OVEN MOUNTAIN
PUMPED HYDRO STORAGE

OMPS New England PHES Benefits Study - Knowledge Sharing Interim Report

Dr Jeremy Moon

April 2022

Photo - Georges Junction, Macleay River. Approximately 6kms downstream from the Oven Mountain project site.

Acknowledgment of Country

The Oven Mountain project acknowledges the Thunggutti people, Traditional Custodians of the land on which we operate, and pay our respects to their Elders past and present. We also extend that respect to Aboriginal and Torres Strait Islander peoples across this nation.

The Oven Mountain Pumped Hydro Energy Storage project received funding from the Australian Renewable Energy Agency (ARENA) as part of ARENA's Advancing Renewables Program.

Foreword
A Conversation Worth Having

If recent conferences on energy and battery storage are anything to go by, it is that challenges are best met as a collective whole. Further, that the wins and set-backs of progress are easier to shoulder in a like-minded crowd.

Continued engagement offers businesses and government agencies the opportunity to show how they are working to meet the challenges posed by our evolving energy market. The dilemma remains the same: how do we maximise Australia's abundance of renewable energy resources in a reliable, sustainable and affordable manner that meets future market needs.

The challenges are ambitious and pressing. The *Draft 2022 Integrated Systems Plan* notes the scenario as a "once-in-a-century transformation in the way society considers and consumes energy" (AEMO, 2021, p.8). In November 2021, the *NSW Electricity Infrastructure Roadmap* sought to "drive integrated and coordinated investment in large-scale electricity infrastructure, specifically generation, transmission, and firming of variable renewable electricity" (DPIE, 2020, p.26). Casting our minds a little further back, in June 2017, in his remarks to the National Press Club, Dr Alan Finkel AO noted that "business as usual is not an option" (Finkel, 2017).

The Oven Mountain Pumped Hydro Energy Storage Project (the Oven Mountain project) uses mature and tested technology to provide long-duration storage and flexible dispatchable renewable generation.

The project will be integral in providing clean, reliable, and resilient energy storage and generation capabilities for the New England Renewable Energy Zone and broader New South Wales.

We are pleased to have received support from the Australian Renewable Energy Agency's (ARENA) *Advancing Renewables Program* and recognise the importance of ongoing engagement and knowledge sharing activities.

This Interim Report is provided as part of Milestone Two of the Program, and highlights our journey so far. The report provides information on the Oven Mountain project, including its timeline. It also examines the merits of both the project and Pumped Hydro Energy Storage on various network system services, and shows how it will help unlock energy initiatives within the New England Renewable Energy Zone.

Our collective path to a more reliable, sustainable and affordable energy future is a discussion worth having. The Oven Mountain project team are pleased to be an integral part of this conversation.

Sincerely,

Dr Jeremy Moon

Project Director

OMPS

Table of Contents

1 Executive Summary

Pumped Hydro Energy Storage has an integral role to play in firming the energy market as it moves away from coal generation, towards varied renewable energy, such as solar and wind.

The *Draft 2022 Integrated Systems Plan* (ISP) notes, “as sun, wind and water become NEM’s (National Electricity Market’s) primary energy resources, supported by gas, it will become increasingly complex to preserve the resilience of the system against a broad array of extreme weather and climate impacts” (AEMO, 2021, p.22).

On the unprecedented challenge ahead, the Plan emphasises the need for coordinated investment that addresses the need to “treble the firming capacity that can respond to dispatch signal, including utility-scale batteries, hydro storage, gas generation, and smart behind-the-meter batteries or ‘virtual power plants’” (AEMO, 2022, p.8). This includes delivering medium storage of 4 to 12 hours duration, including 2GW of storage (in addition to Snowy 2.0) needed by the end of the decade to meet the *NSW Electricity Infrastructure Roadmap* (DPIE, 2020, p.29).

The ISP adds that by 2050, the NEM will require “45GW / 620 GWh (gigawatt hours) of storage in all its forms...Deeper pumped hydro storages will be vital for seasonal and long duration needs as coal exits the market at scale” (AEMO, 2021, p.10).

The Oven Mountain Pumped Hydro Energy Storage project is an ‘off river’ pumped hydro energy development located adjacent to the Macleay River between Armidale and Kempsey.

The project is currently subject to the environmental and planning process via an Environmental Impact Statement. Once completed, the project will be rated at 7.2 GWh with a base case of 12 hours.

The Oven Mountain project has received funding from ARENA as part of their *Advancing Renewables Program*. The funding supports investigations on the behaviour of the Oven Mountain project and the benefits of Pumped Hydro Energy Storage to the New England Renewable Energy Zone (REZ).

As part of the Program, the Oven Mountain project has also undertaken network stability tests and investigated Pumped Hydro Energy Storage (PHES) impacts on interregional transfers and renewables hosting support.

The main outcomes from these studies are that PHES is a strong Renewable Energy Zone and renewable energy supporter; and that Pumped Hydro can increase the amount of reliable dispatchable energy within the REZ when demanded.

Specifically, the studies show that a PHES at 900MW can support at least 1,575MW of new renewable generation in the New England REZ based on stability limitations of the current network and likely more.

Further, PHES is able to add additional generation to the REZ in periods of high demand. Together, these are a win in getting more out of existing networks, supplying energy reliability while keeping downward pressure on the cost of energy.

Situated in the recently declared New England REZ, the Oven Mountain project will bring significant benefits to New South Wales, including an expected increase in the hosting capacity for other renewable plant in the broader area covered by the REZ.

The project will also provide significant firming capacity, improve system strength, increase inertia, provide substantial voltage support, bolster the black start capability and potentially benefit total system losses by providing a load sink in the New England REZ during periods of high renewable output and lower system demand.

The Report serves as an ongoing knowledge sharing opportunity, which aims to assist both current and future policy makers and investors to make informed decisions aimed at balancing energy reliability, energy security, and cost to consumers.

2 Introduction

2.1 The Need for Renewables

The National Electricity Market is experiencing a pivotal shift away from fossil-fuel generation to a greater prevalence of more affordable variable renewable energy. This transformation has resulted in the need to ‘firm up’ renewable technologies that are subject to weather extremes, and modernise the energy network and market.

The *NSW Electricity Infrastructure Roadmap* notes, “NSW’s existing generation and transmission network took around 30 years to plan and build, but the majority of this infrastructure needs to be replaced in less than 15 years. The window to replace generation capacity could narrow further if power stations close early, especially given the growing risk of failure inherent as thermal plants age. This signifies the need for an unprecedented rate of investment in electricity infrastructure” (DPIE, 2020, p.25).

The reasons behind this energy transformation are varied, but include changes in consumer behaviour, government policy, commercial viability of renewable energy products, and the retirement of thermal plants. On the latter, the *Draft 2022 Integrated System Plan* (ISP) states, “coal (is) retiring two to three times faster than anticipated. Current announcements by thermal plant owners suggest that about 5 gigawatts (GW) of the current 23 GW of coal capacity will withdraw by 2030. However, modeling suggests that 14 GW may do so... All brown coal generation and over two-thirds of black coal generation could withdraw by 2032” (AEMO, 2021, p.9). Figure 1 highlights the forecasted coal retirement schedule to 2030, noting AEMO’s projected ‘step change’ scenario.

With the principles to optimise the consumer benefits of affordable, reliable and secure power, the ISP stipulates that investment in the National Electricity Market is needed to - in part - double the electricity it now delivers, requiring a nine-fold increase in utility scale variable renewable energy capacity; treble the firming capacity that can respond to a dispatch signal; and efficiently install more than 10,000 km of new transmission as part of the transformation (AEMO, 2021, p.8).

With the shift in energy reliance moving at a fast pace - what the ISP calls a ‘step change’ - there rises the need for varying duration storage and generation services. By 2050, the ISP notes, there will be a need to provide 45 GW of storage, including long-duration pumped hydro to manage variations in solar and wind output (AEMO, 2021, p.10).

2.2 The Role of Pumped Hydro Energy Storage

In 2017, the Australian National University completed an audit of 22,000 potential sites across Australia for Pumped Hydro Energy Storage.

The audit noted the important role played by Pumped Hydro in providing reliable and dispatchable generation. It added, “the short-term off-river pumped hydro energy storage sites combined had a potential storage capacity of 67,000 Gigawatt-hours (GWh) - much more than the capacity required for a zero-emissions grid” (ANU, 2017).

The audit stated that Australia would only need to actively pursue a ‘small fraction’ of these sites to reach zero-emission targets.

Pumped Hydro Energy Storage provides a range of critical network support services including inertia, frequency control, voltage control, system restart services and system strength support to the network.

Figure 2 looks at the forecasted rise in variable renewable energy resources, and projected role of varied storage and generation - including Pumped Hydro - in the National Electricity Market.

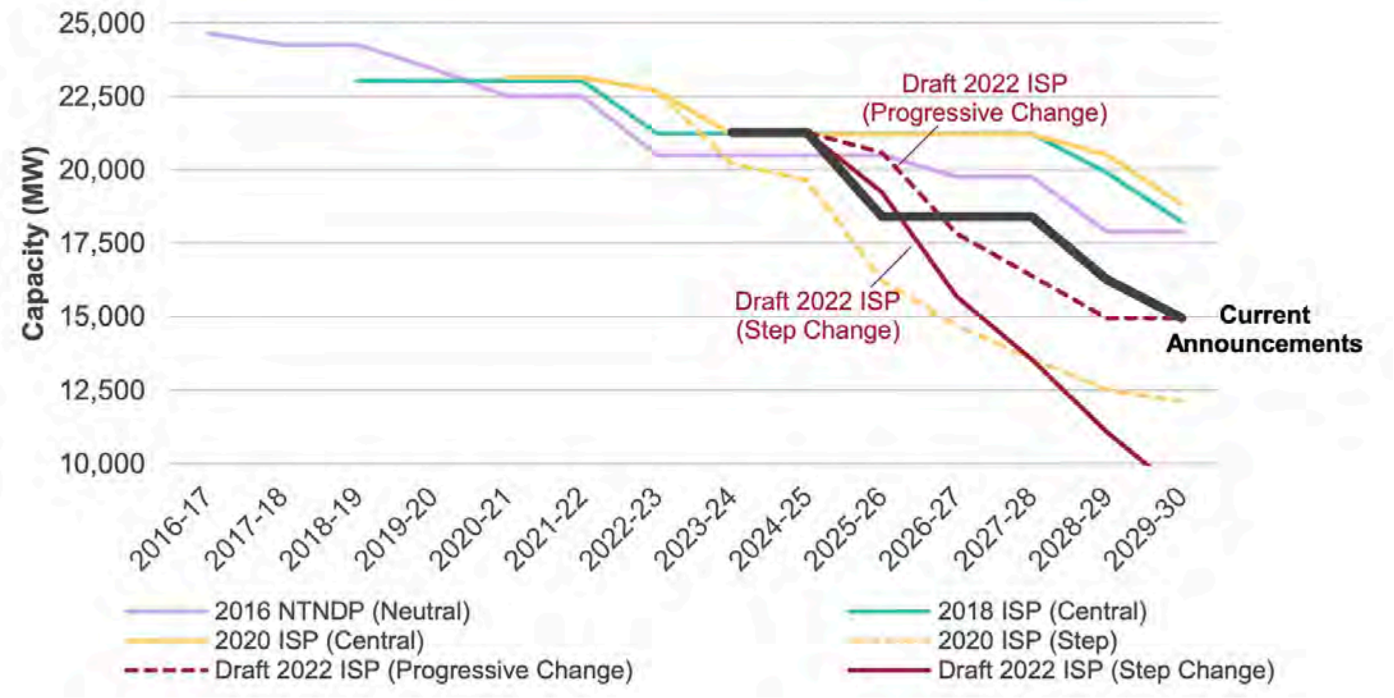


Figure 1 - AEMO's forecast coal retirements and the current announced retirement schedule, 2016-17 to 2029-30 (AEMO, 2022, p.7).

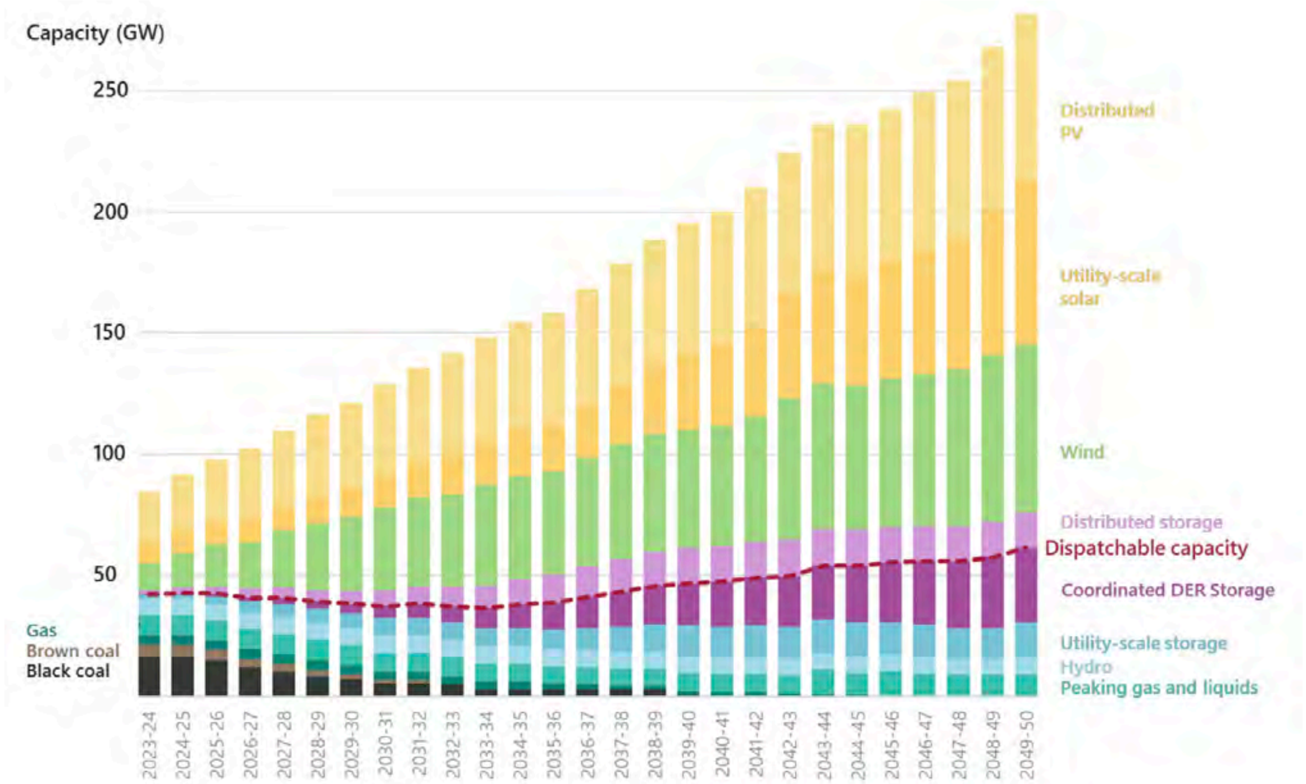


Figure 2 - Forecast NEM capacity to 2050, Step Change scenario, with transmission (AEMO, 2021, p.9).

