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Techno-economic comparison of state-of-the-art compressed air energy storage and pumped hydro storage systems in Aotearoa New Zealand

Zachary Lerman, Alan Colin Brent

Abstract

This paper examines the potential use of compressed air energy storage (CAES) as a utility-scale energy storage solution for Aotearoa New Zealand. The country's strong commitment to renewable energy and the increasing integration of intermittent sources such as wind and solar power necessitate robust energy storage capabilities to ensure grid stability and security. Through techno-economic modelling and sensitivity analysis, CAES clearly shows it can stand competitive against pumped hydro storage (PHS), the dominant form of utility-scale storage. By utilising existing geological formations, such as depleted gas fields in Taranaki, CAES minimises capital costs and surface footprint while avoiding the extensive land inundation and biodiversity impact inherent with hydro reservoirs. Furthermore, CAES technology provides essential ancillary services, including physical grid inertia and frequency stability, which are critical as fossil-fuelled thermal generators are decommissioned. The paper concludes by recommending a dual-track storage strategy. While PHS remains unparalleled for addressing seasonal dry-year risks, CAES should be prioritised for medium-duration (10–100 hour) stabilisation. Deploying modular 300–500 MW CAES facilities near North Island load centres provides grid resilience while reducing reliance on the Inter-Island HVDC link. This integrated approach optimises fiscal responsibility and ecological integrity, offering the most robust pathway toward Aotearoa's net-zero future.

Keywords: Compressed air energy storage; Adiabatic; Utility-scale; Underground storage.

1. Introduction

Aotearoa New Zealand's power grid – the backbone of all modern economies – is on course for a perfect storm of rising demand and variable supply. Increased electrification of its transportation and residential sectors is projected to increase total electricity demand 81%, reaching an estimated 71.7 TWh by 2050 (Gray, 2024). Simultaneously, the government's ambitious target of 100% renewable electricity generation by 2035 is expected to dramatically increase the amount of renewable energy sources, such as wind and solar (Davis, 2024). This presents a significant challenge; such sources are inherently intermittent, meaning when the sun stops shining or the wind stops blowing, power generation drops precipitously (Rendel et al., 2023). To prevent nation-wide blackouts and wild fluctuations in hourly energy costs, these sources must be integrated with substantial energy storage capacity to balance supply and demand variations, ensuring a reliable and stable electricity grid. Without adequate storage, the full potential of renewable energy cannot be realised, and the risk of grid instability and energy insecurity increases. Adding capacity and flexibility to the current system is essential for the nation's aspirations of achieving low-cost, 100% renewable energy independence. Thus long-term, high-capacity energy storage solutions are essential to the government's energy strategy.

The current power infrastructure in Aotearoa New Zealand faces several additional challenges, including rising peak electricity demand coupled with declining natural gas supplies (Rendel et al., 2023). Furthermore, the country's heavy reliance on hydroelectric power makes its energy system particularly vulnerable to climate change, as droughts can significantly reduce water availability and thus electricity generation (Nicol et al., 2022).

The "dry year" problem is now a well-known issue, referring to a recurring instance of low lake-water levels due to reduced rainfall or snowmelt, leading to substantial energy deficits (Spittle et al., 2022). Historically, these deficits have been bridged by relying on fossil fuel generation, undermining the nation's renewable energy objectives. The now-halted NZ Battery Project was established to explore long-duration energy storage options, including pumped hydro storage (PHS) at Lake Onslow (Spittle et al., 2022). The project's numerous pauses and delays, due primarily to high capital costs, underscores the critical importance of identifying viable storage alternatives. While PHS is an excellent solution in specific geologically optimal locations, it is not a "silver bullet"; alternative systems are needed that balance cost, efficiency, and environmental impact. These alternative forms of energy storage will play a crucial role in mitigating the risk of overreliance on hydro storage. Compressed Air Energy Storage (CAES) is one of the most promising options, capable of providing sustainable, long-duration, utility-scale energy storage that could help support Aotearoa's growing energy needs into the future, strengthening the nation's grid resiliency and complementing the transition to a fully renewable energy system.

1.1. Objective

The objective of this paper is to verify that state-of-the-art (SOTA) CAES technologies are, or will be in the near future, competitive with PHS within Aotearoa New Zealand. PHS is currently the dominant form of energy storage used around the world (Nikolaos et al., 2023). It has one of the highest round-trip efficiencies (RTE) of any technology (between 75-80%), significant long-duration energy storage capacity, and high system reliability. However, PHS is not a ubiquitous solution; these systems are expensive and time-consuming to construct, and there is a high environmental cost associated with the creation of the upper and lower reservoirs (Spittle et al., 2022). Put simply, "you cannot put a lake everywhere." There is a need to understand the cost-effectiveness, energy efficiency, and environmental footprint of deploying and operating advanced CAES systems within the Aotearoa New Zealand energy landscape, considering factors such as geological site availability and integration with existing infrastructure. Selecting a viable alternative for long-term, sustainable, utility-scale energy storage requires a balance of three crucial factors: cost, efficiency, and environmental impact. The results derived from this techno-economic analysis are intended to assist decision-makers in accurately assessing the viability and optimal role of CAES as a key contributor to Aotearoa New Zealand's low-carbon energy future.

Each CAES technology is evaluated on its performance economically, technologically, and environmentally, and compared against PHS within the context of Aotearoa New Zealand. Low upfront capital costs are critical for initial investment in utility-scale storage projects (Jankowski et al., 2024). A lower initial cost reduces the financial barrier to deployment and makes the technology more competitive with traditional grid infrastructure solutions or fossil fuel peaker plants.

