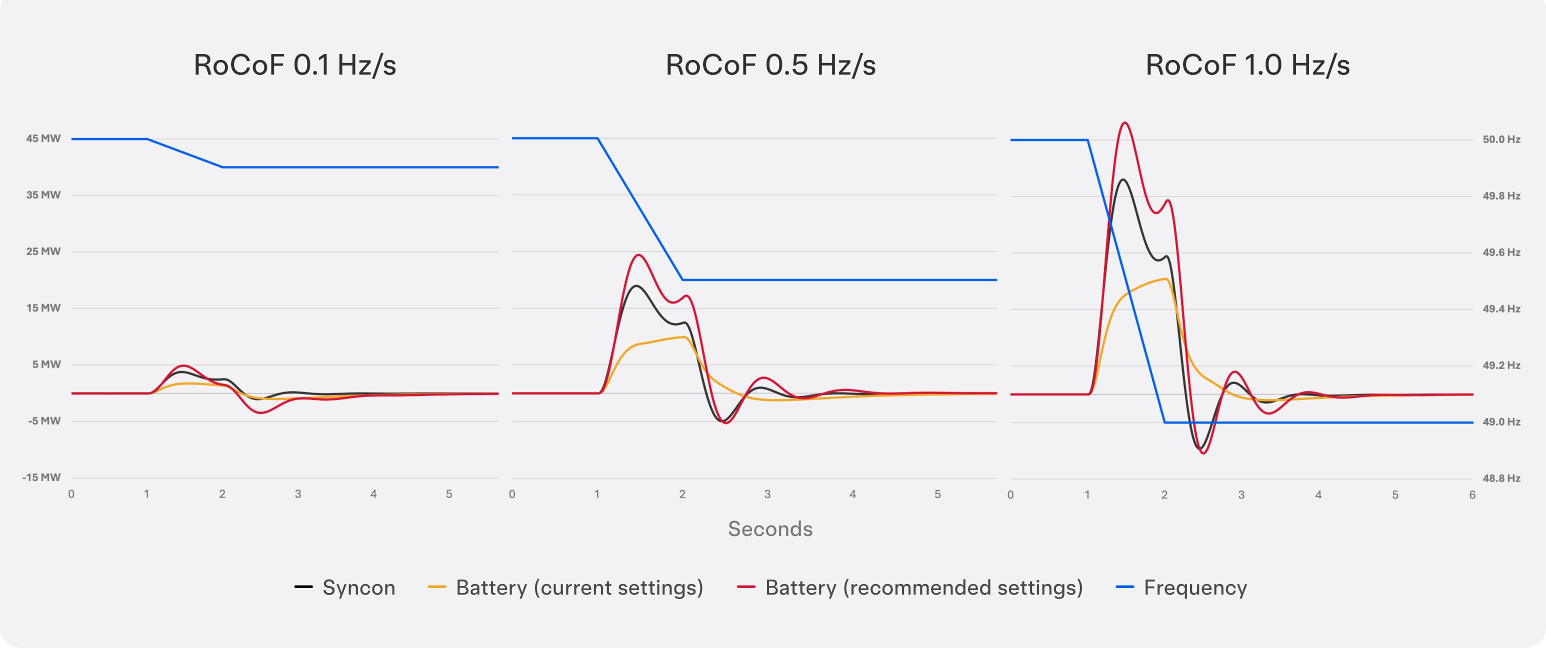


Figure 9: Simulation based inertia response of syncon, existing grid-forming battery, and modified settings battery under RoCoFs of 0.1, 0.5, and 1.0 Hz/s

For RoCoF Events <1 Hz/s, Grid-Forming Batteries Can Stabilise Frequency Through Either Inertia or PFR

For small RoCoF events less than 1 Hz/s, grid-forming batteries can be tuned to mimic a synchronous condenser to provide inertia to arrest frequency nadir (red line vs black).

Additionally, if the grid is strong enough, the same battery can provide a small amount (<1sec) of PFR to arrest the frequency nadir (green line) without any inertia response.[12]

AEMO's 2023 report[13] states that synthetic inertia responses may not necessarily need to be "directly proportional to RoCoF" as the frequency support response can be greater than the peak power of the inertia response from the syncon.