2.3 The Benefits of Pumped Hydro Energy Storage

Pumped Hydro Energy Storage (PHES) has an integral role to play in firming the energy market as it moves away from coal generation; it is a mature technology that has been successfully implemented across the world.

The *Draft 2022 Integrated System Plan* recognises the necessity for long-duration storage, and therefore, the requirement for PHES, as well as other storage technology. On the challenges of PHES, the *NSW Electricity Infrastructure Roadmap* notes, “pumped hydro projects can make a substantial contribution to NSW’s future electricity storage needs, but they require bespoke design, face long lead times and are capital intensive, which creates a high barrier to their development” (AEMO, 2021, p.30).

The shift towards renewable energy sources, as well as the complementary rise in technology, has seen the development of alternative storage capabilities, including battery, compressed air, and hydrogen based. However, PHES continues to represent the largest form of electricity energy storage globally.

As part of ARENA’s *Advancing Renewables Program* (Milestone 2), the Oven Mountain project has undertaken studies to examine the benefits of PHES as an established storage class.

This work has been coordinated with the guidance of Amplitude Consultants - an Australian-based engineering consulting company that provides specialist consulting services to clients involved in the transmission and distribution of electricity.

It is hoped that the preliminary findings in this Interim Report will assist in demonstrating the important role of PHES in the recently declared New England Renewable Energy Zone.

The Report emphasises that PHES can provide extended duration storage efficiently and cost effectively and provide large synchronously connected mass to a network.

Further, it is hoped that – via ongoing knowledge sharing – the Report allows both current and future policy makers and investors to make informed decisions aimed at balancing energy reliability, energy security, and cost to consumers.

As has been noted, there remains a pressing need to make significant investments into electricity infrastructure in a coordinated manner that considers ‘whole of network’ complexities and benefits.

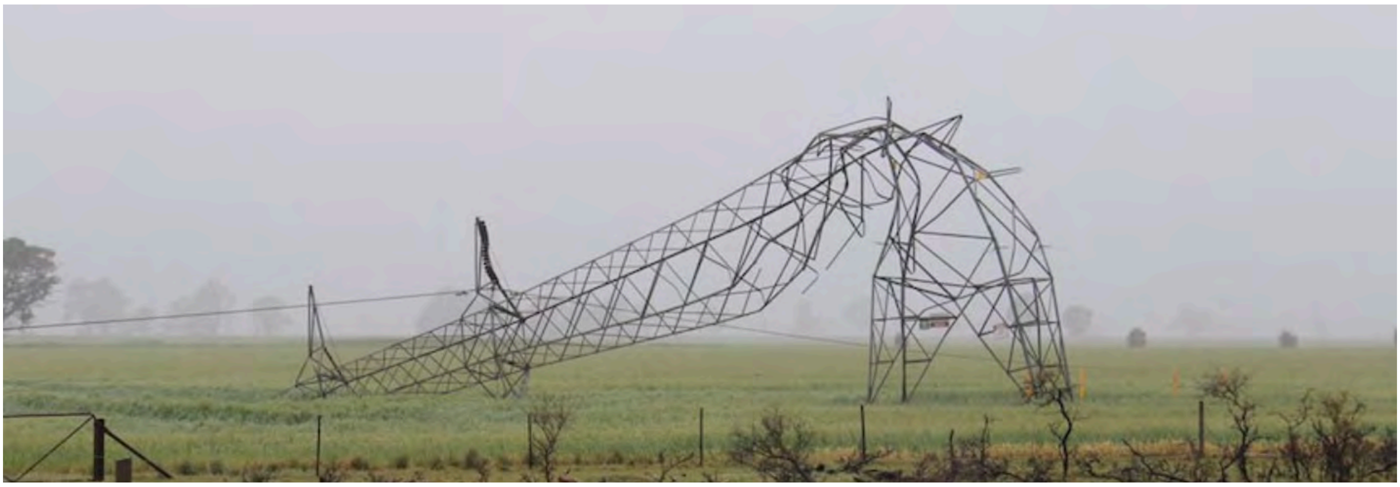


Photo - A collapsed electricity pylon near Melrose, South Australia in 2016 (ABC News, 2016).

Case Study: A State-Wide Blackout and a Step Towards Change

On 28 September 2016, approximately 1.7 million South Australian residents were left without power following a severe storm. The state-wide blackout brought to light the State's reliance on renewable energy resources, with approximately 48 per cent of the State's electricity supply provided by wind farms (AER, 2018).

This major incident also emphasised the need for a coordinated approach to firming and modernising the National Electricity Market, so as to support the growth of more economic variable renewable energy sources, changing consumer demand, retirement of coal thermal power, and extreme weather conditions. The subsequent *Independent Review into the Future Security of the National Electricity Market* (June 2017) noted, "to deliver the desired security, reliability, price outcomes and reduced emissions, the blueprint recommends strengthened governance, system planning and an orderly transition. Without these three supporting pillars, the system will stumble again in future" (Finkel, 2017, p.3).

The key tenets of the National Electricity Market are ensuring future reliability, rewarding customers, providing lower emissions, and increasing security. On the latter, the focus is on ensuring a secure electricity system that is both resilient to the integration of new technology (such as variable renewable energy sources) and to the impacts of extreme weather conditions and natural disasters.

The Review further added:

> security and reliability have been compromised by poorly integrated variable renewable electricity generators, including wind and solar. This has coincided with the unplanned withdrawal of older coal and gas-fired generators. Security should be strengthened through Security Obligations for new generators, including regionally determined minimum system inertia levels. Similarly, reliability should be reinforced through a Generator Reliability Obligation implemented by the Australian Energy Market Commission (AEMC) and the Australian Energy Market Operator (AEMO) following improved regional reliability assessments. These obligations will require new generators to ensure that they can supply electricity when needed for the duration and capacity determined for each NEM region. (Finkel, 2017, p.5)

The subsequent establishment of the Energy Security Board fostered a collaborative environment focused on developing a 'fit-for-purpose' National Electricity Market and a coordinated effort to meet rapidly evolving energy requirements. A key element of this work is the bi-annual report issued by AEMO - the Integrated Systems Plan - which provides a 'whole of system plan' for eastern Australia's electricity system.

Coordination and large-scale investment remain critical in meeting the challenges posed by the evolving energy market. The complexity posed by government policies, changing consumer behaviour, the retirement of thermal power, and commercialisation of renewable energy sources further emphasise the need for collaboration and focused implementation. The resulting dynamic environment necessitates a collective step change.

2.4 The New England Renewable Energy Zone

In December 2021, the NSW Government formally declared a Renewable Energy Zone (REZ) in the New England region around Armidale. This REZ will deliver new network capacity to host up to 8 GW of new generation.

REZs can be considered as modern-day power stations. They combine renewable energy generation such as wind and solar, storage such as pumped hydro energy storage, and high-voltage poles and wires to deliver energy to the homes, businesses and industries that need it.

The development of REZs are integral part of the NSW Government's 'whole-of-system' plan to efficiently develop power systems and community participation that meet the long-term needs of the market. The *Draft 2022 Integrated Systems Plan* (AEMO, 2022, p.38) notes the benefits that REZs will have on variable renewable energy investment, which could then be passed onto consumers:

- Reducing transmission and connection costs and risks,
- Sharing costs and risks across multiple connecting parties,
- Co-locating and optimising system support infrastructure and weather observation stations, and
- Promoting regional expertise and employment at scale.

Under current modeling, the NSW Government believes the New England REZ has the potential to become one of the largest REZs in the National Electricity Market. The *Draft 2022 Integrated Systems Plan* adds, "(the New England REZ) will unlock approximately 5,820 MW of VRE (Variable Renewable Energy) and storage capacity…helping meet the objectives of both the New South Wales Electricity Infrastructure Roadmap and the 2021 IIO Report" (AEMO, 2021, p. 62).

The Plan identifies the need to increase the capability of the transmission network, ensuring sufficient resilience and transfer capacity both within the REZ and broader Hunter region network.

The Oven Mountain project is situated on the eastern side of the New England REZ - within the Armidale Regional LGA, near to the Kempsey LGA.

It is anticipated that the project will play a critical role in ensuring the stability of the future network, complementing other local renewable energy sources, such as solar and wind.

> "New England has some of the best natural energy resources in the country, some of the State's best potential sites for pumped-hydro development and strong investor interest.
>
> Given the proximity of pumped hydro opportunities to the new England Renewable Energy Zone (REZ), these potential projects could complement the development of generation in the REZ, providing dispatchable storage capacity to back up variable renewable generation"
>
> *NSW Electricity Infrastructure Roadmap* (DPIE, 2020, p.8).

Photo - Armidale, situated within the New England Renewable Energy Zone.

3 The Oven Mountain Project

3.1 Project Overview

The Oven Mountain project is an 'off river' pumped hydro energy development located on private land adjacent to the Macleay River between Armidale and Kempsey.

The project is located in the Armidale Regional LGA, approximately 60km southeast of Armidale and 70km northwest of Kempsey, via the Kempsey-Armidale Road. The project is primarily located on private land.

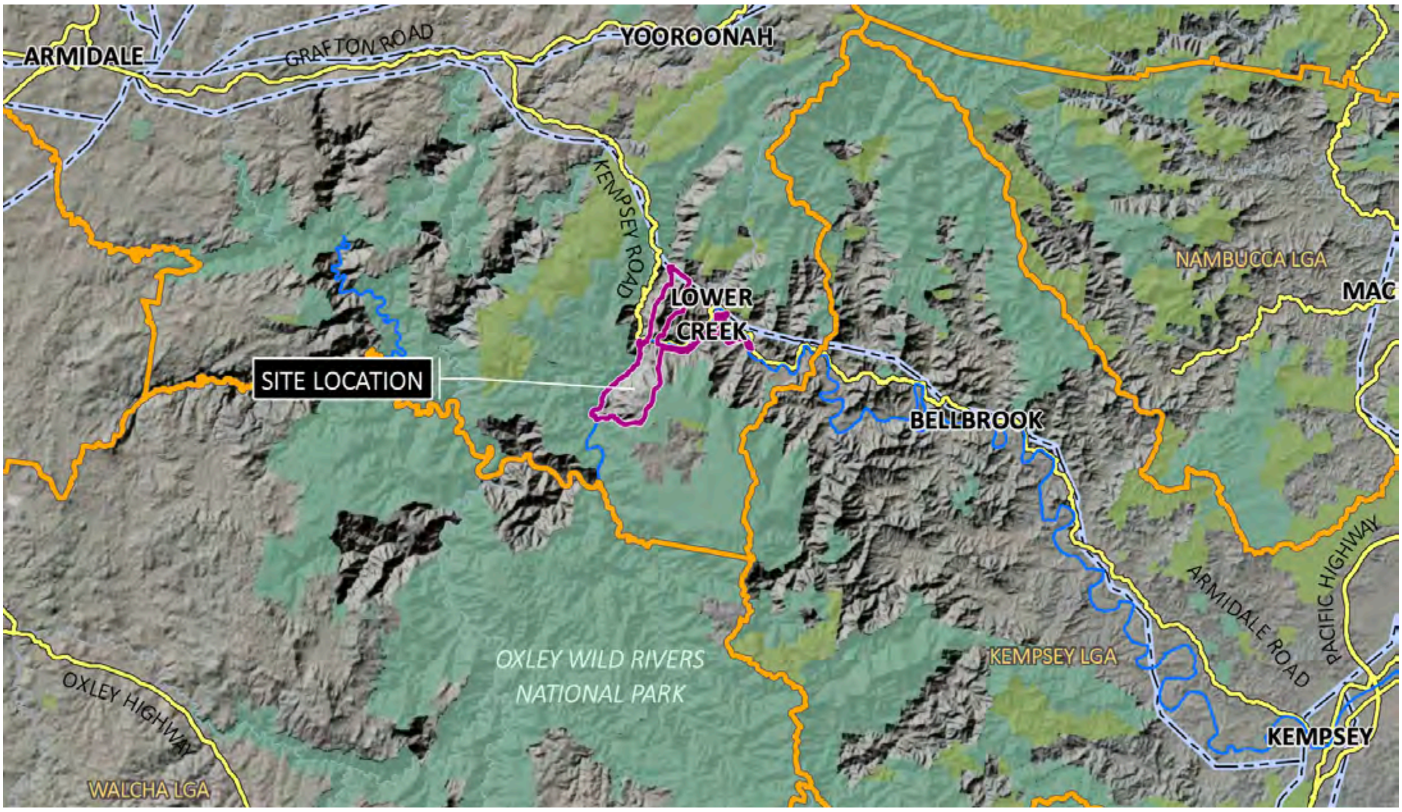
The project is bordered by the Macleay River to the west and Carrai Tablelands to the east. Oxley Wild Rivers National Park, Carrai National Parks and Carrai Conservation Area surround the property, with the New England National Park approximately 1km to the north-west.

Situated within the New England REZ, the project will provide clean energy generation and storage capabilities, ensuring a reliable, resilient, and renewable future energy supply for NSW.

The Oven Mountain project will include the construction of upper and lower reservoirs; an underground hydroelectric power station; spillways; power waterway, and access tunnels.

The project will also include the construction of a new electricity transmission network from the generation site to the Lower Creek area. Additional and independent upgrades to the broader existing electricity transmission network will be required to accommodate the project.

Additionally, the project will include upgrades to existing local and regional roads, allowing for safe construction and operation access.