A high RTE directly translates to lower operating costs and increased revenue potential (Jankowski et al., 2024). If a system operates at a low efficiency, a larger amount of energy must be put in to get a desired amount of energy out. This wasted input energy represents a direct cost, especially when charging from sources with a marginal cost (like electricity from the grid). A more efficient system delivers more marketable energy for the same energy input. The goal is to achieve a balance where the combined capital costs, operational costs (heavily influenced by RTE), and lifespan result in a low levelised cost of storage (LCOS); defined as "the average $/kWh price that energy output from the storage system would need to be sold at over the economic life of the asset to break even on total costs" (PNNL, 2024).

Any large-scale energy storage facility (CAES, pumped hydro reservoirs, battery farms, and so forth) requires land-use change (LUC), which can lead to significant habitat loss and potentially impact biodiversity (Spittle et al., 2022). PHS, in particular, can have significant impacts due to the required reservoirs. As virtually all such facilities will require regulatory approval (and often public acceptance), a commitment to minimising environmental impact is essential. Issues such as public health, noise, and land use are crucial for obtaining consenting and ensuring smooth project development.

2. Literature review

Compressed Air Energy Storage (CAES) is conceptually simple: electricity is used to power a compressor, which compresses ambient air into a storage container or underground cavern during periods of low power demand (Olabi et al., 2021). When power is needed, the air is released through an expander, which spins a turbine to generate electricity. The technology possesses numerous advantages for utility-scale energy storage. In many cases, the modularity of the system allows standard commercial components to be utilised, reducing capital costs and maintenance complexity (Bazdar et al., 2022). Advanced variations of the technology have the potential for zero greenhouse gas emissions, appealing to the rapidly growing renewable energy sector. Most crucially, CAES is one of the most capable energy storage technologies on the market (Olabi et al., 2021), able to provide rapid start-up and "black start" capability to an electrical grid, with significant capacity for both instantaneous power (MW) and long-duration supply of power (MWh provision for hours to days). CAES technology is frequently compared to pumped hydro storage (PHS), the global champion of renewable, utility-scale energy storage (Nikolaos et al., 2023). In recent years, CAES has returned into focus as new technological advancements have been able to increase the round-trip efficiency (RTE) of the system, and demand for storing utility-scale quantities of clean energy continues to increase.

2.1. Types of CAES

2.1.1. Diabatic (D-CAES)

CAES systems are not new; viable utility-scale plants have been in operation since the 1970s. The first large-scale CAES systems were diabatic (D-CAES); the heat generated by compression of air is lost to the surrounding environment, and must be added back in when the air is run through an expander prior to power generation. The Huntorf plant, commissioned in 1978 in Niedersachsen, Germany, is a D-CAES facility (Jankowski et al., 2024). The plant is designed for off-peak energy storage and "black start" capability (able to restart all or part of the electrical grid without any external power); however, RTE is limited to 42% due to the significant heat losses of the diabatic system and the need for natural gas combustion to reheat the compressed air upon entering the expander.

The McIntosh plant in Alabama, United States, also uses a D-CAES system (Foley & Díaz Lobera, 2013). Commissioned in 1991, the facility is able to incorporate a modest level of heat recuperation technology, improving RTE to 54%. Both the Huntorf and McIntosh plants utilize large underground salt caverns for air storage and function as substantial (>100 MWh) assets for baseload energy shifting and providing reserve power. They remain the only large-scale D-CAES facilities currently in operation.

Both the Huntorf and McIntosh facilities highlight the primary limitation of D-CAES: the lack of a thermal management system. A significant amount of heat is generated as the ambient air is compressed, which is allowed to dissipate and thus lost to the surrounding environment before the cooled air can be stored underground. When the cooled air is needed for power generation, more heat must be applied – typically by combusting fossil fuels – before being run through the expander (Jankowski et al., 2024). In terms of efficiency, this creates a significant design flaw; RTE is greatly reduced, and the use of fossil fuels encourages the continued production of greenhouse gas emissions.

2.1.2. Adiabatic (A-CAES)

Adiabatic CAES (A-CAES) seeks to address this limitation by adding a Thermal Energy Storage (TES) system to capture and store the heat generated by compression (see Figure 1). The stored heat, which can exceed temperatures of 600°C (EASE, 2016), is then used to preheat the expanded air during the discharge phase, eliminating or significantly reducing the need for supplementary fuel and significantly improving RTE. Compared to D-CAES systems, A-CAES systems rely solely on off-peak or renewable electricity for their operation, with an expected round-trip efficiency of 70 to 75% (Rabi et al., 2023).