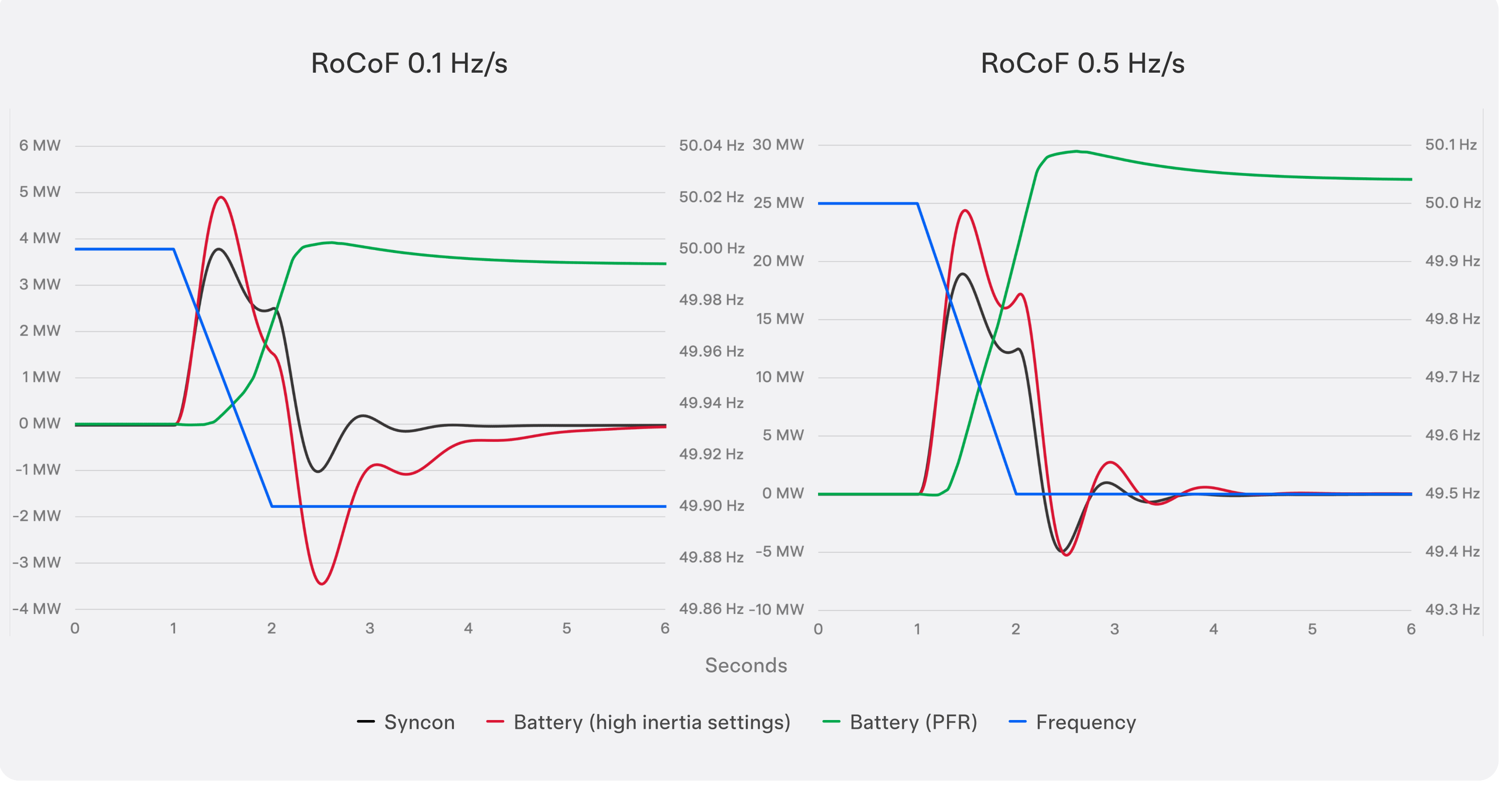


Figure 10: Simulation based inertia response of syncon, modified settings batter, and PFR response of battery under RoCoF of 0.1 Hz/s

Figure 11: Simulation based inertia response of syncon, modified settings batter, and PFR response of battery under RoCoF of 0.5 Hz/s

12 Please note that PFR and inertia shown here are alternative responses to manage frequency deviations (not happening simultaneously)

13 AEMO, "Inertia in the NEM Explained", March 2023

For RoCoF Events >1 Hz/s, The Magnitude of the Inertia Response Is Limited by Overloading Capabilities

Figure 12 shows the inertial response of a syncon (black line), grid-forming battery in existing low inertia settings (orange line), and the same battery with a less rigid GPS requirement (red line), following frequency events with RoCoF 2 Hz/s, 3 Hz/s, and 4 Hz/s (blue line). The magnitude of the inertial response is limited by the inverter overloading capability.

The NER requires a generator to withstand a RoCoF event of up to 4 Hz/s for 250 milliseconds, or 3 Hz/s for 1 second; any event exceeding these durations is considered non-credible. Both syncons and battery with high inertia settings can experience instability at RoCoFs above 3 Hz/s. Typical synchronous machines—including condensers and synchronous generators—are generally unable to tolerate such high RoCoF due to mechanical limitations.

The transient power swings observed below can be improved with hardware and software improvements – demonstrated on the next page.