3.2 Project timeline

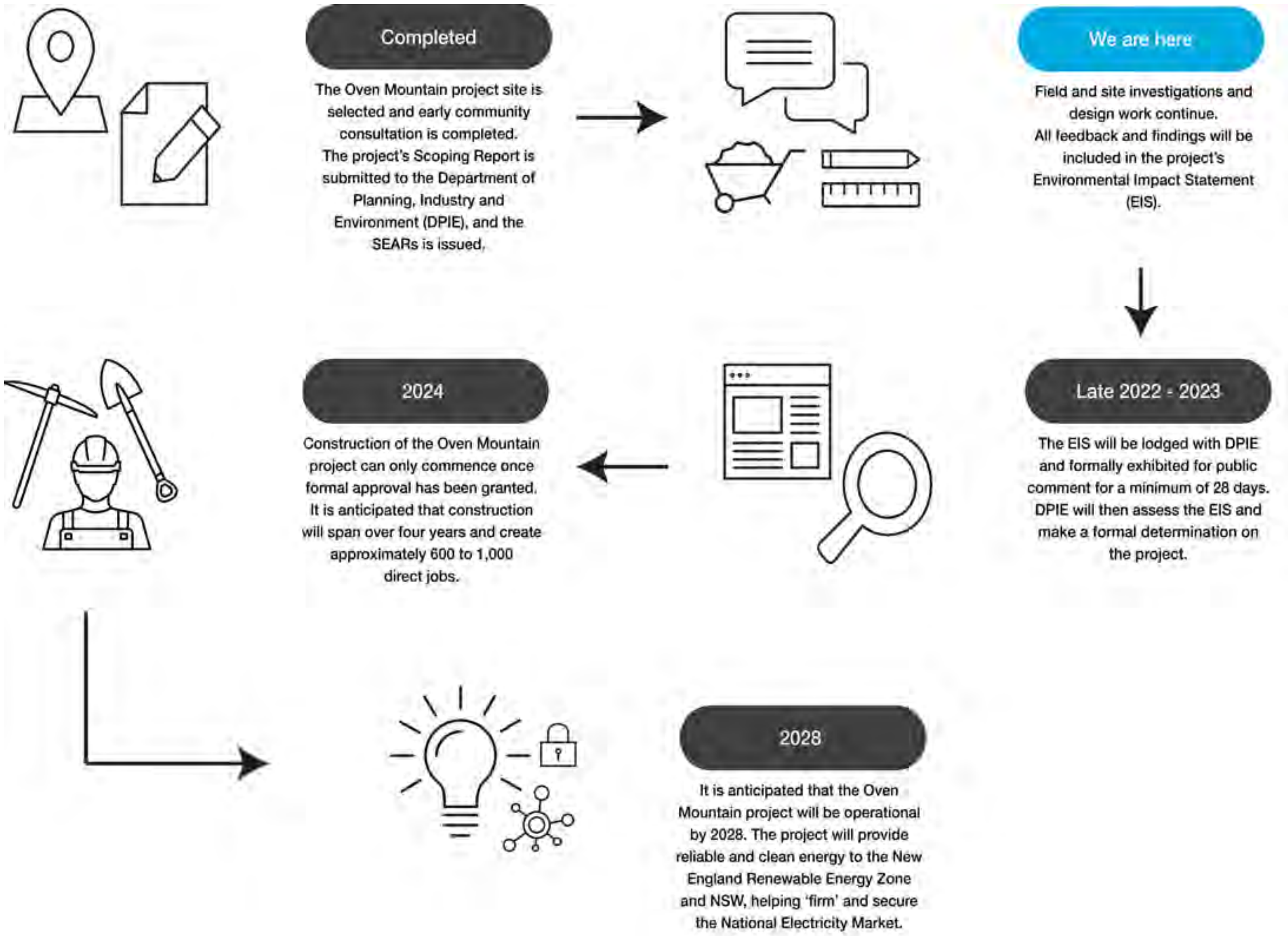


Photo - Geotechnical investigations completed near the project's proposed lower reservoir.

3.3 Project Objectives and Milestones

The Oven Mountain project has received funding from ARENA as part of their *Advancing Renewables Program*.

The funding supports investigations on the benefits of the Oven Mountain project and Pumped Hydro Energy Storage (PHES) to the National Electricity Market.

The study has the following objectives:

- Gain an understanding of how and to what extent PHES can support REZs, including quantifying the level of variable renewable energy that could be unlocked with the presence of the Oven Mountain project.
- Gain an understanding of PHES's capacity to provide inter-regional support.
- Examine the relative merits of PHES in providing various system services.
- Gain an understanding of PHES's potential to provide Marginal Loss Factor (MLF) support.

The Oven Mountain project is broken into the following three sections, each associated with a project milestone:

Milestone 1: Inputs baselining and technology finalisation

This section sets about acquiring the data and models required to undertake the modeling work, validating the models and data, consulting with TransGrid and AEMO regarding network constraints and objectives, consulting with original equipment manufacturers regarding their technologies, and settling upon final scenarios for modeling.

Milestone 2: REZ, Network and variable renewable energy impacts

Through the approach of a connecting generator, this section seeks to quantify the impacts of the Oven Mountain project on the New England REZ, addressing topics including the additionality of new renewable generation to the region, impacts on networks, and impacts on constraints.

This milestone includes a knowledge sharing component which is presented in this report.

Milestone 3: Final Reporting

Building on the two previous milestones, the final reporting will incorporate market modeling of scenarios to review the impact of the Oven Mountain project within the New England REZ including elements such as curtailments and loss factors.

The final report also includes a knowledge sharing component summarising the impacts of pumped hydro on a REZ.

3.4 Progress on Program Milestone Two

Phase	Item	Status
Information gathering and preparation	• Identification of key modeling input requirements • Establishment of generator models for PHES in consultation with OEMs • Documentation of network constraints • Identification of key energy market and network scenarios on which to undertake modeling	Completed
Impact on network considerations	• Model PHES behaviour against known constraints	Section 3.5 and Appendix A
Impact on market considerations	• Model market dispatch outcomes mirroring that of AEMO's NEM-DE • Assess the impact of PHES on network losses • Examine the system strength support to new inverter based connecting parties • Review alternate ways and technologies of providing similar benefits	Q3 2022

3.5 Benefits Assessment and Network Stability Study

The National Electricity Market (NEM) connects over 65 GW of generation to nearly 11 million customers in South Australia, Tasmania, Victoria, NSW, ACT and QLD over a transmission network spanning around 40,000 km. With such a large geographic footprint relative to a small customer base, spend on network can be costly and needs to be carefully considered. As a result, the network contains constraints that limit power flows around the NEM.

AEMO operates the NEM, coordinating the over 500 participants in the market every 5 minutes. It achieves this by using a platform that optimises the cost of energy offered by the available generators with the network constraint limitations to match the expected demand for energy.

Understanding network constraints therefore is very important and can impact the overall cost of energy. Constraints can be divided into two broad families: thermal and stability. Thermal constraints capture the limitation on network element's ability to transfer power due to their design ratings (e.g., power flow in a transmission line may cause the line to heat and sag to an unsafe state).

Stability constraints capture the limitations caused by the dynamic interaction between all NEM elements. This might be for example the behaviour of a single generator on the network after a loss of a transmission line or the complex interaction between numerous generators, loads and network infrastructure after the loss of a large generator.

What We Did

In this phase of the study, an examination of known stability constraints that relate to the Queensland-New South Wales Interconnector (QNI) was undertaken.

QNI was selected as the basis for the study as its limits are well documented, it is electrically very close to the New England Renewable Energy Zone (REZ), and QNI's limits set the limits on the lines passing through the New England REZ. This work was undertaken with consultation of Transgrid, Powerlink and AEMO.

The stability constraints events known to impact the Queensland-New South Wales Interconnector (QNI) are shown in Figure 3, with further information on these events provided in Amplitude's accompanying report (see Appendix A). These events mirror the information noted in the *Draft 2022 Integrated System Plan* regarding the New England REZ Transmission Link consultation, and also the 2021 *Powerlink Transmission Annual Planning Report*.

The team then set about assessing the stability limit for different modes of Pumped Hydro Energy Storage (PHES) operation, namely pumping, generating, and acting as a synchronous condenser. This last operational mode is a key benefit of PHES, and allows key grid support services to be provided outside pumping and generation periods. These results were compared to the stability limits without PHES.

How We Did It

Stability constraints are complex in nature and can be heavily influenced by the addition/removal of generators, loads, and/or network elements. As such, the study used the current network topology and generation mix, with the models provided by AEMO. As the existing stability constraints on QNI are well documented, the modeling could be assessed against these and provide confidence in the results.

PHES models were provided by leading technology original equipment manufacturers and these were incorporated into the broader model. The next step involved adjusting power flows on QNI, which was achieved by adjusting (but not removing or adding) generation distant to QNI to the north in Queensland and to the South in Victoria as shown in Figure 4. The stability of the network was then assessed by triggering the stability constraint events, and the point at which the network was no longer stable informed the limit to stability.

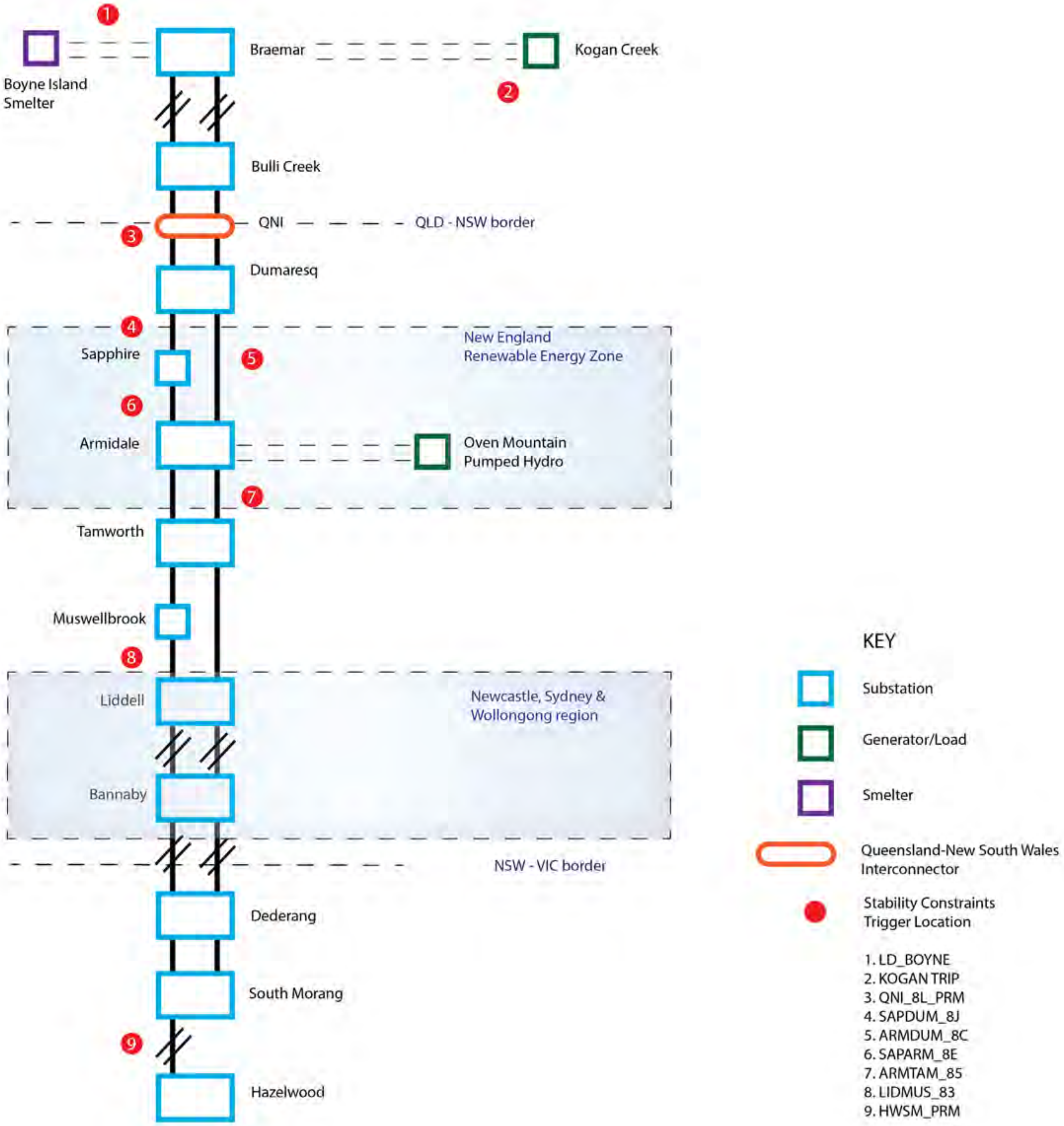


Figure 3 - Stability constraints events known to impact the Queensland-New South Wales Interconnector.

What We Found

PHES is a strong REZ and renewable energy supporter

The team examined cases with high renewable generation levels. In these situations experience shows that high renewable generation depresses wholesale market prices. As such, it was expected that PHES would operate in either a pumping or synchronous condenser mode.

The synchronous condenser results are electrically the same as combining the PHES in pumping mode with matching renewables within the same REZ. That is, the power flow between renewables and the PHES are contained within the REZ and have no further impact on QNI flows.

For the synchronous condenser results, QNI limits were improved by up to 200 MW in the southerly direction and up to 340 MW in the northerly direction.

This means that a PHES at 900MW can support at least 1,575MW of new renewable generation in the New England REZ based on stability limitations of the current network and likely more.

PHES provides electricity when demanded

The team examined cases with peak NSW electricity demand. This is a period where the energy system is stretched and confidence on all generation is needed. As such, it was expected PHES would be operating as a generator.

The team found that operating the PHES at this period slightly increased the stability limit southwards by about 20MW and significantly increased the limit northwards by up to 500MW.

This means that PHES can increase the available NSW dispatchable generation by up to 900MW mix with no negative impact on supporting flows coming in from Queensland in times of energy stress. Further, PHES can support increased sharing of generation between NSW and Queensland in the event the peak demand coincides between the two states.

the New England Renewable Energy Zone by at least the maximum operating pumping demand.

In a time of unprecedented change in the way society views and consumes energy, the Oven Mountain project will serve a critical role in reliably meeting the evolving requirements and renewable character of the National Electricity Market.

3.6 Critical State Significant Infrastructure

The In October 2020, the Oven Mountain project was declared to be Critical State Significant Infrastructure (CSSI). Infrastructure projects are considered CSSI if, in the opinion of the NSW Minister for Planning, they are essential to the State for economic, environmental, or social reasons.

Under the *NSW Environmental Planning and Assessment Act 1979 (EP&A Act)*, projects declared to be CSSI require approval from the NSW Minister for Planning under Division 5.2 of Part 5 of the Act. Applications to the Minister must be accompanied by an Environmental Impact Statement (EIS), which addresses the Secretary's Environmental Assessment Requirements (SEARs).

For more information, visit https://pp.planningportal.nsw.gov.au/major-projects/projects/oven-mountain-pumped-hydro-energy-storage-project.

