Broken Hill Battery Energy Storage System

Lessons Learnt Report #2

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The purpose of this document is to provide details on the lessons learnt during the initial development, construction, and commissioning phases of the Broken Hill Battery Energy Storage Project.

This Project received funding from ARENA as part of ARENA's Advancing Renewables Program.

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Acronyms and Abbreviations

Acronym/abbreviation	Definition
AAS	Automatic Access Standard
AEMO	Australian Energy Market Operator
AGL	Australian Gas Light Company
ARENA	Australian Renewable Energy Agency
BESS	Battery Energy System
BHBESS	Broken Hill Battery Energy Storage System
DLL	Dynamic Link Library
FIA	Full Impact Assessment
FRT	Fault Ride Through
GFM	Grid-forming mode
GPS	Generator performance Standards
HP	Hold Point
HVRT	High Voltage Ride Through
Hz	Hertz
kV	Kilovolt
km	Kilometre
LOR	Lack of Reserve
LVRT	Low Voltage Ride Through
ms	Milli second
MWh	Megawatt hour
MW	Megawatts

Acronym/abbreviation	Definition
NEM	National Electricity Market
NEMDE	National Electricity Market Dispatch Engine
NER	National Electricity Rules
PSSE	Power System Simulator for Engineering
PSCAD	Power Systems Computer Aided Design
p.u.	Per Unit
POC	Point of Connection
SCR	Short Circuit Ratio
SMIB	Single Machine Infinite Bus
SVC	Static Var Compensator
TRC	Transient Reactive Current
TNSP	Transmission Network Service Provider
UNSW	University of New South Wales

Executive Summary

Broken Hill Battery Energy Storage System (BHBESS), developed by AGL is a 50MW / 50MWh large scale battery storage system located 200m from Transgrid's Broken Hill substation in New South Wales.

The performance of the plant will be verified through an agreed Testing Plan. The Testing Plan has been finalised and was developed in consultation with Transgrid and AEMO prior to the construction of the Broken Hill Battery and includes a combination of power system studies, commissioning tests, and ongoing performance monitoring. The findings of the Testing Plan and any other key learnings will be disseminated though knowledge sharing outputs in the form of knowledge sharing reports.

This report specifically addresses lessons learnt during the initial development, construction and commissioning phases of the Broken Hill Battery Energy Storage System.

1. Project Details

1.1. Project Overview

The Broken Hill Battery Energy Storage System (BHBESS) is a 50MW/ 50MWh large scale battery storage system located 200m from Transgrid's Broken Hill substation in New South Wales. It is connected to the Broken Hill substation via a 22 kV underground cable to the substation 22 kV bus. Broken Hill BESS had successfully completed all hold point (HP1 and HP2) testing and achieved approval for unrestricted commercial operation with full output +/- 50 MW from AEMO and Transgrid on 21 Aug 2024.

The responsible EPC contractor, Fluence/ Valmec, has procured inverters from EPC Power that have grid-forming and islanding functionality. For the initial installation, the inverters were configured to switch from grid-forming to grid-following during a system fault to assist the BESS to meet the technical requirements specified in s5.2.5 of the NER implemented in October 2018.

Following the AEMO review of these technical requirements in March 2023, the requirements have been relaxed. Consequently, a 5.3.9 process is underway to retrospectively modify the functionality of the inverters to remain in grid-forming mode throughout a system fault.

1.2. Project Objectives

Real world experience with the grid-forming battery at Broken Hill is expected to provide greater insight into how such inverters can overcome the voltage stability concerns that have been raised with grid-following inverters.

Early generation inverters have been grid-following, acting as current sources which have been known to interact with the grid (particularly with nearby SVCs) to produce sub-synchronous voltage oscillations. These oscillations cause most concern when they continue for extended periods (hours) without attenuation in weaker parts of the grid.

By definition, weaker parts of the grid are more electrically remote from the main system and get less support to maintain a stable voltage waveform. During a severe fault in such locations the voltage waveform will inevitably be quite distorted. The corollary is that voltage disturbances at weak grid locations have little impact on the main grid.

Modelling performed by UNSW on its testbench has confirmed that the voltage source mode of operation employed by grid-forming inverters can mitigate sub-synchronous oscillations in the remoter parts of the grid where many wind farms and solar farms are expected to connect.

The project objectives are listed below:

- Accelerate commercialization of large-scale battery storage (LSBS) with grid-forming inverters in weak-grid areas.
- Provide a cost-effective alternative to expensive grid-supporting equipment like synchronous condensers.
- Improve system strength to reduce investment risks in renewable energy projects.
- Inform key stakeholders, including Transmission Network Service Providers and AEMO, about grid-forming inverters as a credible source of system strength.
- Assess the need for standardized performance specifications for grid-forming inverters and methods to measure their contribution to system strength.