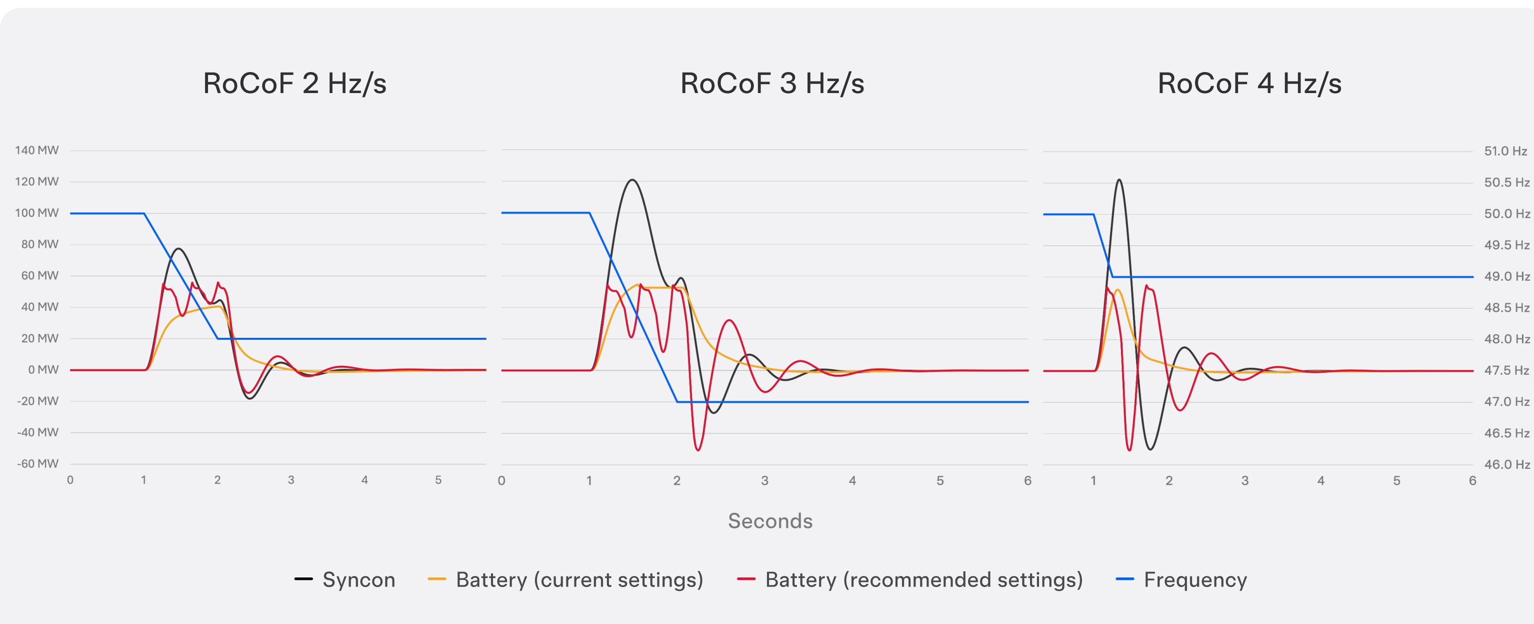


Figure 12: Simulation based inertia response of syncon, existing grid-forming battery, and modified settings battery under RoCoFs of 2, 3, and 4 Hz/s

For RoCoF Events > 1 Hz/s, Altering the Overload Capability (To 128%) Means Grid-Forming Batteries Can Mimic Syncons

If the plant is configured with an overload capability of 128% (2.28 p.u.), the inertia response (red line) can be faster and larger than the baseline synchronous condenser (black line). A higher RoCoF results in greater power output from a synchronous machine. However, the maximum power an inverter can output is limited by its current limit.

The maximum power output of an inverter is restricted by its current limit of 1.2 p.u.. However, Tesla's Megapack can be configured to provide a larger overcurrent capability to be close to the peak power of a syncon.