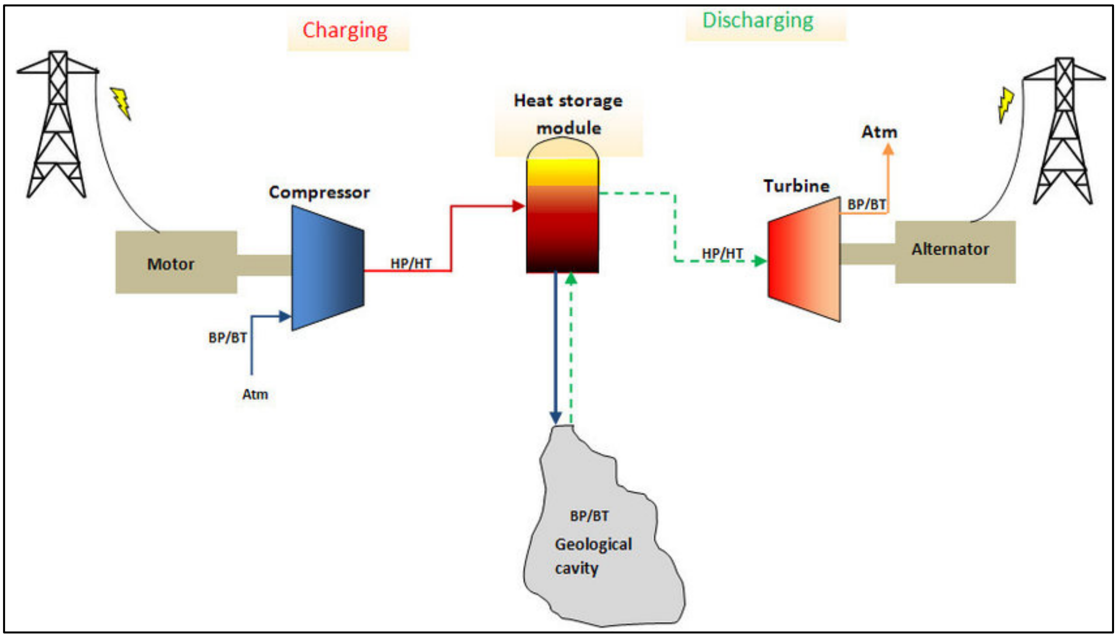

Figure 1. Conceptual diagram of an adiabatic (A-CAES) system
(Source: Kere, 2014)

2.1.3. Isothermal (I-CAES)

Isothermal CAES (I-CAES) is another advanced iteration of D-CAES that has been explored multiple times over the past decade. The core principle of this technology is maintaining a constant temperature during both compression and expansion of air (see Figure 2). To achieve this, a highly efficient heat exchange system is required to continuously remove the heat generated during compression and add it back during expansion. This often involves large heat exchange surface areas or even controlled water sprays to ensure real-time temperature regulation (Odukomaiya, 2016). In theory, this constant-temperature process offers substantial benefits. A complete I-CAES system can achieve much higher air compression compared to other CAES methods, which in turn reduces costs as the size of the storage system can be reduced. While an ideal isothermal system could theoretically achieve 100% efficiency, real-world constraints typically limit it to around

80% (Jankowski et al., 2024). Companies such as Light Sail Energy and GCX Energy Storage (the merger of companies General Compression and SustainX) each attempted I-CAES demonstrator plants. However, the complexity required for these systems made both businesses impractical. Currently, I-CAES is no longer being pursued commercially (Rabi et al., 2023).

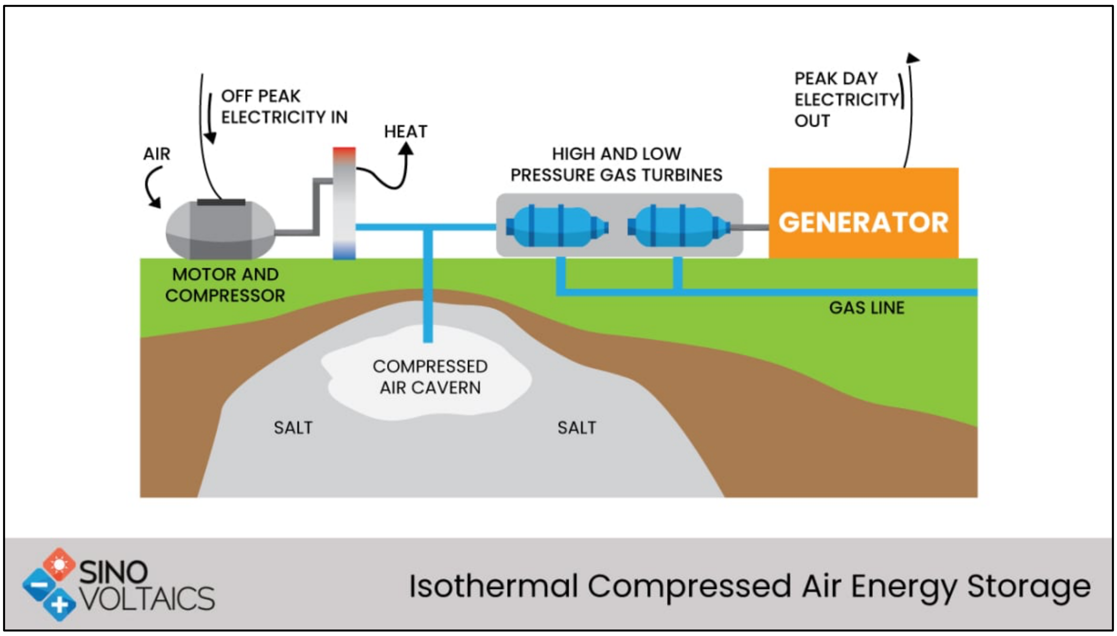

Figure 2. Conceptual diagram of an isothermal (I-CAES) system
(Source: De Rooij, 2023)

2.1.4. Isobaric-Adiabatic (IA-CAES)

Isobaric-Adiabatic CAES (IA-CAES) has emerged in the past few years, seeking to improve on RTE by addressing the issue of fluctuating pressure in the storage container. In conventional isochoric (i.e. constant volume) CAES, the pressure in the storage vessel fluctuates significantly between charging and discharging cycles (Zhang et al., 2025). For example, as the air compressed within the cavern nears depletion, the pressure begins to decrease, reducing power generation in the turbine. Compressors and expanders operate optimally within a specific pressure range, and the fluctuating pressures subsequently decrease their efficiencies. Expanders often require throttling to maintain stable inlet pressure during discharge, further reducing system efficiency. Isobaric storage, however, maintains a near-constant pressure within the storage vessel throughout the charge and discharge cycles. This is typically achieved through displacement of a constant-pressure fluid, such as water or brine, in an underground cavern or reservoir. Maintaining constant pressure allows the turbomachinery to operate closer to its design point, minimising throttling losses and maximising the usable stored energy. Simply put, a constant-pressure storage system is more efficient than a constant-volume system because it avoids the energy losses associated with large pressure changes (Wang et al., 2016).