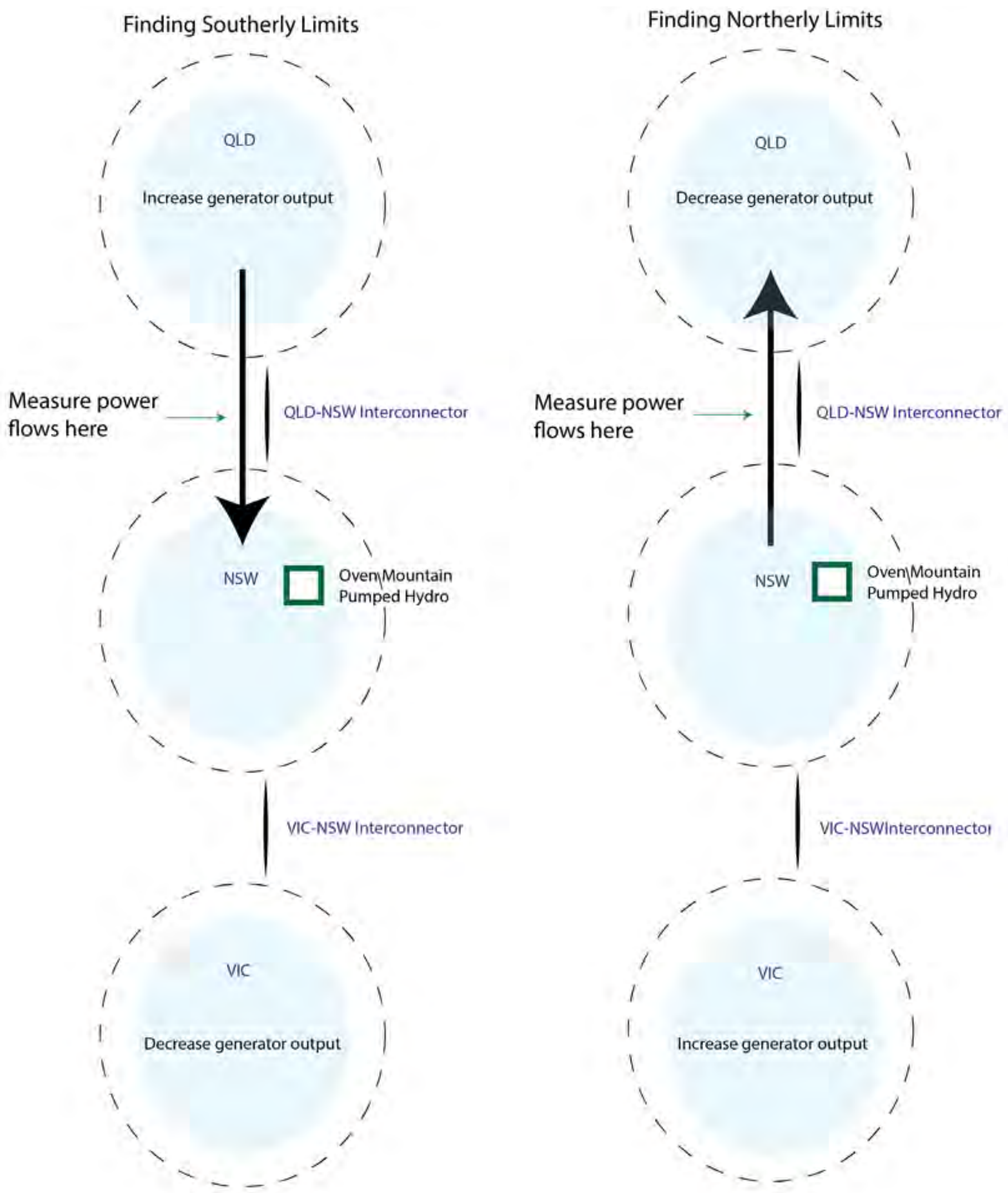


Figure 4 - Demonstration of power flows on QNI, which was achieved by adjusting (but not removing or adding) generation distant to QNI to the north in Queensland and to the South in Victoria.

8 Conclusion

The Oven Mountain project is an ‘off river’ Pumped Hydro Energy Development located on private land adjacent to the Macleay River between Armidale and Kempsey.

Situated within the New England Renewable Energy Zone (REZ), the project will provide clean energy generation and storage capabilities, ensuring a reliable, resilient, and renewable future energy supply for NSW.

Studies have been undertaken exploring the impact of Pumped Hydro Energy Storage (PHES) on stability constraints limiting power flow through the Queensland-New South Wales Interconnector (QNI) and by extension the New England REZ. This work has been coordinated with the guidance of Amplitude Consultants and their detailed analysis can be found in Appendix A.

A key finding is that as a storage device, PHES is able to support more renewables within the REZ than its load at pumping and this is primarily due to the network services it can provide. As such, PHES is a great supporter of renewable energy.

Further, PHES is able to add additional generation to the REZ in periods of high demand without adversely impacting stability constraints towards NSW, and significantly improving constraints towards QLD. This is a win in getting more out of existing networks, supplying energy reliability while keeping downward pressure on cost of energy.

Our next study will look at a future year dispatch analysis of the National Electricity Market and assess the impact of PHES on market outcomes such as curtailments, Marginal Loss Factor, and market benefits of PHES. We will also be looking at the system strength support PHES can supply with a view of providing a different approach to new renewable hosting capacity within a REZ.

The Oven Mountain team look forward to continuing to engage with our diverse range of stakeholders - including government authorities, industry, and community members - as we work to deliver this significant project.

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Appendix A

Photo - Geotechnical investigations near the project's upper reservoir.

Oven Mountain Pumped Hydro Storage

Benefit Assessment – Network Stability Study

Amplitude Document Number:
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Table of Contents

List of Figures

List of Tables

Executive Summary

Amplitude Consultants Pty Ltd (Amplitude) have been engaged by OMPS Pty Ltd (Client) to investigate the impact of the proposed Oven Mountain Pumped Storage Hydro (OMPS)[1] generating system on power system stability. This work is part of a broader study supported by the Australian Renewable Energy Agency (ARENA) through their Advancing Renewables Program (ARP) to analyse the benefits that Pumped Hydro Energy Storage (PHES) would have on the development of the New England Renewable Energy Zone (REZ) in northern New South Wales.[2]

Specifically, the Client requested Amplitude perform power system analysis studies to assess the impact of OMPS on the existing northerly and southerly power transfer stability limits[3] on the Queensland to New South Wales Interconnector (QNI), under various load and generation scenarios, and for different OMPS capacities and connection arrangements.

The NEM transmission grid can be characterised as a long and skinny power system with geographically dispersed generation and demand centres. Given the nature of the network the power transfer capability across the long interconnections between NEM regions is often set by voltage and transient stability limitations rather than thermal constraints. Amplitude anticipates that with further decline in system strength and inertia stability constraints will become more prevalent, especially across the longer NEM transmission corridors.

Understanding the potential impact of a large new PHES on these stability limitations is important because it could significantly impact the power transfer capability between regions. An increase in the stability limits can provide significant market benefits by reducing generation operating costs and wholesale market prices and can also defer very costly network augmentation. Investigating the potential reductions in power transfer capability is obviously important too, as this could present challenges for the connection of the new plant and potentially severe constraints on its operation, or the operation of other facilities.

Thermal constraints are also important but unlike stability constraints, thermal constraints are affected in the similar manner by any type of generation technology injecting power into a certain location. This study therefore focuses on the impact of PHES on stability limitations only.

OMPS is a proposed PHES planned for connection near Armidale in northern New South Wales. The Client is currently considering two options including a 600 MW generating system connected at 132 kV and a 900 MW generating system connected at 330 kV. Whilst preliminary connection arrangements have been developed for both options, the final connection will likely be influenced by the scope of transmission development for the New England (REZ). For these studies OMPS was connected directly to the 132 kV and 330 kV busses at Armidale for the 600 MW and 900 MW options, respectively.

Amplitude has assessed the impact of OMPS on QNI stability limits across a series of scenarios involving different levels of network demand, renewable generation outputs and QNI flow direction. The impact of OMPS when generating and pumping has been investigated. Several sensitivity studies were also performed. This included an investigation of the benefit of OMPS synchronous condenser

[1] Further information on OMPS can be found at https://www.ompshydro.com/project/
[2] https://www.ompshydro.com/news/pumped-hydro-plant-could-unlock-new-england-rez/4
[3] The study considers voltage and transient stability limits only. An assessment of oscillatory stability has not been included as the models required for this purpose are not readily available to registered participants.

operating mode, a comparison of the performance of OMPS and a notional 900 MW BESS and a study showing how much additional network wind farm hosting capacity might be created when OMPS is pumping.

When OMPS is generating under higher demand conditions, being the most likely operating scenario, it provides a marginal improvement of at least 20 MW in the southerly stability limits and a substantial improvement of greater than 200 MW in the northerly stability limits. There was no assessment of the impact of pumping on high demand scenarios as this was considered an unlikely case.

The contribution of OMPS when generating leads to considerably higher power transfers south of Armidale. Under these circumstances the worst-case credible contingencies setting the QNI stability limit shift from north of Armidale Substation to the south on 330 kV transmission lines between Armidale – Tamworth and between Muswellbrook – Liddell, causing a reduction of up to 180 MW on the southerly QNI limit. The impact of OMPS generation on the northerly stability limit remains very positive with around a 220-400 MW increase.

When operating in pumping mode OMPS draws load from Armidale Substation, reducing the southerly power transfer from Armidale to Tamworth. Under these conditions the worst-case contingencies setting the QNI southerly limit are north of Armidale and the QNI southerly limit increases by around 100-120 MW. This highlights a significant benefit from OMPS. During pumping periods OMPS will enable additional generation to inject at or near Armidale at least up to the level of pumping demand, whilst having little or no net effect on transmission loading and also increasing in the QNI southerly stability limit. The northerly transfer limit is reduced by around 120-140 MW in this scenario, but the benefits OMPS offers to the connection of additional generation near Armidale still stand.

Importantly, although there is a reduction in QNI southerly limits when OMPS is generating under low demand conditions, the reduction is substantively less that the generation output from OMPS. Because of this the effect of OMPS is to increase the New South Wales maximum supportable demand (MSD). These studies indicate an increase in MSD of at least 700 MW across all scenarios when generating, assuming a 900 MW connection.

The most significant improvement in QNI transfer capability is seen when OMPS is operating as a synchronous condenser. In this mode there is almost no real power exchanged with the surrounding transmission lines, but the substantial voltage control capability and inertia provide an increase in the QNI voltage and transient stability limits of more than 200 MW in both directions.

When the OMPS facility is compared against an equivalent sized BESS discharging at the same location (Armidale 330 kV) the results show OMPS can provide more reactive power during a fault causing a less severe voltage depression, likely due to its substantively higher short circuit current contribution. The QNI southerly limit with OMPS in service was also 60 MW higher when compared with the BESS.

The studies show that when OMPS is pumping it enables operation of significant additional generation injection at or near Armidale Substation. Under moderate demand conditions with OMPS pumping at 900 MW, additional wind farm capacity of 1,575 MW was supported at Armidale and the southerly and northerly QNI stability limits were also improved by 120 MW and 440 MW, respectively. Under these circumstances the New South Wales MSD increases by 795 MW, being the difference between the wind farm capacity and OMPS pumping demand, plus the additional 120 MW of southerly import capability into New South Wales on QNI.

Overall, these studies have shown OMPS will provide a very valuable contribution to the network. The plant offers substantial voltage control and inertia benefits, it generally improves the QNI stability limits in the direction of flow most likely for given scenarios, it provides an increase in the New South Wales maximum supportable demand under all circumstances and should significantly increase the hosting capacity in the New England REZ by more than the OMPS pumping demand.[4]

[4] Assuming the additional generation is injected at or near Armidale Substation and operating coincident with OMPS pumping.

1. Introduction

Amplitude Consultants Pty Ltd (Amplitude) have been engaged by OMPS Pty Ltd (Client) to investigate the impact of the proposed Oven Mountain Pumped Storage Hydro (OMPS) generating system on power system stability. This work is part of a broader study commissioned by the Australian Government and the Australian Renewable Energy Agency (ARENA) to analyse the benefits that Pumped Hydro Energy Storage (PHES) would have on the development of the New England Renewable Energy Zone (REZ) in northern NSW. Amplitude have been engaged to assist with two major components of this work involving a:

- Network stability benefits study; and
- Available Fault Level and inertia benefits study.

This report documents the outcomes from the network stability benefits study. A separate report will be prepared to quantify the Available Fault Level and Inertia Benefits.

OMPS is located in the Armidale Regional Local Government Area, approximately 60 km southeast of Armidale and 70 km northwest of Kempsey, via the Kempsey-Armidale Road. The project is bordered by the Macleay River to the west and Carrai Tablelands to the east. Oxley Wild Rivers National Park, Carrai National Parks and Carrai Conservation Area surround the property, with the New England National Park approximately 1 km to the north-west. Figure 1 shows the location of OMPS with respect to the surrounding transmission network and the New England REZ.

Figure 1 – Indicative Location of OMPS within the New South Wales transmission network [1]

The Client is currently considering two options including a 600 MW generating system likely connected at 132 kV and a 900 MW generating system connected at 330 kV. Whilst preliminary connection arrangements have been developed for both options, the final connection will likely be influenced by the scope of transmission development for the New England (REZ). For the purpose of the studies in this report OMPS was connected directly to the 132 kV and 330 kV busses at Armidale for the 600 MW and 900 MW options, respectively.

The power transfer capability on QNI is influenced by numerous factors including the in-service network, the status and size and technology of other generating systems online and the demand on the power system, among others. By the time OMPS is operational circa 2028 the transmission system and generating fleet will be different to that which exists today and it will continue to evolve into the future. Given the uncertainty about future plant, this study has considered the impact of OMPS on the existing power transfer capability across QNI set by stability limitations. However, Amplitude considers the general trends shown in this report in relation to the impact of OMPS (a set of large synchronous machines injecting at Armidale) on QNI stability limits should hold true going forward.

The intent of this study is not to show PHES solves a particular problem and Amplitude is aware of existing committed and proposed augmentations that will lift the stability limitations identified in this report. Rather, this study provides the opportunity to illustrate how a PHES impacts documented NEM constraints knowing that these constraints will influence the development of the New England REZ. The outcomes of this work may also help inform the ideal generation mix of other REZ's as the energy transitions matures.

The stability of the power system is critical to the ongoing management of power security and reliability. It is already well known that the rapid uptake of inverter based generation resources (IBR) is displacing large synchronous machines leading to a progressive decline in system strength and voltage control capability. This can affect the stability of some existing IBR that are reliant on relatively strong grid voltage signals to function correctly and presents challenges to the connection of more traditional IBR plant. Declining power system inertia is also problematic too and leads to a higher rate of change of system frequency during certain contingency events.

Whilst new 'grid forming' IBR technology has been shown to assist with managing system strength and inertia issues, such technology is not commonly installed to provide the long duration (> 8 hours) storage requirements being sought by the New South Wales Government in the NSW Electricity Infrastructure Roadmap [2]. PHES on the other hand is a well proven form of long duration energy storage world wide and can provide excellent system strength and instantaneous inertial support, irrespective of its operating point.

The NEM transmission grid can be characterised as a long and skinny power system with geographically dispersed generation and demand centres. Given the nature of the network, the power transfer capability across the long interconnections between NEM regions is often set by voltage and transient stability limitations rather than thermal constraints. Amplitude anticipates that with further decline in system strength and inertia stability constraints will become more prevalent, especially across the longer NEM transmission corridors.

Understanding the potential impact of a new large PHES on these stability limitations is important because it could significantly impact the power transfer capability between regions. Increases in the stability limits, ideally up to to thermal ratings of equipment, can provide significant market benefits by reducing generation operating costs and wholesale prices and deferring large network augmentation capital costs. Investigating the potential reductions in power transfer capability is obviously very important too, as this could present challenges for the connection of the new plant and potentially severe constraints on its operation, or operation of other facilities.

Thermal constraints are also important but unlike stability constraints, thermal constraints are affected in the same manner by any type of generation technology injecting power into a certain location. This study therefore focuses on the impact of PHES on stability limitations only.

2. Stability Studies – Approach and Methodology

2.1. NEM Power System Model

This study was performed using PSS®E. The Client provided Amplitude with PSS®E Standard Snapshot models of the NEM power system sourced from AEMO via its OPDMS.

Amplitude removed the Tasmanian network from the models by replacing Basslink with an equivalent load at the Loy Yang converter station. This was done to reduce total simulation time, recognising that the response of Basslink is likely to have an immaterial impact on the study objectives.

The NEM models were modified to integrate OMPS (refer Section 2.2) and prepare a series of load and generation scenarios (refer Section 2.3). Additional governor models were provided by AEMO for this study as many of the governor models in the Standard Snapshot package were missing or did not account for the recent mandatory primary frequency response Rule change[5] (refer Section 2.4).