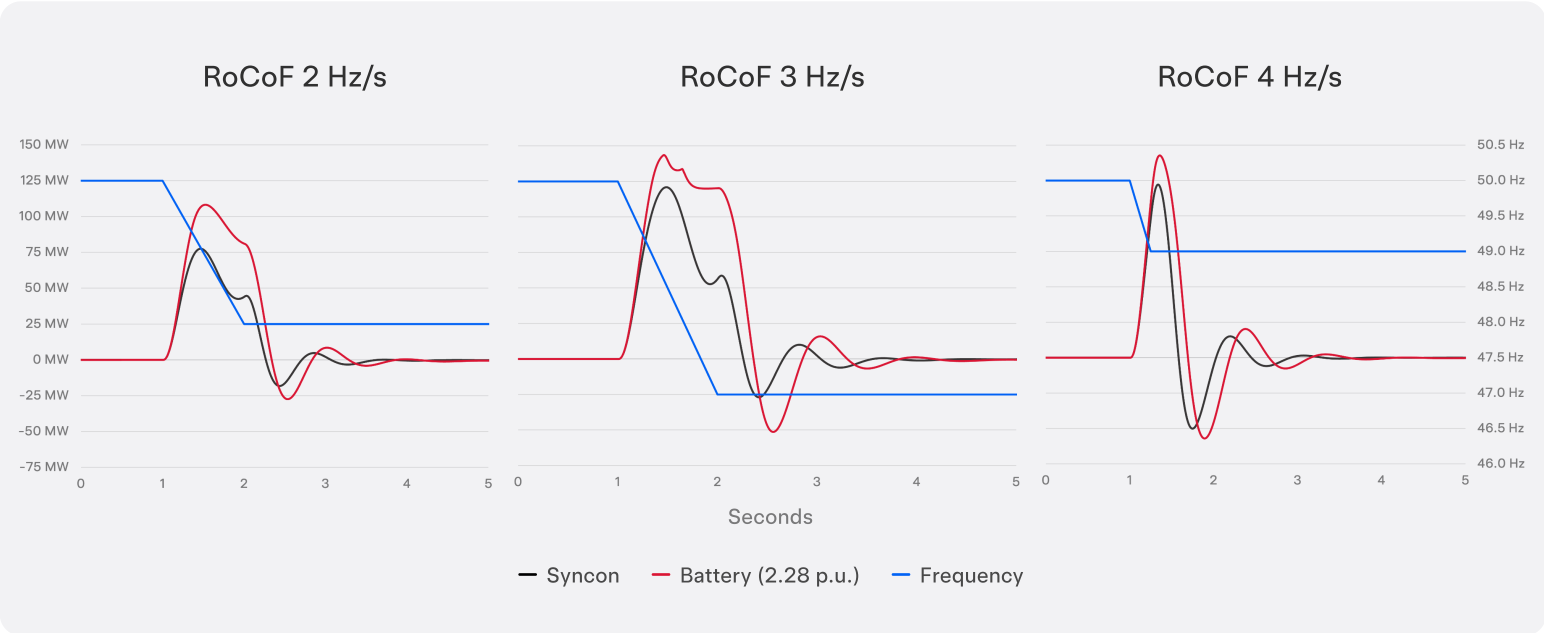


Figure 13: Simulation based inertia response of syncon, modified grid-forming plant with 128% overload capability under RoCoFs of 2, 3, and 4 Hz/s

Grid-Forming Batteries Can Effectively Provide Inertia When Configured With the Appropriate Settings

Tesla's simulation modelling highlights the significant adverse impacts from applying restrictive requirements in the GPS negotiation framework.

When modelled with more suitable settings, the battery was able to provide comparable – or greater– inertial responses to RoCoF events ≤ 1 Hz/s (noting all RoCoF events in the NEM in this range since 2020) and could also respond to those frequency disturbances through PFR. PFR and inertia work together and have a dynamic relationship in balancing frequency disturbances.

For RoCoF events > 1 Hz/s, Tesla recommends adjusting the inverter overcurrent limit if it is required to mimic the response of a syncon. However, a large overcurrent capability of the inverter may not be necessary if RoCoF can be contained to a reasonable value via fast primary reserve before the engagement of the inverter current limiter.

While grid-forming batteries can be tuned to provide similar responses to syncons, it's important to recognise that they are different technologies.

Technical assessments should focus on power system outcomes, rather than replicating the characteristics of legacy synchronous sources of inertia.

Tesla highlights the importance of defining the project goal early in the connection process and having early discussions with network service providers to assess the trade-offs associated with strict GPS requirements.

Future extensions for simulation modelling include considering the battery performance in different grid conditions, operational profiles, and considering a broader suite of network support services beyond inertia.

Site Data

Examples of Grid-Forming Inertial Responses in the NEM and Beyond

Hornsdale Inertial Response to a Frequency Contingency Event

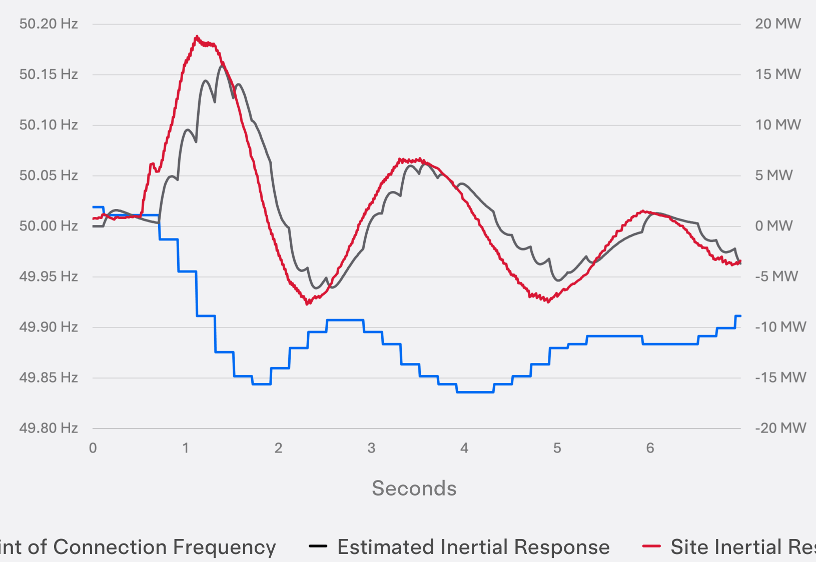
Figure 14 illustrates the inertial response of Hornsdale Power Reserve (HPR) to a frequency contingency event on August 4, 2023.

The black line indicates the estimated inertial response expected from grid-forming batteries, and the red line shows the actual site inertial response from HPR.

At the start of the event, the frequency (blue line) drops below 50 Hz due to a disturbance. In response, HPR rapidly injects power (as shown by the red line), peaking at around 18 MW within milliseconds. This immediate response helps mitigate the RoCoF, stabilising the system.

As the frequency gradually recovers, HPR adjusted its output to maintain stability. The site response closely aligns with the estimated inertial response (black line), demonstrating grid-forming batteries are a predictable and effective solution, as modelled.