2. Lessons Learnt

2.1. Construction

The following are the lessons learnt from the construction phase.

1. ***Category:*** **Technical - Primary Design Simplifications**

Lesson Learnt: Adopt a more standardised primary plant design.

The primary design was simplified for this site to compensate for the space constraints of the location. Instead of designing an incoming switchyard for the site with primary circuit breaker switchgear, the incoming switchyard was only provisioned with an isolation point and direct feeds to downstream site-based switchgear. Although this design is very space efficient and cost effective in the primary equipment, it placed significant interdependencies on plant downstream to interface with a much wider range of plant.

If the primary design had been more standard, then each piece of high voltage switchgear on the site would have only had to be largely dependent on its own self, with much less intertripping and interlocking requirements. This would have made the design coordination, construction coordination and pre-commissioning knowledge burdens simpler and easier to construct. Instead, this design demanded a high level of attention and technical speciality in the commissioning team to understand and test the highly meshed secondary system.

It is expected that the same issues as highlighted above could impact the operational phase and particular attention to these will have to be paid in ongoing testing and maintenance works.

Implications for future projects: It is recommended for future projects to adopt a more standardised primary plant design.

2. ***Category:*** **Financial, Logistical -Technical / Equipment Selection**

Lesson Learnt: Allow sufficient budget for quality and supervision of critical equipment items.

The transformers selected for the project presented a number of construction challenges. The transformers suffered from inaccuracies between drawings and hold down points, oil containment quality, tap changer mechanism robustness, gas blanket pressure issues, and electrical performance issues, all of which required rework at remote locations as well as on site. The transformers were built in an overseas facility, but upon delivery at site required to be sent to a Victorian manufacturer's workshops for corrections and quality uplifts. A lesson learnt for AGL on this project is the importance on quality processes and supervision for critical plant equipment demands, especially in a remote location. AGL resources spent a disproportionate amount of time attending to transformer quality issues on this project.

The battery cubes have suffered some intermittent leaks on the cooling system, mainly at a T-joint. Each battery cube has the cooling system pressure tested in the factory for 5 minutes. During commissioning onsite, leaks were observed due to the threads being damaged during cap fit-up (which had utilised thread sealing tape). The T-joints were replaced and an o-ring has been included to prevent future leaks. Newer designs of the battery cube have eliminated the T-joint from the cooling system.

Implications for future projects: It is recommended that future projects allow sufficient budgets for quality and supervision of critical equipment items.

3. ***Category:*** **Logistical, Financial - Location**

Lesson Learnt: Remote location of the project site, inconvenient flight schedules, and the distance from the nearest major city contribute to a very low resource retention rate.

The BHBESS project presents significant challenges for project construction and commissioning due to a lack of competent resources (engineers and tradespeople) and contractors. This shortage has severely impacted the project schedule. AGL's contractors often had to fly in resources from other states, such as Queensland. Rectification of construction and commissioning issues has also been delayed due to the additional time required to mobilise people to the site.

The remote location, inconvenient flight schedules, and the distance from the nearest major city contribute to a very low resource retention rate. This is an ongoing issue.

Implications for future projects: It is recommended that future projects account for these challenges by allocating additional time and cost contingencies in the project schedule and budget.

4. ***Category:*** **Other - Health, Safety, and Environmental Competency**

Lesson Learnt: Health, Safety, and Environmental Competency

AGL and its contractors struggled to find fully experienced and competent local contractors and resources, particularly in the areas of health, safety, and environmental management. To address these issues, AGL mobilised additional health, safety, and environmental experts to the site to monitor the contractor's work and rectify HSE-related shortfalls. This includes a full-time site representative, a full-time environmental advisor, and increased coverage from the health and safety advisors.

Implications for future projects: It is recommended that future projects include additional supervision, comprehensive training, and stringent safety processes when working with local subcontractors.

2.2. Commissioning and Testing

The following are the lessons learnt from the commissioning and testing phase.

Category: Technical - Hold Point Testing

Lesson learnt: As a result of the commissioning activities conducted under minimum SCR (N-1) network conditions, the BHBESS's full output was frequently curtailed due to network limitations. This is because the dispatch signal from AEMO was capped below 50 MW by the NEMDE engine, based on real-time assessments such as line loading, thermal limitations, outputs of nearby assets, and other factors.