IA-CAES has been explored in underwater and ocean environments, with the intent of maintaining a pressurised vessel of air on the sea floor and thus taking advantage of the increased pressure at depth. Unfortunately, the difficulty of designing and maintaining such large-scale systems in marine environments, including difficulties with power transmission, results in prohibitively high costs and reduced RTE (Wang et al., 2016).

Land-based IA-CAES systems have presented a more promising solution, combining underground storage with a connected water reservoir which maintains constant hydrostatic pressure on the air in the underground storage container as it is injected or removed (see Figure 3). During the process of air compression, condensation is also created – water, which can then be captured and fed back into the surface reservoir for replenishment due to evaporation (Peacock, 2024). The Goderich Energy Storage Centre, built by Hydrostor as the world's first IA-CAES proof-of-concept plant, opened in 2019 in Ontario, Canada (Zhang, 2025).

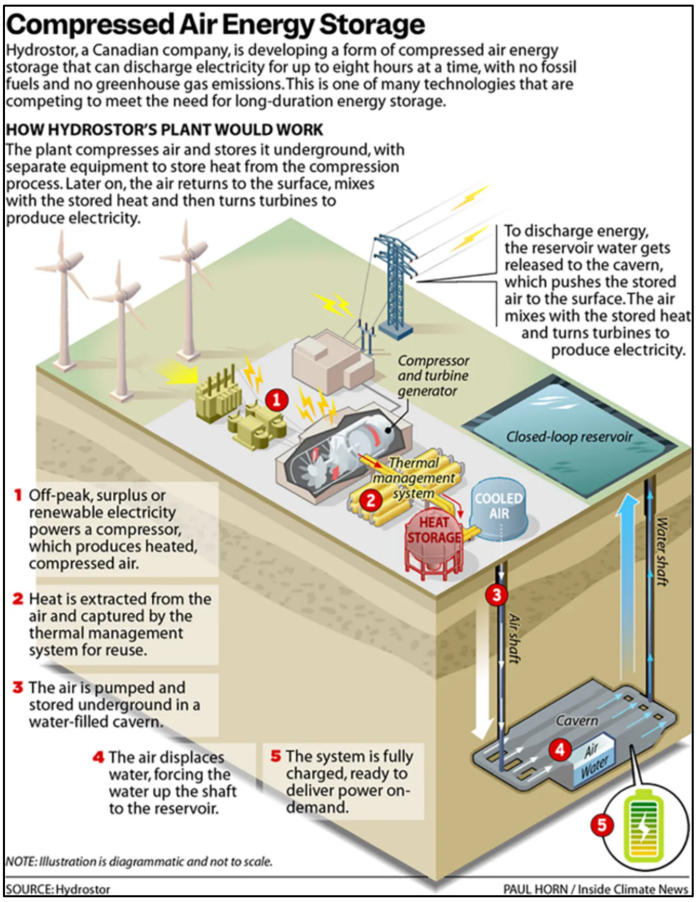

Figure 3. Conceptual diagram of an adiabatic isobaric (IA-CAES) system
(Source: Gearino, 2024)

2.1.5. Multi-Level Isobaric-Adiabatic (MLIA-CAES)

Multi-level IA-CAES (MLIA-CAES) is a recent advancement that seeks to address the practical realities of fluctuating renewable energy availability (see Figure 4). Standard compression and expansion machinery is designed to operate optimally within a specific power range, yet renewable energy sources (such as solar and wind) generate variable amounts of power throughout the day. This implies the equipment is often working in a non-optimal setting, which reduces efficiency of the system. MLIA-CAES solves this through a set of differentially-sized systems, each one designed for optimal operation in different power generation ranges. This includes separate chains of low-, medium-, and high-power compressors, expanders, and isobaric storage containers, using a common TES system. The design allows the overall system to switch between the various-sized equipment as needed, depending on the current power supply. By allowing each component to operate at or near its optimal design condition, the system maximises overall efficiency, producing a theoretical RTE exceeding 83% (Yu & Garvey, 2024). The question remains, however, whether the increase in system complexity and capital cost is worth the small increase in efficiency.

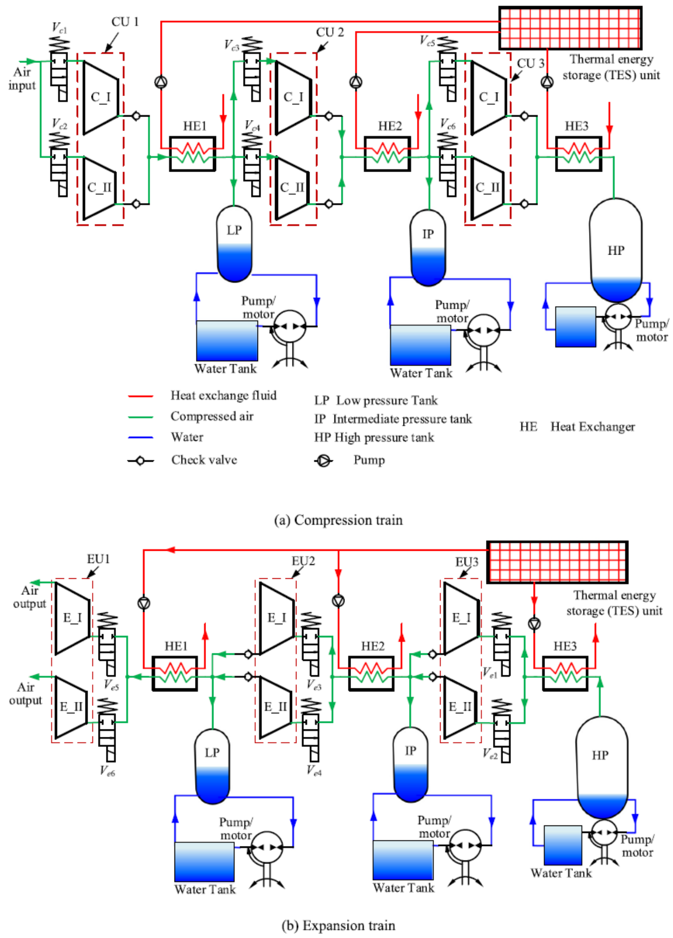

Figure 4. Schematic diagram of a multi-level MLIA-CAES system
(Source: Yu and Garvey, 2024)