Hornsdale Estimated and Measured Inertial Response



Note: estimated inertial response is shown as a less smooth than actual inertia due to a lower resolution frequency reading (blue line) used to calculate it (black line).

Figure 14: Hornsdale Power Reserve response 4 August 2023

Hornsdale Inertial Response to a Frequency Contingency Event – Calculations

The overall site response consists of three key components: AGC, PFR, and inertia response. To analyze the inertia response, the AGC and PFR components were calculated and removed. This approach allows for isolating the site-specific inertial behavior during the frequency contingency event.

The site-specific inertia response was calculated through the following methodology:

- Take half cycle resolution active power and frequency data from Power Quality Meter at point of connection for HPR
- Calculate expected inertia based on the frequency data
- Calculate expected frequency response based on the frequency data
- Sum expected inertia and expected frequency support to get Estimated Total Response and then overlayed with Site Total Response

Minor discrepancies between estimated and site response can be attributed to measurement challenges in the dataset. The half cycle data Tesla has access to is defined at the point of connection, when machine and frequency response is being done at the inverter level, where frequency is likely to vary slightly.

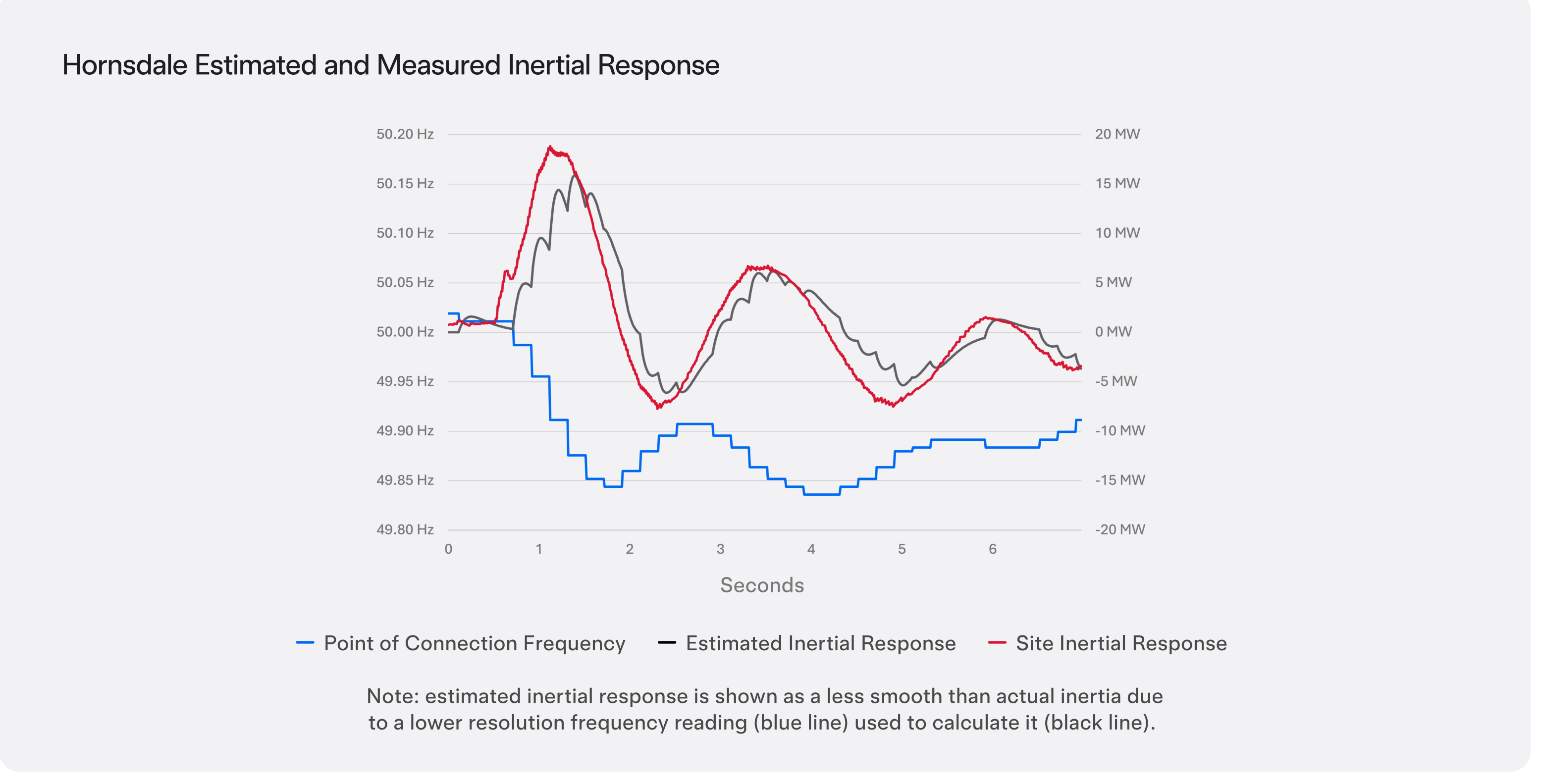


Figure 15: Hornsdale Power Reserve response 4 August 2023

Hornsdale Inertial Response to a Frequency Contingency Event – With PFR

In addition to the site's inertial response, HPR provides PFR during the same contingency event to stabilize system frequency after a disturbance by adjusting active power output in proportion to frequency deviation. Understanding the interaction between inertia and PFR is essential for evaluating the full frequency support capability of grid-forming assets.