Due to the forecasted Lack of Reserve (LOR) in NSW and concerns reactive power oscillations observed during HP1 testing, AEMO also halted BHBESS HP2 testing for a few days, which caused delays. The main issue initially identified was that the BESS exhibited a small duration underdamped reactive power oscillation (1-2 cycles) during the voltage reference step test with a single inverter online. However, this behaviour could not initially be replicated in the PSCAD and PSSE software, which posed challenges to the model's validity for all parties in progressing from HP1 to HP2.

Since the model was aggregated, AGL and Fluence then spent significant time creating a single inverter modelling case in PSCAD and PSSE to replicate the reactive power oscillations observed on-site under voltage control mode with the single inverters online.

When more inverters were brought online, the oscillations became more significant, leading to the hypothesis that the oscillations were primarily originating from the BESS as seen in single inverter testcase. To investigate further, an extended SMIB model was developed in HP2 as well as Transgrid and AEMO did limited FIA studies, which demonstrated that the oscillations were predominantly due to network interactions.

The need to repeat tests due to these oscillations and efforts to identify their root cause also led to unexpected re-testing during HP2, including a single inverter test initially conducted in HP0.

Transgrid required BHBESS to perform an analysis on the single inverter test to address oscillation issues observed during the step test in HP1. Although the adjustments made to dampen the response improved oscillation issues, they significantly impacted other performance aspects, such as frequency disturbances.

Additionally, the model was not previously tuned for single inverter response during earlier stages (i.e., R0, R1). The proposed tuning could further delay the commissioning process, potentially affecting the GPS study and necessitating redoing the GPS and FIA studies, which could push the project back to the R0 stage.

Further inverter tuning doesn't guarantee that the agreed performance for different GPS clauses will remain unaffected, which could only be verified by AEMO/TG through extensive due diligence studies. If the point of connection responses are in line with the GPS, a key lesson learned is that any attempt at inverter tuning to improve responses during the commissioning phase might delay the overall project timeline.

Another challenge was modelling the site's reactive power oscillatory response in the PSSE model. The PSSE SMIB model up to the POC was incapable of doing this. Therefore, an extended SMIB model upstream of the POC was developed to capture the impacts of nearby assets (e.g., Synchronous Var Compensator, Solar Farms, and Wind Farms) to replicate the observed reactive power oscillation at the site in the model.

Implications for future projects: Due to the location of the BHBESS plant and the undertaking of hold point testing with a single Transgrid transformer (22/220kV) in the Broken Hill Substation (a N-1 condition), the commissioning team faced several challenges. Notably, reactive power and active power oscillations were observed during the voltage reference step test and reactive power step test, which could not be replicated through the SMIB PSCAD model. This raised questions among various parties about the source of the oscillations, whether they are originating from the BESS or from the network. Since AGL does not have a wide-area PSCAD model, it remained unclear whether these oscillations result from network interactions. This can only be confirmed through limited FIA studies, which can only be performed by AEMO or the NSP. However, FIA studies might not always be sufficient to reproduce the oscillations, hence a small-signal model analysis may be required to determine the source of the oscillations. Therefore, development of a small-signal model is a key lesson for future projects.

2.3. Registration

***Category:* Regulatory – Registration of the BESS to the NEM**

Lesson learnt: During the registration process, recent changes were encountered in the technical requirements (s5.2.5) due to the latest NER modifications for reactive current injection. The requirement for settling time was removed, and commencement time for reactive current injection was introduced. Additionally, the wording for reactive current injection during balanced and unbalanced faults was modified. This change was necessary because, for grid-forming inverters which operates as a voltage source, there is no direct control over the inverter current; instead, the inverter terminal voltage should be controlled at specific levels such as 1 p.u.

This adjustment was made due to the fact that the BHBESS inverter would operate in grid-forming mode continuously for its normal operation. However, beyond the normal operation with the current design, the BHBESS inverter switches from grid forming to grid-following mode only for a deep fault ride through event (e.g. LVRT or HVRT event). However, at the request of ARENA/AEMO, it was agreed that it will be adjusted to remain in grid-forming mode even during these events following the 5.3.9 process of GPS application.

Moreover, as part of the registration process, AEMO requested modifications to the BHBESS inverter performance to align with their voluntary specifications for grid-forming inverters. Although these voluntary specifications are not part of the NER/GPS, complying with them was necessary for registration. This alignment was crucial to ensure the BHBESS operates efficiently and meets the anticipated performance standards set by AEMO.