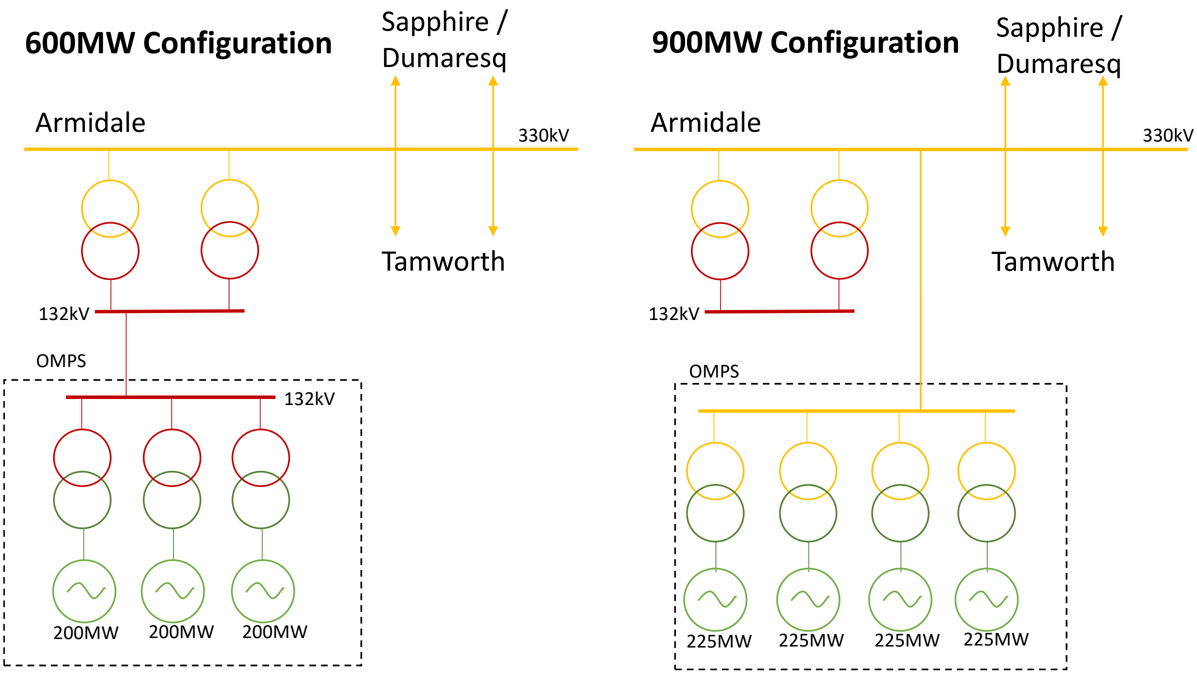
2.2. OMPS Model

Original Engineering Manufacturers (OEM) supplied PSS®E dynamic models to represent OMPS. Amplitude modified the NEM models (refer Section 2.1) to include both the OMPS 600 MW and OMPS 900 MW options.

In scenarios where OPMS is assumed to be a 600 MW facility it is modelled with three 200 MW turbines connected to Armidale 132 kV as shown in Figure 2. Figure 2 also shows the 900 MW configuration with OMPS modelled with four 225 MW turbines connected to Armidale 330 kV. Whilst in practice OMPS will be connected to the national grid via some length of connection assets possibly with other enabling network augmentations, the scope of the connection assets and potential enabling works is not known and a direct connection to Armidale is considered appropriate for the analysis undertaken.

[5] https://www.aemc.gov.au/rule-changes/mandatory-primary-frequency-response

Figure 2 – OMPS indicative layout for 600 MW and 900 MW configurations



2.3. Load and generation scenarios

Amplitude has assessed the impact of OMPS on the QNI stability limits across a series of scenarios involving different levels of network demand, variable renewable generation outputs and QNI flow direction. The impact of OMPS when generating and pumping has been investigated including 600 MW and 900 MW options. Several sensitivity studies were also performed. This included an investigation of the benefit of OMPS synchronous condenser operating mode, a comparison of the performance of OMPS and a notional 900 MW BESS and a study showing how much additional network hosting capacity might be created for wind farm connections when OMPS is pumping.

Table 1 provides the network configuration for each of the scenarios, noting that each scenario is developed with both northerly and southerly flows on QNI. Cases where OMPS is not included were studied for each network demand condition to establish a baseline for the QNI northerly and southerly stability limits for comparative purposes.

The scenarios have been prepared with consideration of the likely OMPS operating mode and potential output from other renewable sources at certain demand levels, but also with an intent to study broad operating conditions. No pumping cases have been studied under evening peak demand conditions as this is considered an unlikely operating condition. The most likely operating modes for each demand level are shaded in grey.

Table 1 – Study scenarios

Demand	OMPS	Solar Generation	Wind Generation	Scenario ID
Peak (evening) 10.8 GW in NSW	Not included	Low	Moderate	Peak None
	High Generation, 600 MW			Peak G600
	High Generation, 900 MW			Peak G900
Low (midday) 5 GW in NSW	Not included	High	Moderate	Low None
	High Generation, 600 MW			Low G600
	High Generation, 900 MW			Low G900
	High Pumping, 600 MW			Low P600
	High Pumping, 900 MW			Low P900
Shoulder (midmorning/ midafternoon) 6 GW in NSW	Not included	High	High	Shoulder None
	High Generation, 600 MW			Shoulder G600
	High Generation, 900 MW			Shoulder G900
	High Pumping, 600 MW			Shoulder P600
	High Pumping, 900 MW			Shoulder P900
	Synchronous Condenser, 900 MW			Shoulder Syncon
	BESS sensitivity, 900 MW discharging (OMPS not included)			Shoulder BESS
	Wind Farm sensitivity, OMPS High Pumping			Shoulder WIND

The Peak demand scenarios were developed off the summer high Standard Snapshot (SummerHi-20210124-180000) provided by AEMO. The Shoulder and Low demand scenarios were both developed off the autumn low Standard Snapshot (AutumnLo-20210328-110152). For the Shoulder scenarios, demand in New South Wales was increased from ~5 GW to ~6 GW with most of the increase in load supplied by increased wind generation output in New South Wales.

High voltages were observed in the snapshot used to prepare the Low and Shoulder demand scenarios, despite one Hazelwood to South Morang 500 kV circuit already being out of service to help manage these conditions.[6] The 2021 Victorian Annual Planning Report [3] includes information on the Victorian Reactive Power Support RIT-T. This project is a committed project to install an additional 100 MVAr 220 kV reactor at Keilor[7] and two 100 MVAr reactors at Moorabool. These reactors were

[6] AEMO currently switches one South Morang 500 kV line out of service to manage high voltages during low demand – refer Section 2.7, 2021 Victorian Transmission Annual Planning Report.
[7] The reactor installed at Keilor 220 kV bus under the Victorian Reactive Power Support RIT-T is additional to the 100 MVAr 220 kV reactor commissioned at Keilor in 2021 under the approved Network Capacity Incentive Parameter Action Plan (NCIPAP). Amplitude has modelled two additional 100 MVAr reactors at each of Keilor and Moorabool.

not included in the provided snapshot case and were added by Amplitude to assist with managing the high voltage conditions and improve initialisation of the dynamic simulations.

2.4. Governor models

Governor models can be of little significance for power system studies that do not involve frequency disturbances such as tripping of major loads and generating units. This study investigated the response of the power system to a trip of Kogan Creek Power Station from around 750 MW as well as a trip of a Boyne Island Smelter potline from 360 MW, so governor models were considered important.

When preparing the initial study scenarios Amplitude noticed that for a trip of Kogan Creek Power Station from around 750 MW the NEM system frequency would drop rapidly, falling below 49 Hz. This caused protection relays on other generators to disconnect plant leading to cascading failure. This was a surprising outcome as the NEM Standard Snapshots were assumed to reflect a secure operate state. Investigations revealed that many of the synchronous machines did not have governor models, which was identified to be the root cause of the significant frequency deviation.

AEMO subsequently provided generic governor models to use for all plant, noting the models are not verified and hence not supplied as part of the Standard Snapshot Package. Amplitude incorporated the governor models provided by AEMO into the NEM models used in this study and the previous 49 Hz frequency deviation following a trip of Kogan Creek was no longer apparent.

2.5. Determining stability limits

2.5.1. Critical contingencies

When determining the QNI stability limit it is important to account for a range of credible contingencies so that the most critical contingency setting the lowest limit can be identified. The Powerlink Transmission Annual Planning Report 2021 [4] provides a summary of the credible contingencies most likely to set the southerly and northerly transfer limits on QNI.

All the contingencies mentioned by Powerlink which can lead to stability limitations in the southerly direction have been considered. Amplitude also included contingencies on the Armidale – Tamworth 330 kV circuit, recognising that OMPS is a significant new generator injection at Armidale and could result in contingencies on this circuit becoming most onerous.

When assessing the northerly QNI stability limit Amplitude only considered a trip of Kogan Creek Power Station from maximum output. The Powerlink TAPR does indicate that the northerly limit could be set by "transmission line faults in NSW" although it is unclear what line faults should be assessed. In any event a trip of Kogan Creek Power Station was found to be the worst case contingency via information in the public domain (refer Section 3.1).

Table 2 summarises the credible contingencies considered when assessing the northerly and southerly stability limits on QNI. All contingencies were assumed to be 2 phase to ground faults cleared in primary protection clearance times per the National Electricity Rules S5.1a.8.

Table 2 – Contingencies for dynamic studies

QNI Direction	Contingency	Chart Label
Southerly	Trip of 8E Sapphire – Armidale 330 kV	SAPARM_8E
	Trip of 8C Sapphire – Dumaresq 330 kV	SAPDUM_8J
	Trip of 8J Armidale – Dumaresq 330 kV	ARMDUM_8C
	Trip of 83 Liddell – Muswellbrook 330 kV	LIDMUS_83
	Trip of 8L Bulli – Dumaresq 330 kV	QNI_8L_PRM
	Trip of Hazelwood – South Morang 500 kV	HWSM_PRM
	Trip of Boyne Island Smelter Pot Line Load	LD_BOYNE
	Trip of 85 Armidale – Tamworth 330 kV	ARMTAM_85
Northerly	Kogan Creek Power Station Trip	KOGAN TRIP

2.5.2. Limit search

The stability limits on QNI have been determined separately for each of the relevant contingencies in Table 2. For example, the southerly QNI stability limit for a contingency on the Sapphire – Armidale circuit has been determined separately to the southerly QNI stability limit for a contingency on the Sapphire – Dumaresq circuit. The contingency which results in the lowest QNI stability limit is treated as the 'worst case contingency' and may shift depending on the power system operating conditions.

To establish the southerly limit, each of the contingencies relevant to the southerly direction were studied separately in progressively higher increments of 20 MW of power transfer on QNI until instability was observed. The power transfer on QNI was varied by increasing generation in northern and central Queensland while generation in Victoria was reduced. The QNI southerly stability limit for a given contingency was assumed to be 20 MW lower than the QNI power transfer in the marginally unstable case for that contingency.

An unstable power transfer was determined based on a relative angular separation between any two synchronous machines of more than 180 degrees, voltage collapse, very poorly damped response in any monitored variable, or non-convergence.

A similar approach was used to establish the northerly limit considering a trip of Kogan Creek Power Station at progressively higher increments of 20 MW of power transfer on QNI. In this case generation in Victoria was progressively increased while generation in central and northern Queensland was reduced.

In all cases, generation scaling to adjust QNI power transfer relates only to the dispatch of active power from online generating units remote from QNI. No generators were switched on or off, only the machine output is altered to achieve the desired change in flow. This avoided potential step changes in voltage control capability and inertia on the network that might lead to significant distortion in the results. In ensuring that the cases are representative of likely operating scenarios Amplitude discounted cases where pre contingent voltages on the QNI corridor, being the 330 kV network between Bulli Creek and Bayswater, dropped below 0.9 PU (90% of the nominal voltage).

In practise Transmission Network Service Providers can assess thousands of different load and generation scenarios to determine the stability limit and develop operational limit equations for central dispatch purposes. Amplitude acknowledges that there are also alternative approaches involving steady state as well as other dynamic simulation techniques. As the purpose of this study is to compare the relative impact of OMPS on the QNI stability limits found with and without OMPS the approach taken is considered fit for purpose.

2.5.3. Monitored variables

The following variables were monitored throughout each simulation.

- Bu voltage and voltage angle relative to South Pine 275 kV:
    - Braemar 330 kV
    - Bulli Creek 330 kV
    - Dumaresq 330 kV
    - Sapphire 330 kV
    - Armidale 330 kV
    - Tamworth 330 kV
    - Muswellbrook 330 kV
    - Liddell 330 kV
    - OMPS 330 kV
- Voltage, Machine Power (P, Q)
    - Kogan Creek
    - OMPS Unit 1
- Machine Angles relative to Loy Yang Unit 1
    - Eraring Unit 1
    - Tarong Unit 1
    - OMPS Unit 1
- Branch Flow
    - 8E Sapphire – Armidale
    - 8C Sapphire – Dumaresq
    - 8J Armidale – Dumaresq
    - 83 Liddell – Muswellbrook
    - 8L Bulli Creek – Dumaresq
    - 85 Armidale - Tamworth
    - Armidale SVC[8]
- System Frequency
    - Braemar 330 kV

[8] Armidale SVC is modelled as a controlled shunt in the power flow model. The dynamics library does not have an API to extract shunt data, so the line flow was used as a proxy.

3. Results

3.1. Existing limits on QNI

The present range of northerly and southerly stability limits on QNI in the NEM is provided in Table 3. This information is used to compare the operational performance of QNI against the stability limits determined in this study in the 'no OPMS' scenarios and help validate study outcomes.

The information in Table 3 has been extracted from the QNI minor consultation PACR [5][9]. The limits in Table 3 are considered notional in that they are derived using constraint equations based on a set of assumptions that would represent typical operating conditions.

Table 3 shows the southerly limit on QNI ranges from about 950-1225 MW and the northerly limit ranges from 70-670 MW depending on the system demand and generation as well as the output of Sapphire Wind Farm.[10]

Table 3 – QNI existing limits

Operating Condition		Notional QNI Limit (Summer)		Notional QNI Limit (Winter)	
		Northerly Direction	Southerly Direction	Northerly Direction	Southerly Direction
High Sapphire Wind Farm	Day High	365	1070	425	1070
	Day Medium	480	970	570	1070
	Day Low	670	950	670	1030
	Night High	330	1100	365	1000
	Night Medium	475	990	545	990
	Night Low	635	985	635	985
	Average	518	999	557	1015
Low Sapphire Wind Farm	Day High	190	1215	245	1215
	Day Medium	300	1205	375	1205
	Day Low	525	1130	525	1200
	Night High	70	1225	110	1225
	Night Medium	220	1215	285	1215
	Night Low	445	1210	445	1210
	Average	312	1197	348	1211

Amplitude also reviewed the AEMO Annual NEM Constraint Report for 2021 [6] and the monthly reports for January 2022 to February 2022 [7]. This review identified the following constraint equations as the most binding on QNI during 2021 and early 2022. Note only the system intact

[9] Limits in the table are derived from table 5.2 and 5.3 of the QNI Minor Project Assessment Conclusions Report (PACR) [5] by subtracting the limit increase for option 1A from the notional limits in the tables.