There are two other SOTA CAES technologies worth mentioning: Liquid Air Energy Storage (LAES), and Supercritical Compressed Air Energy Storage (SC-CAES). Both technologies are still in development (low TRL); they are advanced forms of energy storage that allow for a much greater energy density, meaning large amounts of energy can be stored in a relatively small volume. This is meant to address the primary limitation of conventional CAES: geographical flexibility. While traditional CAES relies on large underground caverns with specific geologic characteristics, these newer technologies can store an equivalent amount of condensed air in large, pressurised above-ground vessels (Rabi et al., 2023). Of course, the improved siting flexibility comes at a significant increase in cost and complexity. The advanced components and system maintenance required for cryogenic or supercritical systems means a highly skilled workforce must be employed, further increasing long-term operating costs.

2.1.6. Liquid Air (LAES)

Liquid Air Energy Storage (LAES), also known as a "cryo-battery" or "Cryogenic Energy Storage," uses the thermal properties of air in its liquid state to store energy. The core principle involves three main stages: liquefaction, storage, and power generation. During periods of low electricity demand or when surplus renewable energy is available, ambient air is drawn in, filtered, and then compressed and cooled to extremely low temperatures (around -196°C), liquifying the air and charging the system. The liquid air is then stored at low pressure in large, insulated cryogenic tanks. The tanks are designed to minimise heat loss, allowing the energy to be stored for extended periods with minimal degradation. When electricity is needed, the liquid air is pumped to high pressure. It is then heated by absorbing heat from the surrounding environment or from a dedicated TES system (which stores waste heat from the compression phase). This rapid heating causes the liquid air to expand back into a gaseous state, which drives a turbine connected to a generator to produce electricity (Rabi et al., 2023).

2.1.7. Supercritical (SC-CAES)

Supercritical Compressed Air Energy Storage (SC-CAES) is a hybrid approach that combines elements of both CAES and LAES. It aims to achieve a higher energy density and efficiency than conventional CAES by leveraging the properties of a supercritical fluid – a substance that exists at a temperature and pressure above its critical point, where it can no longer be condensed into a liquid by pressure alone. For air, this means the system operates at very high pressures. While there are various designs for SC-CAES, the general process involves similar phases to LAES. During the charging phase, air is compressed to a supercritical state. The heat generated during this compression is captured and stored in a TES system. The compressed, supercritical air is then further cooled to be stored. The air is stored in a cryogenic tank, similar to an LAES system. The key difference is that the air is stored at a supercritical pressure, which allows for a much higher energy density. When power is needed, the stored air is retrieved and heated using the previously captured compression heat (and/or external heat sources). This highly pressurised, heated air then expands through a turbine to generate electricity (Rabi, 2023).

2.2. CAES system components

While much theoretical research has been done, there is limited availability of the actual cost and lifecycle of the various CAES systems – particularly the more advanced A-CAES, IA-CAES and MLIA-CAES. These technologies are still relatively new commercially, and have limited field testing from which to gather cost and performance data. An information gap exists, particularly for future deployment in Aotearoa New Zealand.

All CAES technologies contain the following core components that are essential to understanding the technical and financial analysis comparison:

- The **compressor**, driven by an electric motor, is responsible for compressing the ambient air to high pressures, typically 70 to 100 bar (EASE, 2016). This compression process increases both the pressure and the temperature of the air.
- Air storage – an **underground cavern**, or other similar geological formation such as a salt cavern, hard rock formation, depleted gas field, or aquifer, is typically used to store the compressed air. These caverns provide the large volumes needed to store significant amounts of compressed air at high pressures.
- The **thermal energy storage (TES)** system is a crucial element of advanced CAES systems, capturing and storing the high-temperature heat generated during the compression phase. Various materials can be used for storing the thermal energy, including ceramic materials, concrete, natural rock, molten salt, or thermo-oil, depending on the specific system design and temperature requirements (EASE, 2016). The TES system needs to be well-insulated to minimise heat losses during the storage period.

- The **turbine**, coupled to an electric generator, is used during the discharge phase to generate electricity (EASE, 2016). The high-pressure compressed air, after being preheated in a heat exchanger using the stored thermal energy from the TES, expands through the turbine, causing it to rotate and drive the generator.
- A **heat exchanger** facilitates the transfer of heat between the hot compressed air exiting the compressor and the TES during charging, and between the TES and the compressed air withdrawn from the cavern before it enters the turbine during discharging (EASE, 2016). Efficient operation requires advanced turbomachinery capable of handling high pressures and temperatures during both compression and expansion (EASE, 2016). The availability of reliable high-temperature piping technology is also a critical challenge for the implementation of A-CAES systems.

Cost is critical for achieving successful deployment of CAES systems at a significant volume in Aotearoa New Zealand. High capital cost is the biggest factor in the overall lifetime cost of CAES systems. However, long operating lifespan and lack of waste materials help to offset this expense and reduce the system's lifecycle cost. A major component of the capital cost comes from creating or preparing the underground storage, with the cost being directly related to the internal volume and pressure they must be able to withstand (Rabi et al., 2023). This pressure-dependent cost is a key driver for all CAES systems, including the high-pressure heat reservoirs used in advanced A-CAES systems.

Beyond the sale of electricity, another potential revenue stream available to Aotearoa New Zealand includes arbitrage of the nation’s wholesale electricity market (Blois, 2025). This involves charging the storage facility during periods of low electricity prices, often when renewable generation is high, and discharging the stored energy back to the grid during periods of high prices, typically during peak demand. The increasing price volatility in electricity markets due to the growing penetration of variable renewables could enhance the profitability of arbitrage.

