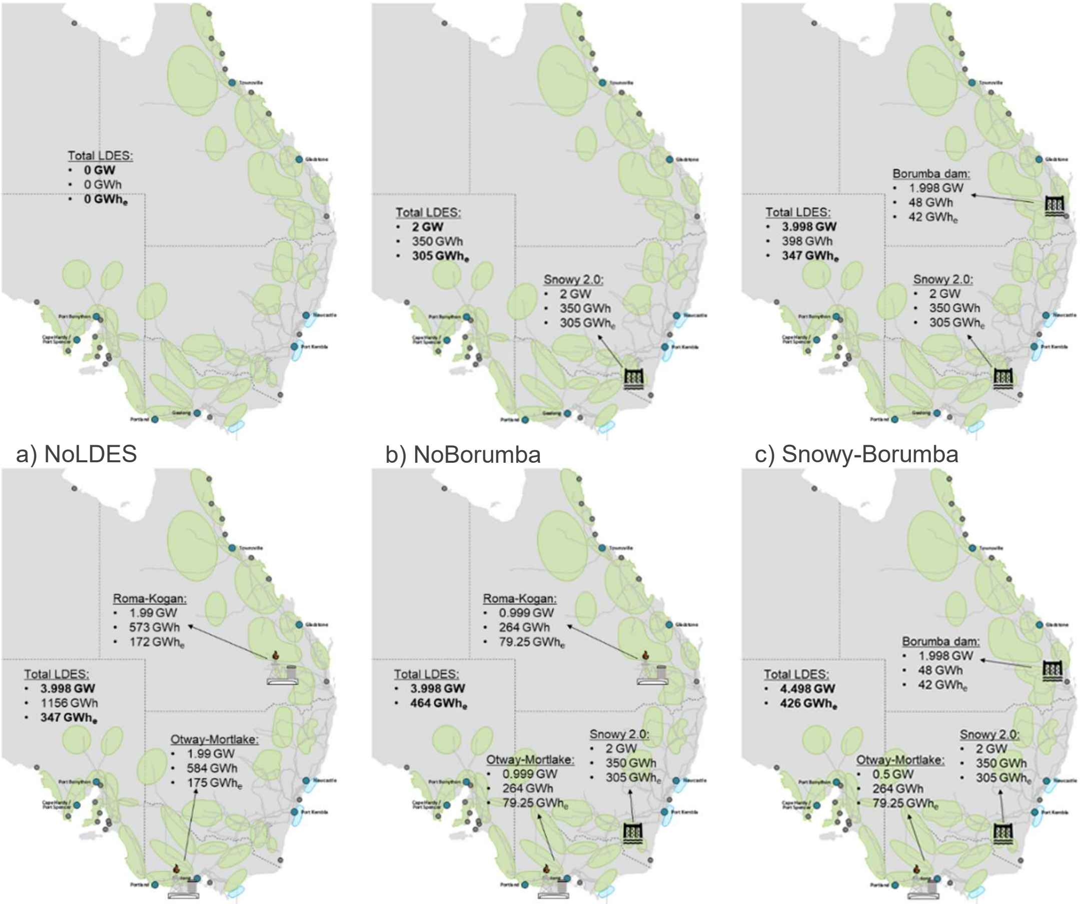
Enabling the decarbonisation of Australia's energy networks

RP1.1-07 Long-Duration Energy Storage: Techno-economics and provision of reliability and resilience to the NEM

Long-duration energy storage (LDES) systems, such as pumped hydro energy storage (PHES) and potentially hydrogen energy storage systems (HESSs), are essential for managing and maintaining reliability and resilience as the National Electricity Market (NEM) transitions to a renewables-dominated electricity system.

A new comprehensive techno-economic framework, founded on an optimisation-based market dispatch model, has been developed by the authors to provide valuable insights into the techno-economics of these LDES technologies and their contribution to reliability and resilience. The framework is informed by a set of well-defined engineering and economic assumptions derived from reputable and publicly accessible sources. A range of scenarios is modelled to evaluate the merits of different LDES options, including the anticipated Snowy 2.0 and Borumba projects; a scenario with HESSs located in Victoria and southern Queensland; and combinations of these, as shown in Figure ES1.



a) NoLDES b) NoBorumba c) Snowy-Borumba

d) HESS-VIC-QLD-4GW e) HESS-VIC-QLD-2GW f) HESS-VIC-0.5GW

Figure ES1: Illustration of the proposed six LDES scenarios to assess the merits of Snowy 2.0, Borumba, and two HESSs in Victoria and southern Queensland.

The overarching aim of this work is to objectively assess the techno-economic merits of LDES technologies such as HESSs and PHES, depending on a variety of factors, including:

- location in the NEM,
- market conditions,
- weather conditions, and
- availability of suitable storage sites—be they depleted gas reservoirs, as in the case of HESSs, or rivers and dams in the case of PHES.