[10] Sapphire Wind Farm is connected to the 330 kV network between Armidale and Dumaresq, and as such is considered independent of other generation in assessing the QNI limits.

constraint equations which bound more than 25 hours have been considered. This information is useful to understand the most critical contingencies presently setting the lowest limit on QNI.

In the Northerly direction:

- N^^Q_NIL_B1 - Out= Nil, avoid Voltage Collapse on loss of Kogan Creek.
- N^^Q_NIL_A - Out= Nil, avoid Voltage Collapse on loss of Liddell to Muswellbrook (83) line.

In the Southerly direction:

- Q^^NIL_QNI_SRAR - Out = Nil, limit QLD to NSW on QNI to avoid voltage instability on trip of Sapphire - Armidale (8E) 330 kV line.
- Q:N_NIL_AR_2L-G & Q::N_NIL_AR_2L-G - Out=Nil, limit Qld to NSW on QNI to avoid transient instability for a 2L-G fault at Armidale.

3.2. Study Findings

The following sections of this report provide a summary of the QNI stability limits determined in this study. The results are initially presented without OMPS to form the baseline and then compared with the results for both OMPS 600 MW and 900 MW options.

3.2.1. Limits without OMPS

Figure 3 shows the QNI southerly limits without OMPS. The SAPARM_8E (Sapphire to Armidale) contingency is most limiting setting QNI limits in the range 1040 MW to 1160 MW in the Low None scenario and Peak None scenario, respectively. This finding is consistent with existing dispatch outcomes in Section 3.1 where the constraint equation Q^^NIL_QNI_SRAR (Out = Nil, limit QLD to NSW on QNI to avoid voltage instability on trip of Sapphire - Armidale (8E) 330 kV line) had the highest incidence of binding hours in on QNI. The stability limit is also consistent with with the range of outcomes identified in Table 3. The study results are consistent with historical performance.

Figure 3 – QNI stability limits without OMPS – Southerly direction

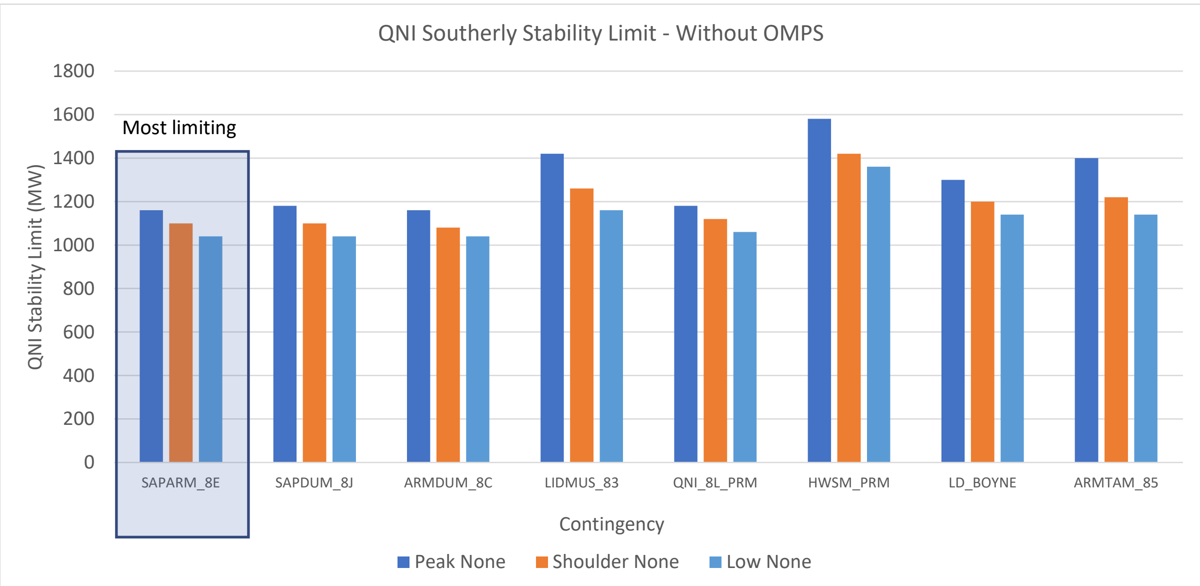
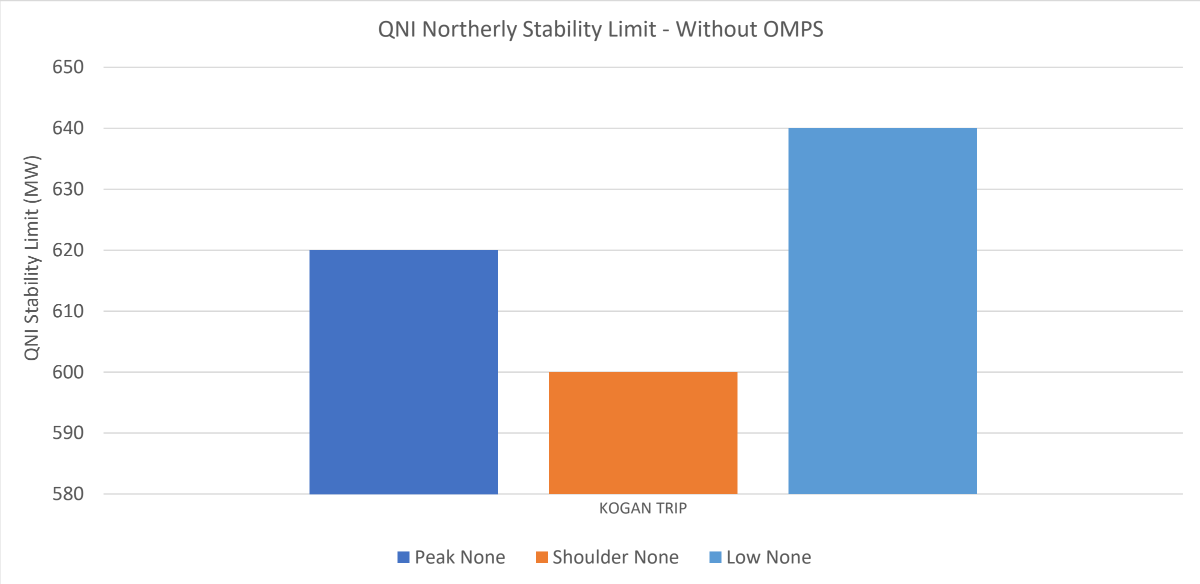


Figure 4 shows the QNI northerly limits without OMPS in service range from 600 MW in the Shoulder None scenario to 640 MW in the Low None scenario. These results fall within the range of existing northerly limits identified in Table 3. The study results are consistent with historical performance.

Figure 4 – QNI stability limits without OMPS – Northerly direction



3.2.2. Impact of OMPS on Transmission Network Flows

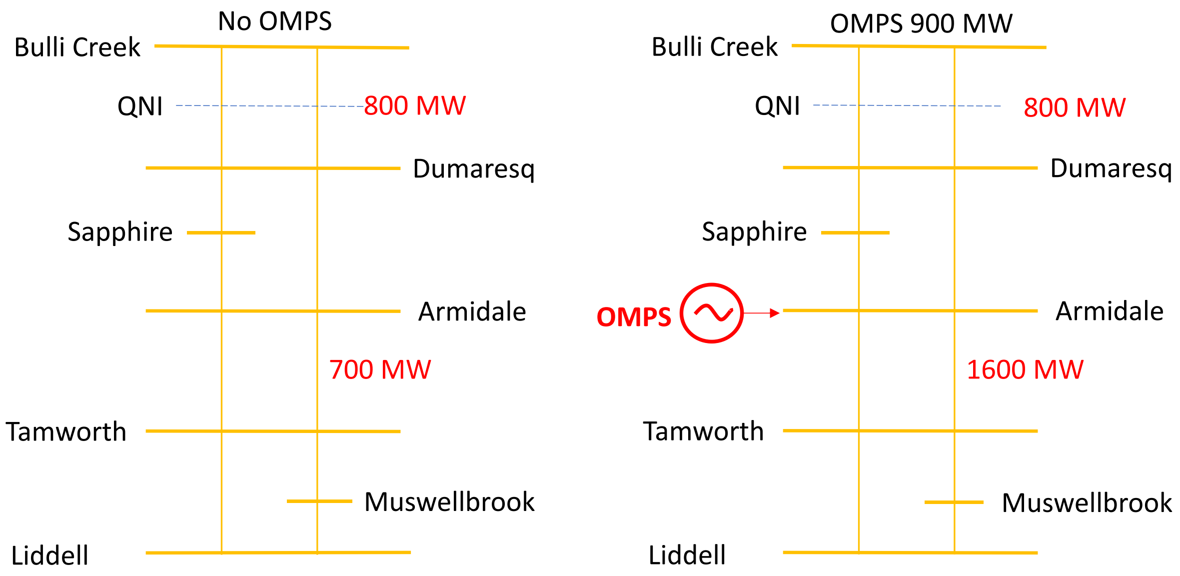
OMPS is assumed in these studies to inject directly into the Armidale Substation. For any given QNI transfer measured across the Bulli Creek to Dumaresq 300 kV lines the impact of OMPS generation at Armidale, all else equal, is to substantially increase the power transfer south of Armidale on the Armidale to Tamworth and Liddell to Muswellbrook 330 kV circuits.

Figure 5 provides an example of this showing the difference in transmission flows south of Armidale between the Shoulder None and Shoulder G900 scenarios for a notional 800 MW southerly power transfer on QNI (measured across the Bulli Creek to Dumaresq 330 kV lines). In the Shoulder None scenario the transfer south of Armidale is 700 MW, being 100 MW less than QNI due to the load offtake at Armidale Substation. In the Shoulder G900 scenario this increases to 1600 MW because of the 900 MW being injected into Armidale.

Conversely, when OMPS is pumping it acts as a substantial load at Armidale Substation and for a given southerly power transfer on QNI it works to significantly reduce the power transfer south of Armidale.

Changes in New South Wales demand also have a similar effect, although less pronounced. As demand increases there is more demand supplied from Armidale Substation, leaving less southerly 'spill' towards Tamworth on the 330 kV network.

Figure 5 – Impact of OMPS on flows south of Armidale (shoulder case)



3.2.3. Limits with OMPS Generating

3.2.3.1. Southerly Limits with OMPS Generating

Figure 6 shows, for each scenario, the relative impact OMPS has on the southerly QNI stability limit set by the worst case contingency.

When OMPS is generating under higher (Peak) demand conditions, being the most likely operating scenario, it provides a marginal improvement of 20 MW in the southerly stability limits. As the demand for electricity on the New South Wales network decreases there is less load offtake from Armidale Substation.

This leads to higher power transfers south of Armidale which is exacerbated with increasing OMPS generation output from the 600 MW to the 900 MW scenarios. Under these circumstances the worst-case credible contingencies setting the QNI stability limit shift from north of Armidale Substation to the south on 330 kV transmission lines, including Armidale - Tamworth and Liddell – Muswellbrook, causing a reduction of up to 180 MW on the southerly QNI limit.

Figure 7 shows the relative impact of OMPS on the southerly QNI stability limits set by the individual contingencies. OMPS generation is generally seen to have a positive impact on the QNI limits set by contingencies to the north of Armidale Substation (the first four contingencies to the left) but a reduces the QNI limit set by contingencies to the south. The biggest impact is seen for the Liddell to Muswellbrook contingency (LIDMUS_83) followed closely by the Armidale to Tamworth contingency (ARMTAM_85).

Figure 6 – Impact on QNI southerly stability limit (worst case contingency) – OMPS generating

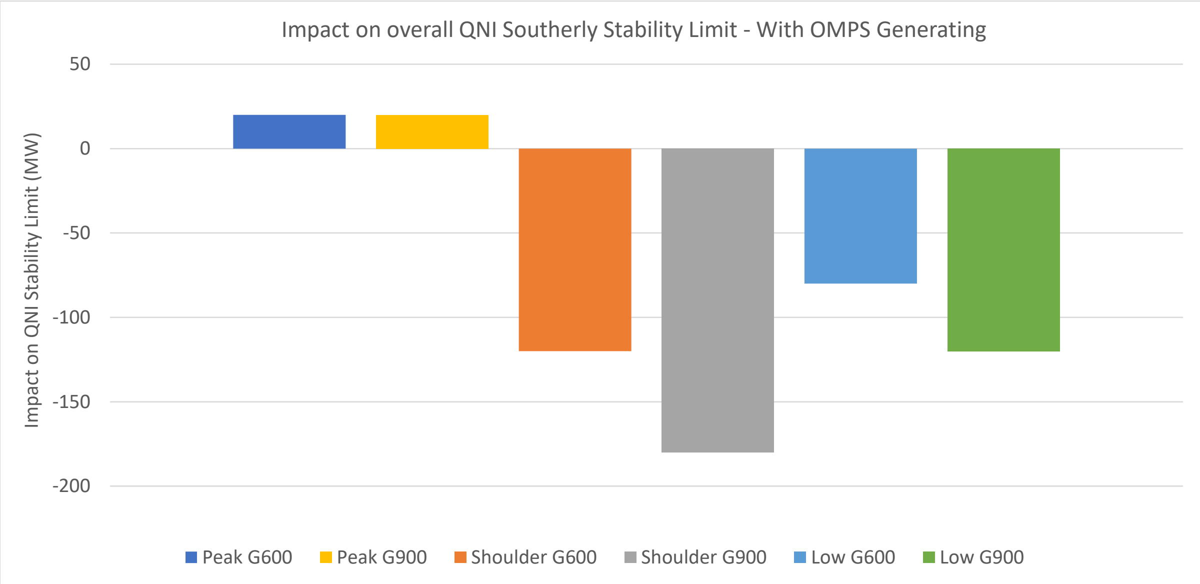
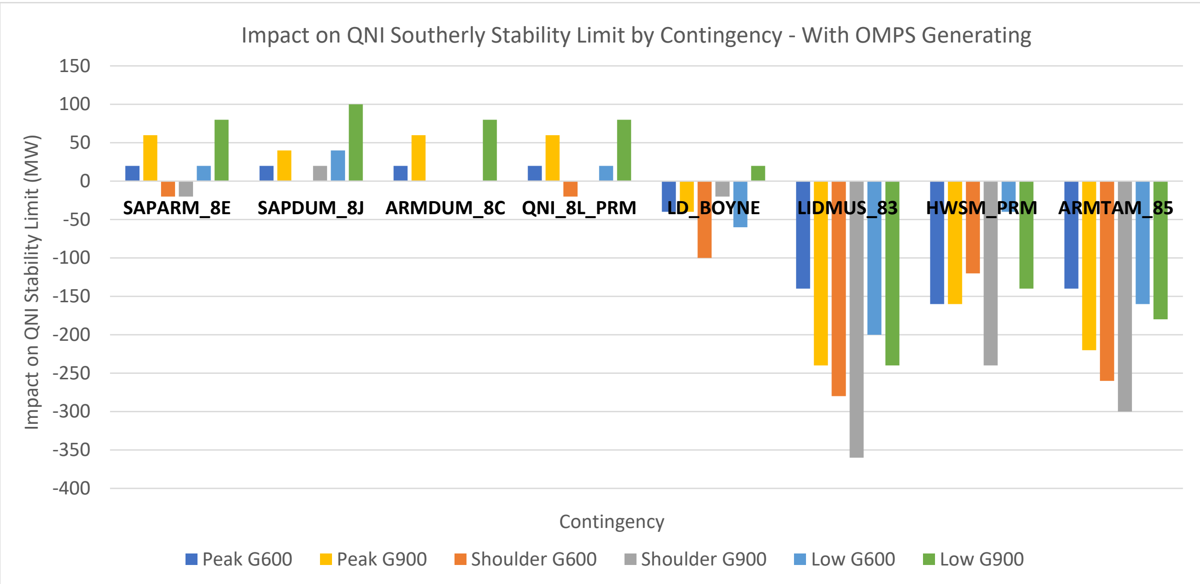


Figure 7 – Impact on QNI southerly stability limits by contingency – OMPS generating



The QNI Minor project is currently under construction and is intended to relieve the limitations south of Armidale Substation. The scope targets increases in both northerly and southerly QNI stability limits by installing dynamic reactive support (SVC) at both the Tamworth and Dumaresq 330 kV substations and installing additional 330 kV shunt connected capacitor banks at Tamworth, Armidale and Dumaresq 330 kV substations [5]. The scope also includes uprating the Liddell to Tamworth 330 kV lines to improve thermal capacity although this will not have a material impact on the stability limits.