Another important consideration for deploying CAES in Aotearoa is the geological feasibility of underground air storage. While Aotearoa New Zealand lacks extensive salt formations, there is significant potential in repurposing the depleted gas fields of the Taranaki Basin, to be used as air storage reservoirs (Nicol et al., 2022). The suitability of hard rock formations and aquifers for creating or utilising underground storage caverns also warrants investigation.

An alternative to using large underground caverns for energy storage is Porous Medium Geological Energy Storage (PM-GES). PM-GES stores energy in a vast network of pores found within certain types of subsurface rock. This technology works by injecting compressed gases or fluids into these porous rock layers, which are naturally high in porosity and permeability (Rendel et al., 2023). Crucially, these layers are sealed by a low-permeability rock layer on top, known as a caprock. This geological arrangement creates a natural trap that keeps the stored fluids or gases securely contained for long periods. This type of rock formation is quite common and is similar to what is found in natural aquifers and hydrocarbon reservoirs. Because these formations have already proven their ability to trap fluids over long geological timescales, they are ideal for repurposing as energy storage sites. Depleted hydrocarbon reservoirs are particularly good candidates because their geological characteristics are well-understood and thoroughly documented. PM-GES allows for high-capacity, long-duration energy storage, able to support seasonal or even yearly storage needs. The technology required for this process is a mature and readily available approach that has been used in the oil, gas, and geothermal industries for decades (Rendel et al., 2023).

3. Research methods

A semi-systematic approach has been used for the research, which is considered appropriate for the identification of key knowledge gaps and trends in emerging technologies such as advanced forms of SOTA CAES (Jankowski et al., 2024). There is a need to understand the cost-effectiveness, energy efficiency, and environmental footprint of deploying and operating these systems within the Aotearoa New Zealand energy landscape, considering factors such as geological site availability and integration with existing infrastructure.

For each system (A-CAES, IA-CAES, MLIA-CAES), the following aspects are investigated:

- Technological performance data (overall system efficiency – RTE);
- Economic data (i.e. CAPEX, O&M costs, LCOS);
- Geological data (potential underground storage sites); and
- Overall performance compared to PHS within the context of Aotearoa New Zealand.

3.1. Research details

The first steps were to build a model in Excel to conduct sensitivity analysis, establish parameters and determine the critical variables. The primary set of equations follow the guidance established by the Pacific Northwest National Laboratory (PNNL, 2024):

$$LCOS = \frac{(FCR \times CAPEX) + O\&M}{AH} + ECC \tag{1}$$

Where:

- LCOS = Levelised Cost of Storage ($/kWh);
- FCR = Fixed Charge Rate (%);
- CAPEX = Present value of capital expenditures ($/kW);
- AH = Annual hours discharged; and
- ECC = Electricity charging cost ($/kWh-discharge): the charging cost for purchased energy, divided by system RTE (%).

The Fixed Charge Rate (FCR) provides the percentage of capital expenditures that must be recovered each year to meet annual revenue requirements. The FCR is calculated as:

$$LFCR = CRF \times \frac{1 - \tau \times PVD}{1 - \tau} \times CFF \tag{2}$$

Where:

- CRF = Capital recovery factor (%);
- τ = Corporate tax rate;
- PVD = Present Value of Depreciation (straight-line); and
- CFF = Construction finance factor (%).

The Construction Finance Factor (CFF) represents the financing costs that are incurred during the construction period of the project. The cost typically increases with construction time, as interest accumulates with no incoming revenue. CFF factors typically vary from 1.05 – 1.4, depending on the number of years of construction required. A table of CFF values can be found in the supplementary material, along with the sensitivity model.

The Capital Recovery Factor (CRF) represents the constant annual payment needed to amortise a loan over a given timeline. The CRF is calculated as:

$$CRF = \frac{d}{1-(1+d)^{-t}} \tag{3}$$

Where:

- d = WACCReal; and
- t = Economic life (years) needed to pay off asset costs.

The Weighted Average Cost of Capital ($WACC_{Nominal}$) represents the rate paid to financial assets using a weighted average of project equity and debt. The $WACC_{Real}$ is the $WACC_{Nominal}$ adjusted for inflation. The values are calculated as:

$$WACC_{Nominal} = \frac{E}{I} \times r_E + \frac{D}{I} \times r_D \times (1-\tau) \tag{4}$$

$$WACC_{Real} = \frac{1+ WACC_{Nominal}}{1+r_D} - 1 \tag{5}$$

Where:

- E = Equity ($);
- rE = Cost of Equity (%);
- D = Debt ($);
- rD = Cost of Debt (%);
- I = Total Investment ($); and
- τ = Corporate tax rate (%).

Additional data and insights that helped inform the model were acquired from industry. Leading companies active in the CAES sector were contacted for information, and interviews were conducted with Hydrostor, an emerging CAES company based in Canada, and Siemens Energy, a subsidiary of the German multinational Siemens conglomerate.

4. Results and discussion

Adiabatic (A-CAES), Isobaric-Adiabatic (IA-CAES), and Multi-level Isobaric-Adiabatic (MLIA-CAES) were selected for comparison against a pumped hydro (PHS) baseline. These three CAES options were specifically chosen from the range of technologies available, due to the fact that 1) they are able to take advantage of commercially available components, creating the potential for favourable economics and rapid expansion as they grow their presence in Aotearoa New Zealand, and 2) they possess medium- to high technology readiness levels (TRL), as these technologies have been tested and demonstration plants built on almost every continent.

Based on industry guidance, baseline project specifications for all technologies evaluated were established as shown in Table 1.