Although only the design of HESSs is optimised—along with the operation of the NEM by adjusting assumptions on Snowy 2.0, Borumba, and the proposed HESS designs—other assumptions, which are taken directly from the *Step Change scenario* in AEMO's 2024 ISP but could still influence outcomes, include (but are not limited to):

- network development (transmission expansion),
- forecast regional and sub-regional demand,
- uptake of VRE,
- uptake of utility-scale and distributed battery energy storage systems (BESSs),
- uptake of electric vehicles (EVs),
- degree of coordination of consumer energy resources (CERs),
- domestic and export hydrogen demand, and
- technology cost curves.

While the insights are not intended to serve as commercial recommendations on LDES options, the key findings include:

Suitable geology

- Australia has suitable underground geological formations—particularly depleted gas reservoirs—located near the high-voltage (HV) transmission network for large-scale HESS deployment.

Capex

- Large-scale HESSs may have a CapEx up to 30% lower than that of a PHES with equivalent power and energy storage capacities.

LCOE and LROE

- Compared to PHES, which has a capacity factor (CF) of approximately 38%, current HESS technology is expected to achieve a CF of around 10%, resulting in a levelised cost of energy (LCOE) up to three times higher than that of a PHES with equivalent power and energy storage capacities.
- The same low CF for HESSs that drives their high LCOE also results in a correspondingly high levelised revenue of energy (LROE), significantly strengthening the business case.
- Under the projected generation, storage, and transmission expansion plan in AEMO's 2024 ISP, the LROE analysis in this report indicates that HESSs in strategic locations such as Victoria and Southern Queensland may be able recover their costs within the first 20 years of operation exclusively through participation in the wholesale NEM.
- The expected increase in price volatility as the NEM becomes more renewables-dominated presents greater opportunities for HESSs to maximise their revenue by capitalising on high prices that may occur when residual demand is high or during reliability events.

Reliability

- The projected generation, storage, and transmission capacities in AEMO's 2024 ISP may not be sufficient to maintain reliability in the NEM through to 2050.

- The 2 GW Borumba facility with 24 hours of storage may be insufficient to maintain reliability in Queensland; at least 86 hours of storage may be required instead.
- In a scenario where both Snowy 2.0 and Borumba are present, installing a HESS in Victoria with 500 MW and 158 hours of net storage may significantly enhance the reliability of the NEM, particularly in the southern states of Victoria, South Australia, and Tasmania.
- Together, the Otway-Mortlake HESS in Victoria and the Roma-Kogan HESS in southern Queensland, in the HESS-VIC-QLD-4GW scenario, are capable of maintaining reliability in New South Wales until 2043, under a counterfactual case in which Snowy 2.0 is delayed by five years.

Resilience

- In the process of selecting variable renewable energy (VRE) drought days for assessment, it is important to consider both residual demand and VRE CFs. Focusing solely on the latter may overlook instances with potential reliability risks.
- Due to their strategic locations, the Otway-Mortlake HESS in Victoria and the Roma-Kogan HESS in Southern Queensland (the HESS-VIC-QLD-4GW scenario) could significantly enhance resilience by maintaining reliability during extended VRE droughts.
- While the HESS-VIC-QLD-4GW scenario improves resilience, unplanned generator or interconnector outages beyond those modelled could still pose reliability risks. This is particularly critical in winter when residual demand is high, and the power system operates with low reserve margins. As a result, maintenance schedules for dispatchable generators must be carefully planned and coordinated during winter to mitigate reliability concerns arising from VRE droughts. These concerns are further compounded by the impact of weather forecast accuracy on the ability to anticipate unfavourable conditions, which affects the accumulation of sufficient energy in LDES to maintain resilience during periods of severe VRE drought.
- If a severe VRE drought event similar to that of May 2024 occurs during periods of high residual demand—such as in winter—the NEM, under both the HESS-VIC-QLD-4GW scenario and the projected generation, storage, and transmission expansion in AEMO's 2024 ISP, may not be resilient. This suggests that additional firming and backup generation should be planned—particularly in Victoria and Queensland—beyond what is projected in AEMO's 2024 ISP and in this report, to hedge against events like the one in May 2024.
- In resilience studies involving prolonged VRE droughts, optimisation-based market dispatch models with extended time horizons (spanning months rather than days or weeks) not only provide the necessary temporal granularity (e.g., 30 minutes) and foresight (e.g., 20 years) to rigorously assess such events, but they eliminate the need for strong assumptions about the state of energy (SoE) at the onset of such events. This helps avoid shortsighted assumptions that may compromise the accuracy of resilience assessments.