Figure 16 illustrates this relationship between providing PFR and inertia from HPR during a frequency contingency event on August 4, 2023.

- Site inertial response (red line) corresponds and is proportional to delta RoCoF.
- Site frequency support response (green line) corresponds and is proportional to delta frequency. If POC frequency is below the deadband, then the PFR will be correspondingly above 0 MW.

The combination of the two active power responses enabled HPR to contribute to balancing the NEM after a frequency disturbance.

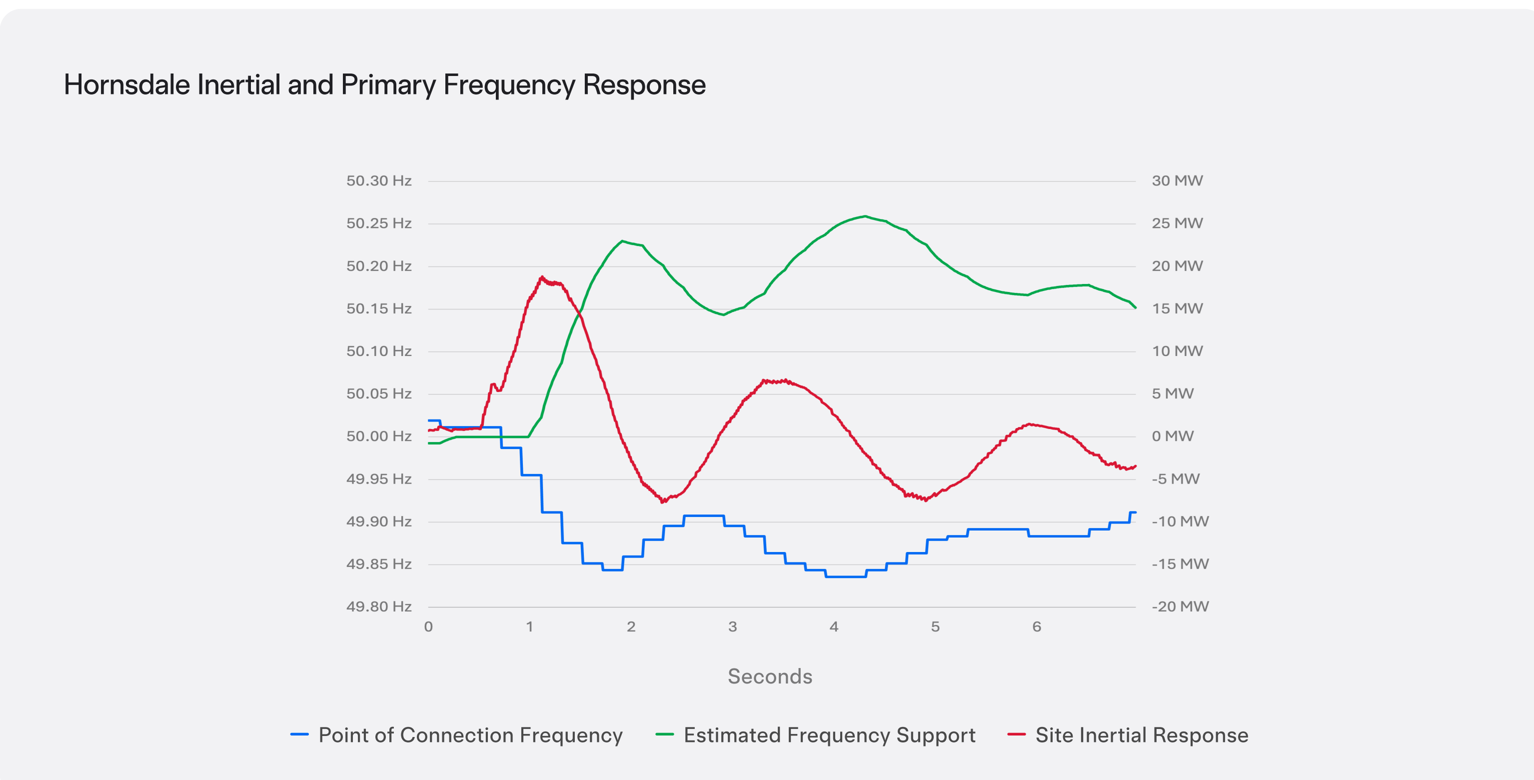


Figure 16: Hornsdale Power Reserve response 4 August 2023

Misconceptions

Challenging Common Misconceptions of Grid-Forming Batteries

Common Misconceptions of Grid-Forming Batteries

Myth	Reality
① **"Grid-forming batteries can't provide inertia like traditional synchronous generators as they lack physical spinning mass or is slower to respond to disturbances."**	Grid-forming batteries can provide synthetic inertia by emulating a voltage source behind an impedance and the swing equations of synchronous machines. Unlike grid-following inverters, they don't rely on frequency measurements to respond. Instead, their response is intrinsic to their control architecture, delivering a fast, stabilising response in milliseconds comparable to physical inertia.
② **"Synthetic inertia is less reliable than traditional inertia because it is software driven and not mechanical."**	Synthetic inertia offers similar response speeds and is more reliable than traditional inertia. Grid-forming batteries are a more reliable source of inertia due to the modular nature of batteries, with the average availability rate of batteries in ERCOT (Texas) at 97.7% in 2023. In contrast, a small mechanical issue in a synchronous machine can cause the entire plant to go offline.
③ **"Syncons are a commercially superior option to grid-forming batteries as networks can directly procure a syncon with lower capex and therefore expand their network asset base at lower cost to consumers."**	Grid-forming batteries are multi-use assets that can value stack across a range of market services such as energy, frequency, bilateral contracts, as well as inertial and system strength contributions. Unlike single-use assets, they can recover their cost through other market-facing activities while still providing reliable inertia contributions when needed. Grid-forming batteries are also able to be flexible based on market signals and can evolve their services as system needs change. As battery installs scale, capital costs continue to drop, and deployment timeframes are accelerating. In contrast, syncons face increasing lead times and costs. New syncons face a lead time of greater than 30 months for delivery and installation, around 12-18 months to add a clutch to existing generator if no foundation modification, and up to 48 months for larger units to add a flywheel, all excluding connection. Retrofitting existing generators as syncons have further significantly higher opex than a purpose built syncon.[14] The Australian Energy Market Commission's (AEMC) 2024 Directions Paper on the Efficient Provision of Inertia placed the fixed and variable costs of new syncons as both being multiples larger than supplying inertia from inverter-based resources (see figure 17).

	Fixed Cost ($ / MW•s / year)	Variable Cost ($ / MW•s / hour)
New syncon for inertia	$7,600	$0.20 - $0.50
New grid-forming BESS	$0 - $806	$0.02 (avg)

Figure 17: AEMC, "Efficient provision of inertia directions paper", December 2024

14 ARENA, "Repurposing existing generators as synchronous condensers", June 2023

Common Misconceptions of Grid-Forming Batteries (Continued)

Myth	Reality