Table 1. Project specifications

Project Specifications	Value
Project Life	60 years
Rated Power Output	500 MW
Rated Power Duration	8 hours
Rated Power Storage	500* 8 = 4,000 MWh

While these values are reasonable for a CAES facility being built today, a rated power duration of 8 hours is on the low end for PHS, making for an unfair comparison. Thus, a modified scenario of 24 hours of rated power duration is considered for PHS to model a more realistic comparison.

Accurately modelling capital expenditures (CAPEX) is critical to the effectiveness of the sensitivity analysis, as CAPEX is one of the most significant variables affecting the competitiveness and thus viability of the technology (Jankowski et al., 2024). The low sample size of individual CAES projects means CAPEX costs vary considerably, making them difficult to compare directly. Instead, the industry metric of $/kW (in USD) is used for a more accurate comparison across technologies. Initial rates were selected from a range of industry values (Baniamerian et al., 2024) as shown in Table 2.

Table 2. CAPEX costs

CAPEX costs	$/kW (USD)
Adiabatic (A-CAES)	$ 2,500/kW
Isobaric-Adiabatic (IA-CAES)	$ 3,500/kW
Multi-level (MLIA-CAES)	$ 4,000/kW
Pumped Hydro (PHS)	$ 10,000/kW

Using the rates above, a 500 MW storage system would cost approximately 2-3 billion NZD for CAES technologies, and approximately 8 billion NZD for PHS. This aligns closely with the recent cost estimates for the renewed Lake Onslow proposal (Morning Report, 2026). These values are in line with current industry CAPEX costs today.

To estimate an appropriate benchmark value for the levelised cost of storage (LCOS) across all projects, wholesale electricity pricing trends were reviewed from the Electricity Authority's Electricity Market Information (EMI) website. Five years of the most recent data available was analysed, from January 2021 to December 2025. A snapshot of the data is shown in Figure 5.

Figure 5. Wholesale electricity pricing trends ($/MWh) over the past 5 years

Based on available data, an average LCOS of $150/MWh was used as the benchmark target for all technology projects being modelled.

Finally, the model assumes a total of four 15-year power purchase agreements (PPA) will be negotiated over the 60-year life of each project. The price of negotiated electricity is assumed to decrease with each successive PPA, as the growth of renewable energy increases over the coming decades throughout Aotearoa New Zealand. The model utilises Excel's Goal Seek functionality to arrive at optimal PPA values by setting the LCOS of each project to the previously-determined $150/MWh, and allowing the model to iterate each initial PPA value ("PPA 1"). The following PPA values for each technology in the first 15-year term are shown in Table 3.

Table 3. PPA term 1 values

PPA Values – Initial Term	$/MWh (NZD)
Adiabatic (A-CAES)	$ 89/MWh
Isobaric-Adiabatic (IA-CAES)	$ 124/ MWh
Multi-level (MLIA-CAES)	$ 142/ MWh
Pumped Hydro (PHS)	$ 119/ MWh

The full sensitivity model and all related assumptions can be found in the supplementary material.

The final step in the research was to obtain geological data of Aotearoa New Zealand, to locate viable sites for potential CAES systems. Detailed geological surveys and feasibility studies are essential in identifying specific sites with the necessary storage capacity and permeability to allow for efficient injection and withdrawal of air, and containment properties to ensure the long-term integrity of the storage reservoir (Nicol et al., 2022). The primary data source used was the New Zealand Petroleum and Minerals website, maintained by the Ministry of Business, Innovation & Employment (MBIE). The site's Geodata Catalogue has extensive historical records and interactive maps of thousands of datapoints from existing, capped, and exploratory oil and gas wells located across both the North and South Islands. An example is shown in Figure 6.

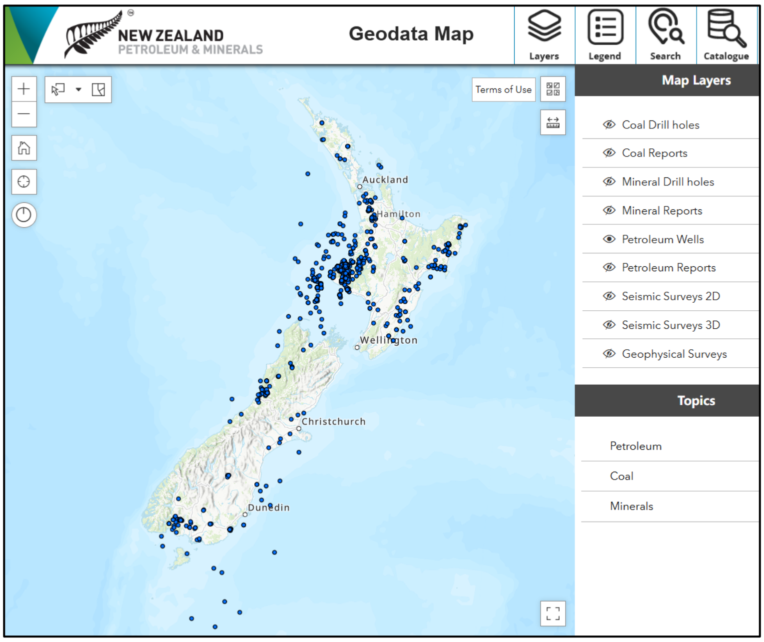

Figure 6. Map of petroleum wells
(Source: New Zealand Petroleum & Minerals website)

The map analysis shows the majority of potential sites for large-volume CAES fall in the Taranaki region, located on the western side of the North Island. This region is also identified as the most suitable area for PM-GES due to the high porosity of its geology, an abundance of existing subsurface data, and an established petroleum industry infrastructure (Rendel et al., 2023). Taranaki's onshore oil and gas reservoirs are considered the most suitable candidates for CAES, as they could be repurposed once depleted.