Implications for future projects: When the project was kicked off, the industry's knowledge of grid-forming technology was not mature. Before AEMO published its voluntary grid-forming mode (GFM) specifications, no other recognized industrial standards for GFM were available. This posed a significant challenge for the BHBESS project in understanding AEMO's and TG's expectations while also meeting the existing NER requirements.

The contemporary NER primarily focuses on grid-following capabilities, such as reactive current injection/absorption performance under S5.2.5.5 clauses. Since grid-forming BESS does not have direct control over current, meeting this GPS requirement necessitated significant functional and architectural changes to the project. This highlights the need for future projects to have some flexibility in the NER to accommodate new technologies and for NSPs or regulatory bodies to treat them differently.

2.4. Alteration to the performance standards in the connection agreement - 5.3.9 process

Category: Technical

Lesson learnt: During the wide area studies (FIA) performed by Transgrid/AEMO in the wide area PSCAD model including the BHBESS, the following issues were identified:

- **Reactive Current (Iq) Control Issues:**
  For shallow faults, the reactive current (Iq) did not follow the Iq reference while in grid-forming mode. The Iq reference responded correctly to voltage changes, but the actual response remained in phase with the voltage. This behaviour was not as expected for a grid-forming inverter.
- **Inconsistent Response During Disturbances:**

The plant did not exhibit a consistently controlled response during disturbances. The Iq response to grid voltage changes did not always stabilize the grid voltage, especially in grid-forming mode during shallow faults and in grid-following mode for some deeper faults. The controller struggled to follow the reference during disturbances, although the measured response eventually aligned with the reference signal once the fault was cleared.

- **Bandwidth and Realignment Timeframe:**
  Questions remained about the bandwidth where grid-forming/voltage source-like behaviour is expected and the timeframe for realignment of the voltage angle during faults. Uncontrolled behaviour was observed for time frames greater than 200ms.
- **Simulation vs. Real Performance:**
  There were concerns about whether the observed issues were due to modelling artifacts or actual design/hardware limitations. It was suggested that the model response is likely close to the real response, but validation through R2 testing is required.

Also, in the PSCAD SMIB studies, the following issues were found:

- **Tripping for some of the multiple FRT faults:**
  BHBESS trips on certain multiple fault sequences with time between recurring faults less than 250ms. AGL proposed to use negotiated access standard for this in the GPS for registration to reflect the actual modelled performance of plant. AGL believe that a negotiated position is acceptable for this clause at this point in time due to the very unlikely nature of two consecutive faults at the connection point.
  AGL committed to reviewing the performance and attempting to return to the AAS for this clause and will propose a solution with an appropriate amount of justification. This may require the use of the s5.3.9 process to complete. AGL will continue to work with Transgrid and AEMO to ensure that the fix is appropriate in terms of plant and power system impact.
- **Iq Response and HVRT exit:**
  When HVRT is activated, the plant shows an oscillation in Iq response when operating under minimum SCR (new minimum of 4.12 at the 22kV POC bus). This also leads to early HVRT exit. The issue is due to a more aggressive voltage response with the new

SCR tuning of 4.115 leading to an oscillation against the system voltage and a false trigger on the HVRT exit threshold.

AGL believe that this can be fixed by applying a further filter to the TRC response.

AGL proposes to accept the behaviour for registration and commits to working through the implementation of the fix and demonstration of its effect prior to commercial operation. This may require the use of a s5.3.9 process to complete a fix and AGL will work with Transgrid and AEMO to agree a scope as more details become available.

As a result, due to timeline of the project and to progress the project, AEMO and Transgrid have requested AGL to undertake a s5.3.9 process after registration to fulfill the following actions:

- Clarify grid-forming behaviour: Confirm if the grid-forming mode is controlled like a voltage source and specify the bandwidth where voltage source-like behaviour is expected to stop.
- Voltage Angle Realignment: Determine the expected timeframe for voltage angle realignment during faults and assess if realignment time increases with voltage changes.
- Model Validation: EPC to provide a letter confirming that prior HIL testing has validated the PSCAD model for Broken Hill BESS.
- Post-Registration Considerations: Address any necessary changes post-registration, with the understanding that any modifications to the agreed GPS will trigger the NER s5.3.9 process.

Implications for future projects: BHBESS is planned to go through the s5.3.9 process to improve the aforementioned performance through a firmware/software update. Since this process involves changes in the model, further due diligence studies will need to be conducted by AEMO and NSP, followed by the verification of the modelling performance through the commissioning process. This process entails additional cost and resourcing impacts.

As discussed earlier, GFM expectations were not well defined at the project's outset, which is why the project is proceeding with this change at a later stage instead of addressing these issues from the beginning. This highlights the need for future projects to have some flexibility in the NER to accommodate new technologies and for NSPs or regulatory bodies to treat them differently.