The studies in this report do not account for the impact of the QNI Minor augmentations as these are not yet complete and are not included in the AEMO Standard Snapshots of the existing network. Powerlink indicates these augmentations will improve QNI capability by up to 240 MW in the Southerly direction depending on operating conditions [5].

If these committed augmentations were accounted for in the studies OMPS would have a less onerous impact on the QNI limits set by contingencies south of Armidale.

In addition to QNI Minor, the New England REZ Transmission Link is now an actionable ISP project [8] to extend the 500 kV network from Bayswater to south of Armidale, including new 500/330 kV substations south of Armidale and east of Tamworth, dynamic and static reactive plant and reconfiguration of the 330 kV network between Armidale and Tamworth. When completed in 2027, this project is expected to increase the transfer capacity across this corridor by over 3,000 MW in both directions.

Figure 7 also shows OMPS causes a reduction in the QNI southerly limit set by a Hazelwood to South Morang 500 kV contingency. In this scenario the QNI southerly limit being reported is not caused by instability following the contingency. Rather, the pre-contingent southerly transfer on QNI exceeded 1400 MW causing low voltage conditions on QNI below 0.9 PU. In this case the transfer south of Armidale becomes so high before the fault that 330 kV voltages are depressed.

Although there is a reduction in QNI southerly limits when OMPS is generating under lower demand conditions, the reduction in the limit is substantively less that the generation output from OMPS. Because of this the effect of OMPS is to increase the New South Wales maximum supportable demand (MSD).

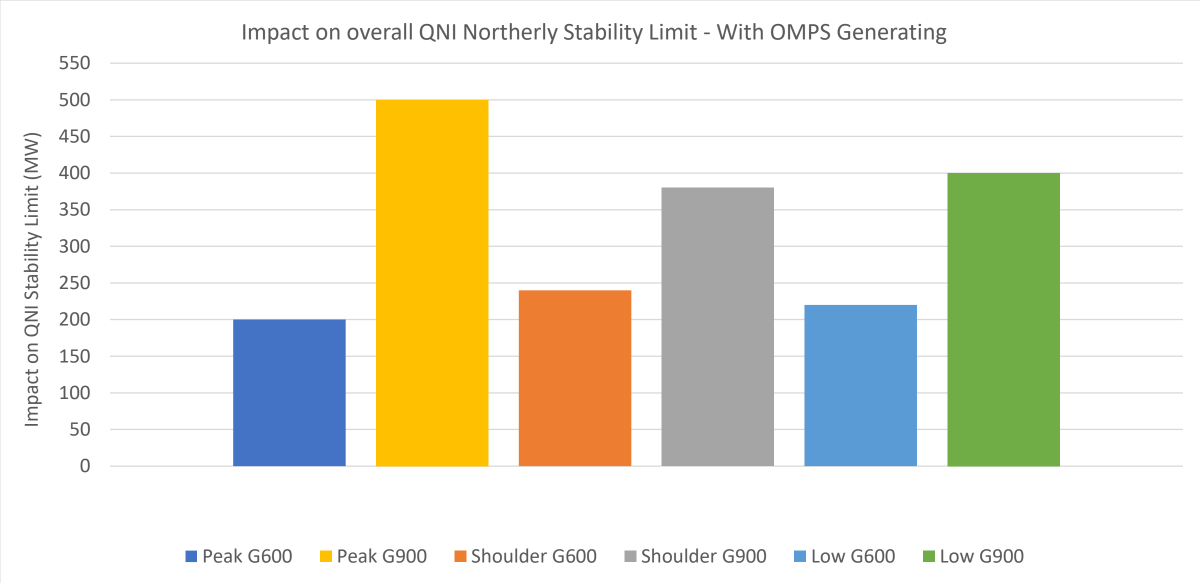
These studies show, from a stability perspective, if OMPS injects 900 MW at Armidale there may be a corresponding reduction in the southerly QNI capability of around 200 MW (ignoring the impact of QNI Minor). This suggests that OMPS provides an increase in MSD of at least 700 MW under these circumstances.

3.2.3.2. Northerly Limits with OMPS Generating

Figure 8 shows, for each scenario, the relative impact OMPS has on the northerly QNI stability limits set by the trip of Kogan Creek.

When OMPS is generating there is a considerable increase in the QNI northerly stability limit in all scenarios ranging from 200 MW to 500 MW.

Figure 8 – Impact on QNI northerly stability limit for Kogan Creek Trip – OMPS generating



3.2.4. Limits with OMPS Pumping

3.2.4.1. Southerly Limits with OMPS Pumping

Figure 9 shows, for each scenario, the relative impact OMPS has on the southerly QNI stability limits set by the worst case contingency. There was no pumping scenario under for Peak demand conditions as this was considered an unlikely outcome. When pumping the worst case QNI southerly limit increases by around 100-220 MW.

When operating in pumping mode OMPS draws load from Armidale Substation, reducing the southerly power transfer from Armidale towards Tamworth. This results in contingencies north of Armidale setting the QNI southerly limit, with contingencies south of Armidale having the largest increase in capability as shown in Figure 10.

Figure 9 – Impact on QNI southerly stability limit (worst case contingency) – OMPS pumping

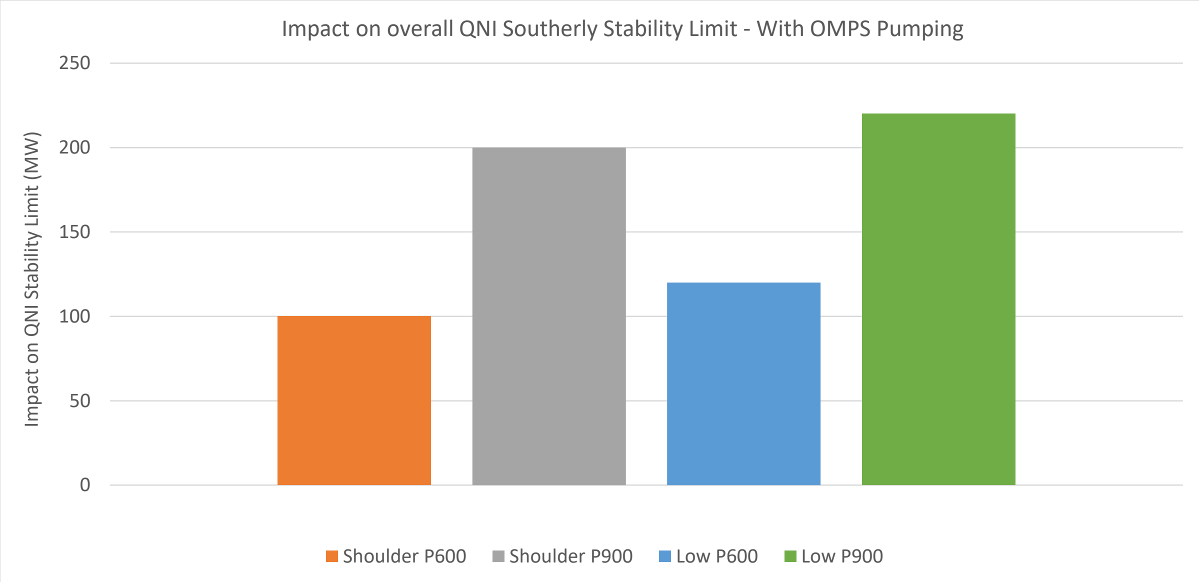
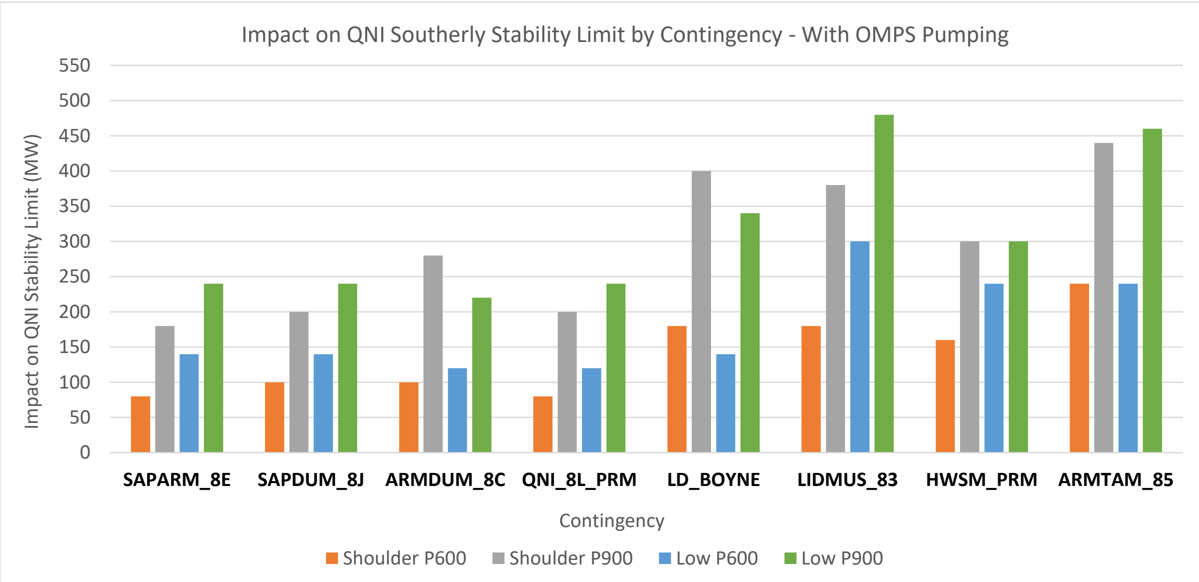


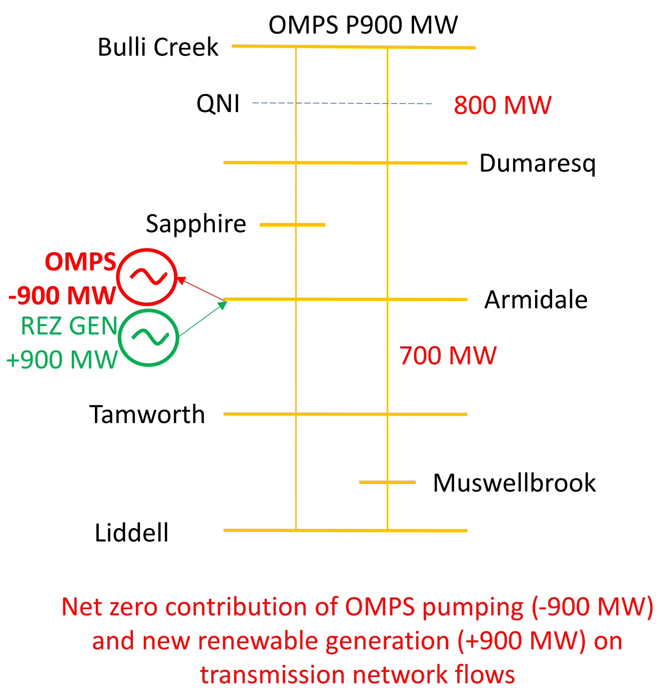
Figure 10 – Impact on QNI southerly stability limits by contingency – OMPS pumping



During pumping periods OMPS will enable additional generation to inject at or near Armidale at least up to the level of pumping demand. The pumping load and additional generation cancel one another leading to negligible net effect on transmission loading as shown in Figure 11, but the benefits of voltage control, inertia and system strength is retained. The ability for OMPS to increase network hosting capacity for other renewable generation is explored further in Section 3.5.

This is analogous to the results in Section 3.3 showing the impact of OMPS in synchronous condenser mode. In this case the net impact of transmission loading is also immaterial and QNI stability limits are increased by around 200 MW in both directions. This highlights a significant benefit of OMPS in supporting increased renewable generation connections at or near Armidale.

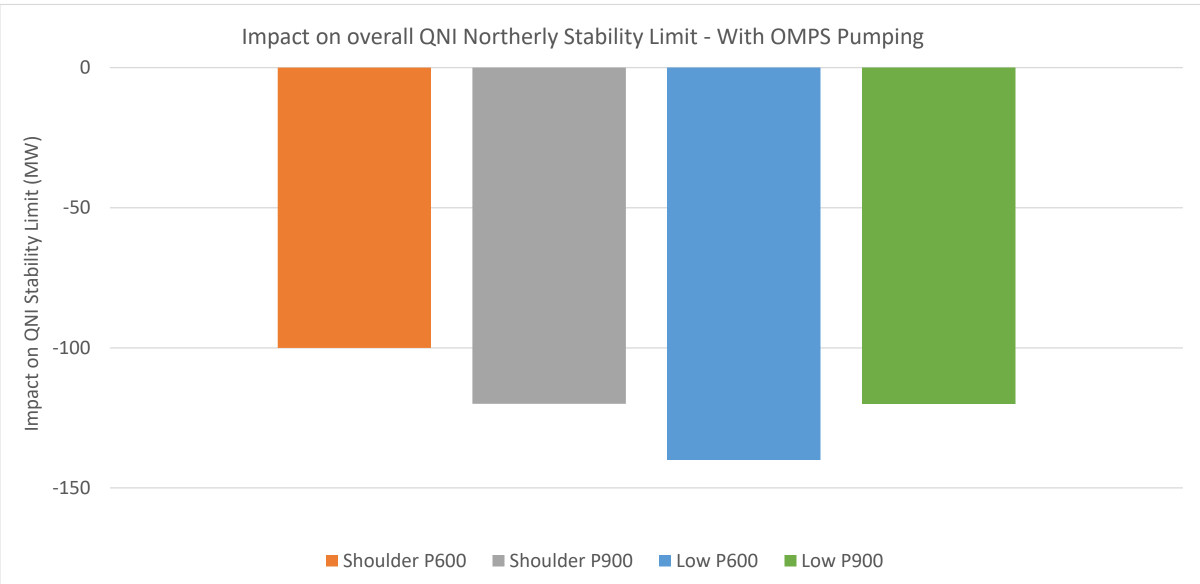
Figure 11 – 900 MW pumping increasing hosting capacity



3.2.4.2. Northerly Limits with OMPS Pumping

Figure 12 shows, for each scenario, the impact OMPS has on the northerly QNI stability limit when pumping. The northerly transfer limit is reduced by around 120-140 MW in this scenario, but OMPS continues to provide a significant benefit overall by increasing the capacity for additional generation to operate near Armidale.