VRE curtailment

- The modelled HESSs in this report present opportunities to accommodate more VRE in the NEM that would otherwise be curtailed. This is due, among other factors, to the fact that HESSs typically have a capacity factor (CF) of up to 10.5%, while PHES options generally have a CF of up to 38%.
- An LDES system in Victoria can access VRE from four subregions: Central South Australia, Southeast South Australia, Tasmania, and South New South Wales. In contrast, an LDES system in South New South Wales has access to VRE from three subregions: Victoria, Central New South Wales, and Central South Australia.
- Higher LDES power and energy storage capacities in VIC, SA, and TAS, beyond what is projected in AEMO's 2024 ISP, contribute to a higher accommodation of VRE, in addition to a higher contribution to reliability.

Operational costs

- A 2 GW LDES in New South Wales can displace more generation from gas-fired generation (GFG) and coal-fired generation (CFG) compared to other states, resulting in a notable reduction in overall operational costs and emissions across the NEM. According to AEMO's 2024 ISP, 33% of the 14.44 GW of GFG across the NEM in 2035–36 is located in New South Wales. At the same time, New South Wales is forecast to still have around 1.42 GW of CFG in 2035–36—about 2.53% of the total dispatchable capacity.

Price volatility

- In general, LDES helps reduce price volatility by lowering the frequency and magnitude of both extremely low and extremely high prices.
- LDES in strategic locations like Victoria and Southern Queensland can greatly reduce price volatility by enhancing reliability, leading to a decreased reliance on expensive demand-side programs (DSP) to mitigate unserved energy (USE).

Market dispatch modelling

- Long-horizon, optimisation-based market dispatch models can play an instrumental role in scheduling energy reserves in LDES systems over weeks and months, helping to hedge against forecasting errors, imperfect foresight, unplanned outages, and gas supply chain risks.
- While the market dispatch analysis in this report focuses on the wholesale energy market, HESSs can also offer regulation and contingency services in the frequency control ancillary services (FCAS) markets by leveraging the flexibility of proton-exchange membrane (PEM) electrolysers and hydrogen turbines, potentially increasing revenue opportunities even further.

In summary, this work stress-tests AEMO's 2024 ISP using comparable zero-emissions LDES technology case studies and advanced modelling techniques that not only replicate the 2024 ISP operational modelling but also introduce the additional granularity and foresight needed to evaluate both current NEM benefits and the enhanced reliability and resilience provided by LDES. This work also demonstrates that both HESSs and PHES, when deployed in strategic locations, have distinct merits and can coexist synergistically—particularly when assessed across a broad set of metrics, including reliability and resilience.

Overall, this research underscores the need for advanced optimisation-based market dispatch modelling frameworks that can adequately evaluate and quantify the potential benefits, as well as the challenges, risks, and opportunities that different types of LDES systems offer to the NEM or other electricity networks and markets. In general, such a framework can assist system planners in pre-emptively minimising the risk of investing in a suboptimal power system architecture today or being locked out of a more cost-effective one in the future. This is especially true since PHES projects are at risk of cost blowouts and delays, as such projects are generally specific to the geography in which they are envisaged to be built, along with many other factors including availability of existing dams, distance between existing and/or new dams, terrain characteristic, access to nearby rivers, and proximity to existing electricity infrastructure, to name a few. This work also demonstrated that a system with higher energy efficiency may not necessarily lead to a more reliable, more resilient, and more cost-effective system.

Future work involves extending the developed long-horizon optimisation-based framework to jointly optimise the development of generation, transmission, and storage, alongside gas infrastructure development—resulting in a truly integrated model that simultaneously incorporates all three energy vectors: electricity, natural gas, and hydrogen.

Policy Implications

The above findings have the potential to initiate new evidence-based policy discussions, from which specific market and policy settings may evolve to facilitate the deployment of alternative LDES technologies—such as HESSs—particularly when:

a) The maximum installed capacity of GFG is constrained by CO_2 emissions and pumped hydro energy storage (PHES) is limited to specific regions in the NEM;
b) Cost recovery is not limited to actual use (i.e., the value of reliability and resilience these technologies provide to the NEM), or extends beyond their participation in the NEM (i.e., using hydrogen directly as feedstock to decarbonise hard-to-abate industries such as steel, cement, and aluminium production); and
c) Energy system planning, initiated by a review of the ISP by the Energy and Climate Ministerial Council (ECMC), is now undergoing its most significant transformation since its inception in 2017. As a result, AEMO is establishing new processes to evaluate a range of gas infrastructure options to support planning for a resilient, cost-efficient, and decarbonised grid.

Acknowledgements

This project was delivered by a research team at the University of Melbourne led by Dr Sleiman Mhanna which was supported by industry advisors from Energy Networks Australia, Lochard Energy, Australian Pipelines and Gas Association, APA Group, Woodside, Jemena, and NSW Government. Their contributions to the project and the CRC are gratefully acknowledged.

Future Fuels CRC is supported through the Australian Government's Cooperative Research Centres Program. We gratefully acknowledge the cash and in-kind support from all our research, government and industry participants.

Australian Government
Department of Industry, Science and Resources

Cooperative Research Centres Program