3. Technical Requirement Challenges

As discussed in section 2.3, during the registration process, recent changes were encountered in the GPS requirements due to the latest NER modifications for reactive current injection. The requirement for settling time was removed, and commencement time for reactive current injection was introduced. Additionally, the wording for reactive current injection during balanced and unbalanced faults was modified. This change was necessary because, for grid-forming inverters which operates as a voltage source, there is no direct control over the inverter current; instead, the inverter terminal voltage should be controlled at specific levels such as 1pu.

This adjustment was made in anticipation that the BHBESS inverter would operate in grid-forming mode continuously. Currently, the BHBESS inverter switches to grid-following mode during LVRT/HVRT events. However, at the request of ARENA/AEMO, it will be adjusted to remain in grid-forming mode even during these events.

Moreover, as part of the registration process, AEMO requested modifications to the BHBESS inverter performance to align with its voluntary specifications for grid-forming inverters. Although these voluntary specifications are not part of the NER/GPS, complying with them was necessary for registration. This alignment was crucial to ensure the BHBESS operates efficiently and meets the anticipated performance standards set by AEMO.

4. Conclusion

In summary, the Broken Hill Energy Storage System (BHBESS) project has raised several critical lessons across its stages, through development, construction and commissioning. The registration phase saw the introduction of new regulatory requirements and necessary alignment to grid forming standards, which introduced additional complexities and potential project delays. Specially, changes in technical requirements (s5.2.5), including the removal of settling time and modification to reactive current injection protocols, required significant adjustments to the inverter's operational modes and performance.

The remote location significantly impacted construction execution, demanding the need for better logistical planning and additional contingencies to address the lack of resource availability.

During commissioning and testing, challenges such as network operates under N-1 condition, oscillation issues, and unexpected retesting emphasized the importance of a need for well-designed testing schedule and responsive adjustments to address performance abnormalities.

For future projects to take advantage of these lessons, considering the need to improve modelling activities, make the modelling consistent throughout all phase of the project and proactive engagement with regulatory changes. Addressing these challenges comprehensively will be essential for optimizing project execution, ensuring compliance, achieving successful integration into the grid.

5. Associated Parties and Project Contact Details

agl	Proudly Australian for more than 185 years, AGL operates Australia's largest private electricity generation portfolio within the National Electricity Market, comprising coal and gas-fired generation, renewable energy sources such as wind, hydro and solar, batteries and other firming technology, and gas production and storage assets. We are building on our history as one of Australia's leading private investors in renewable energy to now lead the business of transition to a low emission, affordable and smart energy future in line with the goals of our Climate Transition Action Plan. AGL owns and maintains the 50MW / 100MWh battery, which provides both regulated network services and competitive market services.
Australian Government Australian Renewable Energy Agency ARENA	ARENA is the Australian Renewable Energy Agency and supports improvements in the competitiveness of renewable energy and enabling technologies, increase the supply of renewable energy in Australia, and to facilitate the achievement of Australia's greenhouse gas emissions targets by providing financial assistance and sharing knowledge to accelerate innovation that benefits all Australians. ARENA is partially funding this project as part of ARENA's Advancing Renewables Program.
aurecon	Aurecon Group Pty. Ltd. is an engineering, management, design, planning, project management, consulting and advisory company based in Australia. Aurecon is undertaking the power system network modelling for this Project.
UNSW SYDNEY	The University of New South Wales (UNSW) is a public research university based in Sydney, New South Wales, Australia. UNSW, in conjunction with AGL is undertaking the power system studies and the simulations for this Project.

FLUENCE A Siemens and AES Company	Fluence Energy brings proven energy storage products and services, and digital applications for renewables and storage to support the modernization of our energy networks. Fluence Energy is the Engineering, Procurement and Construction (EPC) Contractor for this project.
worley consulting	Worley Consulting Pty. Ltd. is the advisory and specialist consulting arm of Worley Pty. Ltd. Worley Consulting is the Knowledge Sharing Partner for the Project.

For more information on the Project, please visit the Broken Hill BESS Project Portal located at the following address: https://www.agl.com.au/about-agl/how-we-source-energy/broken-hill-battery-energy-storage-system?zcf97o=vlx3ap

The portal contains the ability to ask questions of the project team. It also contains relevant information including:

- Construction update of the Broken Hill BESS
- Planning and environmental approvals

All publicly published Knowledge Sharing material, including key reports, operational updates, presentations and access to live and historical data from the operational BESS will be uploaded progressively as they are made available.