Figure 12 – Impact on QNI northerly stability limit for Kogan Creek Trip – OMPS pumping



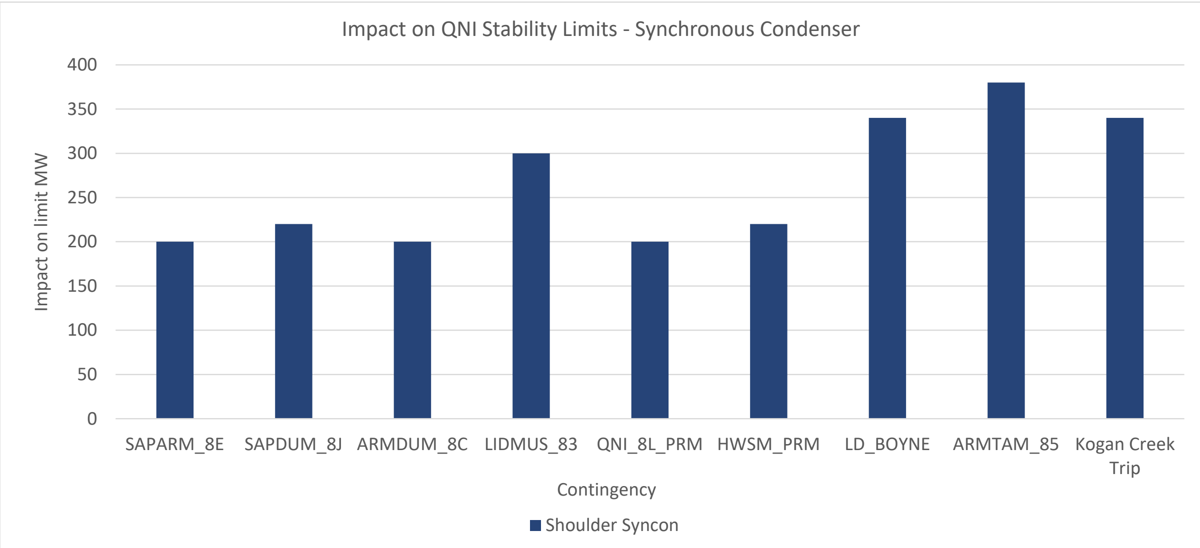
3.3. Synchronous Condenser Mode

OMPS is capable of operating in synchronous condenser mode; a mode of operation where the generating system can continue to provide system strength, voltage support and inertia but does not generate active power.[11]

A sensitivity study was performed to demonstrate the impact of OMPS operating in synchronous condenser mode on the QNI northerly and southerly limits under shoulder demand conditions. The results are provided in Figure 13 showing that in this mode of operation OMPS provides a significant improvement across all contingencies with a bidirectional increase in the QNI stability limit of more than 200 MW.

The synchronous condenser mode of operation is a particular benefit of OMPS. The units can provide substantial system strength, voltage control and inertial support in this mode in a similar manner to generation and pumping modes, but without being reliant on economic security constrained dispatch outcomes. This makes the synchronous condensers a very flexible option to support increased renewable generator connections as they can provide a power system "pillar of strength" for the surrounding network irrespective or wholesale market pricing signals.

Figure 13 – Impact on QNI Stability Limits – Synchronous Condenser



When operating as a synchronous condenser there is negligible contribution to transmission network flows as the units only draw a small amount of active power from the grid. Amplitude considers the results shown in Figure 13 would be also representative of a case where OMPS was pumping at 900 MW at the same time as an additional 900 MW of renewable generation was injecting into Armidale. In this case there would also be minimal impact on surrounding transmission network flows but the OMPS pumps would still provide the same system strength, voltage control and inertia as they do when in synchronous condenser mode.

[11] When in synchronous condenser mode each OMPS unit uses a small amount of electricity from the network sufficient to spin the machine rotor and supply rotational energy (approximately 1 MW).

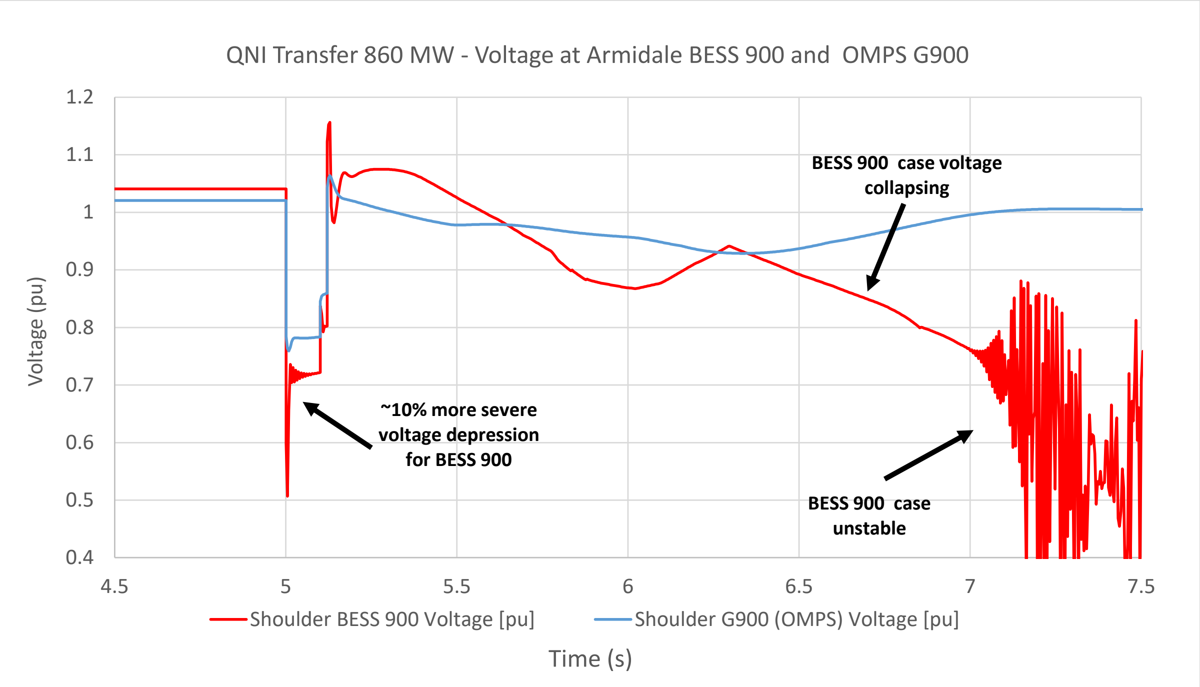
3.4. BESS Sensitivity

An additional sensitivity study has also been carried to compare the performance of a 900 MW OMPS facility with a notional 900 MW BESS model when discharging. This study was performed to investigate the impact on the QNI southerly limit for a single contingency only, the Liddell – Muswellbrook contingency, under shoulder demand conditions. The study found that the 900 MW BESS also reduced the QNI southerly transfer limit for a Liddell – Muswellbrook contingency but by 60 MW more than OMPS.

Figure 14 shows a comparison of the voltage at Armidale 330 kV in the BESS 900 and OMPS G900 scenarios for a QNI transfer of 860 MW, being the marginally unstable case for BESS 900.[12] Note the Liddell – Muswellbrook contingency occurs at five seconds and is cleared 120 ms later.

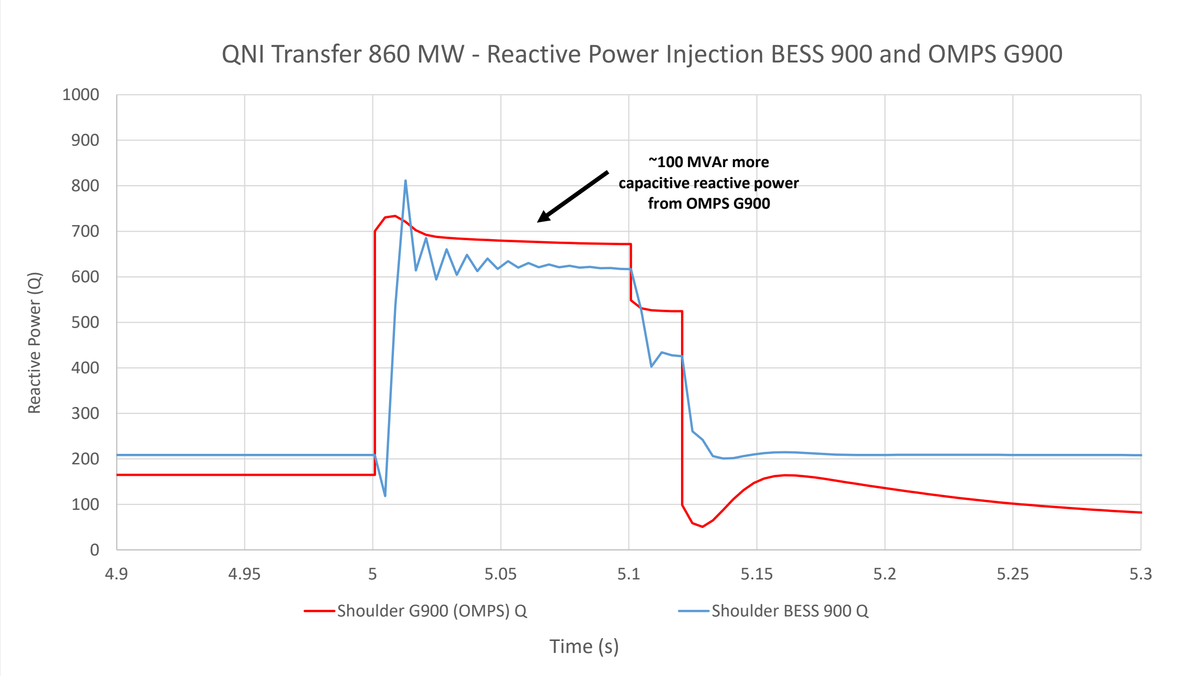
Figure 14 shows that for an 860 MW QNI transfer, unlike the BESS, OMPS G900 can maintain continuous uninterrupted operation. Furthermore, the response from OMPS G900 is favourable as it causes around a 10% less severe voltage depression at Armidale 330 kV when compared with the predisturbance voltages. This is attributed to higher amount of capacitive reactive current injected by OMPS G900 during the fault as shown in Figure 15.

Figure 14 – Voltage response at Armidale 330 kV



[12] The marginally unstable case for OMPS G900 occurred at a southerly transfer of 920 MW on QNI.

Figure 15 – Reactive Response of BESS 900 and OMPS 900



Amplitude acknowledges that both the OMPS and the the BESS models could be further tuned to maximise performance. For example, the BESS model could be configured to provide a more aggressive capacitive current injection during the fault potentially resulting in a voltage depression more comparable with OMPS. Amplitude has not attempted this but considers it unlikely that this would prevent the post fault voltage collapse seen in this case.

Ultimately, for a given nameplate rating, the short circuit current contribution from PHES machines like OMPS is far higher than that of a typical inverter-based facility (circa 3-6 times higher) and this additional short circuit current can assist with maintaining system voltages and preventing voltage collapse following disturbances.

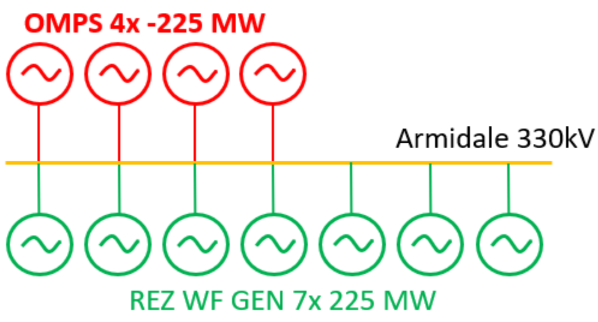
3.5. Increased Hosting Capacity When Pumping

Section 3.2.4.1 explains how operation of OMPS in pumping mode is expected to increase network hosting capacity for other renewable generation at or near Armidale Substation by at least the amount of pumping demand.

Amplitude investigated this further through sensitivity studies with additional wind farm generation capacity injecting into Armidale Substation at 330 kV while OMPS pumping at 900 MW. The wind farm capacity was modelled as several different generators each of which was based on a notional 225 MW wind farm site as shown in Figure 16.

The studies assessed the impact of increasing amounts of wind generation on the QNI southerly stability limit set by the Sapphire to Armidale (SAPARM_8E) contingency and the Liddell to Muswellbrook contingency (LIDMUS_83). These two contingencies were selected as they typically represent the worst case contingencies north and south of Armidale. The QNI northerly stability limit was also assessed for a trip of Kogan Creek Power Station.

Figure 16 – Additional Wind Farm Capacity at Armidale 330 kV



The results showed that with lower amounts of wind farm generation the QNI southerly stability limit was set by the Sapphire to Armidale (SAPARM_8E) contingency. This was expected based on previous studies given the effect of pumping demand on reducing power transfers south of Armidale. As the wind farm capacity is increased so too is the power transfer south of Armidale. Eventually a point is reached where increasing generation further causes the QNI southerly limit to be set by the Liddell to Muswellbrook contingency (LIDMUS_83).

Amplitude found that with 1,575 MW of additional wind farm capacity the QNI southerly limit was 1,220 MW for both the SAPARM_8E and LIDMUS_83 contingencies (the crossover point), which is 120 MW higher than the scenario with no OMPS or wind farm generation at all. The QNI northerly stability limit also improved by 440 MW. As wind farm capacity increases above 1,575 MW the QNI southerly stability limit reduces.

These outcomes show OMPS can provide a significant improvement in renewable generation hosting capacity at or near Armidale during pumping periods. The maximum supportable demand (MSD) in New South Wales also increases by 795 MW, being the difference between the wind farm capacity and OMPS pumping demand, plus the additional 120 MW of southerly import capability into New South Wales on QNI.

4. Conclusion

The studies presented in this work demonstrate that OMPS should provide a valuable contribution to the stability of the power system. The plant offers substantial system strength, voltage control and inertia benefits and can do so irrespective of its mode of operation. This flexibility allows OMPS to support power system stability and improve generation hosting capacity independent of central dispatch processes.[13]

OMPS generally increases the QNI stability limits in the direction of flow most likely for given operating scenarios. It also provides an increase in the New South Wales maximum supportable demand of at least 700 MW[14] and should also increase the hosting capacity for other generation in the New England REZ by at least the maximum operating pumping demand.

[13] A synchronous condenser is not subject to security constrained economic dispatch limitations.
[14] For a 900 MW option.

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