④ **"Inertia from inverters requires constant energy draw, reducing battery efficiency."**	Grid-forming batteries provide small inertial responses during normal conditions, with immaterial impact on efficiency. Frequency disturbances in typical operations tend to have low Rates of Change of Frequency (RoCoF) and short duration, so the associated energy loss is minimal. While large disturbances can have a greater impact on battery operation, such events are infrequent and do not affect day-to-day performance. This is demonstrated in HPR, where the batteries operate in "inertia mode" for mere seconds during disturbances, using a reserved power margin that doesn't disrupt their primary functions, such as energy dispatch.
⑤ **"Grid-forming batteries are limited in providing inertia due to the need to reserve energy headroom."**	The need to reserve energy headroom to provide inertia service is a commercial consideration that can be optimised rather than a technical limitation. A relatively minor amount of battery energy is consumed to provide because of inertial responses. While inverters in grid-forming do draw more switching losses than grid-following inverters that could be inactive, these losses can be offset from the grid via control modes that maintain battery energy, reducing throughput, but at some cost to the owner. Batteries typically avoid reaching minimum state of charge (SOC) for commercial reasons and spend limited time at their active power limit, and this behaviour is not representative of their usual cycling patterns, maintaining energy headroom. Energy reserves are not always fully utilised, and in cases of positive RoCoF, adjustments can be made based on operator requirements, indicating that this is more of an operational decision than a technical constraint. Operators have the flexibility to manage the balance between inertia and reserve on a site-by-site basis and have the option to adjust the inverter's overload capability. Moreover, the required reserve doesn't have to be substantial; energy bursts for inertia are very short, so the demand is not significant. In the mainland NEM, AEMO has not monitored any RoCoF event of greater than 0.8 Hz/s.[15]

15 AEMO "Frequency Monitoring – 4th Quarter 2024", January 2025

Common Misconceptions of Grid-Forming Batteries (Continued)

Myth	Reality
⑥ **"Synchronous condensers have a much better overload capability, making them a better provider of inertia."**	In the NEM, syncons have a 3 – 5 p.u. overload capability, whereas grid-forming batteries are currently around 1.2 p.u.. However, if there is a market or actual need for such characteristics grid-forming battery facilities can have more inverters installed to increase the fault current as required.
⑦ **"Grid-forming batteries cannot provide fault current, which is a requirement for providing network support services (system strength)."**	Historically, fault current was used as a proxy for system strength because it was directly tied to the physical characteristics of synchronous machines. These machines inherently produced large amounts of fault current due to their rotating mass and electromagnetic design, which also made them capable of maintaining voltage and frequency stability. Because fault current and system strength came from the same source, one was used to infer the other. However, this relationship no longer holds with grid-forming batteries, which can provide system strength without needing to produce high fault currents. As a result, fault current is no longer a necessary metric for providing network support services. Tesla's position is that new technologies should aim to replace the functional outcomes of legacy systems, not replicate their underlying characteristics. Today, the main application for fault current is to distinguish between a fault and normal operation in protection relays. Almost all transmission networks already use differential relays for primary and distance for backup rather than legacy overcurrent relays for their protection schemes.[16] For the distribution network that still uses overcurrent protection relays, a deep fault in distribution is a shallow fault in transmission – therefore there is not a significant overload contribution required. Furthermore, as we see an increase in generators, the base MVA will increase with more plants contributing to fault current, reducing the need for significant overcurrent capability.

16 Powerlink, "Protection Design – Standard Version 11.0", December 2024

Recommendations

Technical, Policy and Regulatory Recommendations

Reviewing the Suitability of the Automatic Access Standard for Grid-Forming Batteries

As more technologies deliver inertia and system services, their implementation should focus on enabling optimal grid outcomes – not mimicking legacy dynamics. AEMO's staged Access Standard Reform has made some progress in streamlining grid-forming battery connections.

However, Clause 5.3.4A(b1) of the National Electricity Rules remains outside the review's scope. It requires proponents to aim for the Automatic Access Standard, prioritising performance metrics over grid stability. As a result, grid-forming batteries are assessed against standards designed for grid-following batteries, creating a major barrier to their adoption. Tesla recommends that issue is addressed through a rule change through the AEMC, or to be addressed by the upcoming grid-forming specific access standard reforms.

(b1) When submitting a proposal for a *negotiated access standard* under clauses 5.3.4(e), 5.3A.9(f), 5.3.9(b)(3), 5.3.12(b)(3) or subparagraph (h)(3), and where there is a corresponding *automatic access standard* for the relevant technical requirement, a *Connection Applicant* must propose a standard hat is as close as practicable to the corresponding *automatic access standard*, having regard to:

(1) the need to protect the *plant* from damage;

(2) *power system* conditions at the location of the proposed connection; and

(3) the commercial and technical feasibility of complying with the *automatic access standard* with respect to the relevant technical requirement.

Figure 18: AEMC, "NER Clause 5.34A (current rules version 227)", April 2025

Grid-Forming Batteries Are a Proven Technology That Play a Key Role in Stabilising the Grid, and Thus Should Be Supported by Targeted Policy Recommendations to Accelerate Their Uptake

This white paper illustrates the technical ability of grid-forming batteries to provide inertia and establishes their equivalence to synchronous condensers in technological maturity. Considering the critical role of inertia in maintaining grid stability, and the flexibility and reliability offered by grid-forming batteries, policymakers should address regulatory barriers to facilitate their integration into the NEM.

Streamline Connection Process

Simplify access standard requirements and fast-track connection processes for grid-forming batteries under the NER for projects demonstrating inertia provision.

Accelerate Deployment

Partnering with ARENA, CEFC and/or government loan programs, offer tax credits or grants to grid-forming batteries to further incentivise developers to increase investment.

Incentivise Retrofitting

Expand ARENA's Grid-Forming Funding program to update suitable grid-following batteries – maximising efficiency of existing grid connections and avoiding additional spend on network assets.

Design Mandatory Specification

AEMO, OEMs, and NSPs to jointly define a mandatory spec embedded in the NER for the provision of mandatory and additional inertia, as well as system strength and voltage stability.

Improve Transparency on Inertia Requirements

Through the NEM Wholesale Market Settings review, design new approach to supersede the current TNSP RIT-T process, which biases RAB additive outcomes such as AEMO publishing annual inertia shortfall assessments per sub-region, triggering tenders if levels fall below 80% of the floor.

Education and Collaboration

AEMO, NSPs, state and federal government, and project proponents to share technical knowledge to improve the procurement and connection process for grid-forming batteries, drawing on insights from global best practice (e.g., per EirGrid's DS3 program).

Accelerate Inertia Procurement Mechanisms

Operational procurement through a real-time inertia market will provide transparent price signals for investment, ensuring that inertia is procured efficiently and cost-effectively.

Glossary

AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AGC	Automatic Generation Control
ARENA	Australian Renewable Energy Agency
CEFC	Clean Energy Finance Corporation
CRI	Commercial Readiness Index
ERCOT	Electric Reliability Council of Texas (system operator)
FCAS	Frequency Control Ancillary Services
FOS	Frequency Operating Standard
GPS	Generator Performance Standards
H	Inertia Constant
HPR	Hornsdale Power Reserve
Hz/s	Hertz per second
IBR	Inverter Based Resources
MW	Megawatts
NEM	National Electricity Market
NER	National Electricity Rules
NSP	Network Service Provider
OEM	Original Equipment Manufacturer
P band	Proportional Band
p.u.	Per Unit
PFR	Primary Frequency Response
PLC	Programmable Logic Controller
POC	Point of Connection
PQM	Power Quality Meter
PSCAD	Power Systems Computer Aided Design
RAB	Regulated Asset Base
RIT-T	Regulated Investment Test for Transmission
RoCoF	Rate of Change of Frequency
SC	Synchronous Condenser
SCR	Short Circuit Ratio
SMIB	Single Machine Infinite Bus
TRL	Technology Readiness Level
UFLS	Under-Frequency Load Shedding
X	Reactance
X/R	Reactance to Resistance Ratio

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