A prime example is the Ahuroa Gas Storage Facility; an underground depleted gas field reservoir, currently being used to store large volumes of natural gas, mainly for backing up peak demand at the Stratford Power Station (Dempsey et al., 2024). With a known capacity of 7-18 PJ of natural gas storage, a conservative estimate puts volumetric capacity at roughly 182 million m^3, providing tremendous potential for compressed air storage. With this underground volume, a conversion, provided in the supplementary material, shows a deployed A-CAES system could provide approximately 400 GWh of continuous power. Existing oil and gas reservoirs in the McKee and Waihapa/Ngaere fields also appear to be suitable candidates for large-capacity CAES operations (Rendel et al., 2023). The largest onshore field, Kapuni, also has potential but may actually be too large, requiring significant amounts of air to pressurise (Rendel et al., 2023). Other fields in the region offer more limited storage capacity.

4.1. Discussion

Interviews held with both Hydrostor and Siemens Energy provided a wealth of insights on the future integration of CAES technology into Aotearoa New Zealand's energy system. Obtaining detailed component cost and performance information remained a challenge, as both companies typically only share this with potential customers. Nonetheless, valuable high-level information was provided for the techno-economic model.

Hydrostor is currently one of the global leaders in A-CAES. They specialise in IA-CAES, using hydrostatic compensation via an above-ground water reservoir to maintain constant air pressure as the turbine generations power, thereby increasing overall RTE (currently in the 65-70% range) (Rabi et al., 2023). The company has several large-scale projects in active development, including a 500MW/4,000MWh project in Willow Rock, California (United States), and a 200MW/1,600MWh project in Silver City, New South Wales (Australia) (Gearino, 2024).

Discussions with Hydrostor confirmed that the single largest cost driver of a CAES system is the siting and excavation of the cavern – approximately 30% of the overall cost of a given 500MW facility. Unlike lithium-ion battery storage, costs do not scale linearly (where 10 hours of storage costs 10x more than 1 hour). CAES has a "decoupled" cost; once the cavern has been built the marginal cost for each additional MW decreases rapidly along a declining curve. At 8-10+ hours, CAES becomes one of the most cost-effective energy storage solutions available. This is one of the primary advantages of CAES; the LCOS decreases as the system scales in size. Project viability depends on whether the chosen site allows for a high-volume, high-pressure cavern at a low CAPEX, which enables the long-duration advantage of CAES to outweigh the short-duration, high system efficiency of battery storage.

Hydrostor noted that one of the strongest pathways for success for long-duration energy storage (LDES) projects such as A-CAES is an out-of-market commercial pathway, similar to the Long-Term Energy Service Agreements (LTESA) in New South Wales, Australia or the LDES procurement process in California and New York. Having long-term revenue certainty decreases the risk to developers, allowing them to invest in capital and advance development of the technology. Without revenue certainty, there is limited capital a prudent developer is willing to put at risk. More pathways for revenue certainty are the key driver for the LDES industry to take off, both in Aotearoa New Zealand and the world.

Siemens Energy manufactures industrial components for long-duration, grid-scale energy storage solutions. They provide high-performance compressors, expanders, turbines, generators, heat exchangers, and Balance-of-Plant (BoP) components (encompassing all auxiliary components, infrastructure, and systems necessary for operational functionality) for a wide range of power plant technologies, including CAES systems.

Discussions with Siemens Energy further elaborated on system costs – after cavern excavation, the largest expenses are typically BoP/commissioning costs, followed by the thermal storage system (TES). These are complex systems that require considerable time and subject expertise for proper installation and system execution. Furthermore, the company indicated that for CAES technology to accelerate in Aotearoa New Zealand, the following factors or conditions should be met:

- A grid with high amounts of fluctuating power generation (i.e. wind/solar PV)
- A need to stabilise the fluctuating power and provide a reliable power source
- High energy prices within the wholesale market; and
- Additional revenue streams other than arbitrage – storing energy when it is cheap/excessive (e.g., windy nights) and releasing it when it is expensive (e.g., evening peaks). Examples given include:
    a. A capacity market – receiving payment for simply being available to generate power, even when the plant isn't running. This provides grid reliability and redundancy, helping to strengthen overall grid resiliency.
    b. An incentive to provide inertia – the mechanical resistance to changes in grid frequency, provided by massive, rotating generators. Grids with higher percentages of solar and wind often lack this inertia, becoming unstable; the large turbines used in CAES to generate power help provide that inertia.
    c. A "bonus" for having little to no rare earth elements – CAES systems are mostly comprised of steel and concrete, unlike lithium-ion battery systems which rely heavily on minerals such as lithium, cobalt and nickel. Thus, CAES systems provide geopolitical independency of supply from foreign countries controlling their supply – a feature that could easily become invaluable in the coming years.

With mining and excavation operations emphasised as the single largest expense for CAES, and the size of the cavern linked near-linearly to the cost of excavation, industry has focused heavily on reducing the necessary cavern size by increasing efficiency of the system (Rendel et al., 2023). The higher the RTE, the more energy can be produced from the same volume of air. Put another way, a higher RTE implies that the same amount of energy can be produced using a smaller volume of air, reducing the size of underground cavern needed. Finding ways to reduce the amount of underground work required is critical to project selection and approval.

Additionally, CAES systems provide inertia, stability and resilience to the overall electrical grid (Nicol et al., 2022). Their deployment can lead to avoided costs in other areas of New Zealand – such as the need for increasingly expensive natural gas. CAES's long-duration storage capability can reduce the need for investments in new fossil-fuelled peaker plants.

By managing peak loads and providing a reliable source of energy during high demand periods, CAES could also contribute to the deferral of costly upgrades to the transmission and distribution grid (Nicol et al., 2022). Integrating CAES with New Zealand's growing offshore wind energy sector could create a synergistic effect, allowing for the storage of large amounts of clean energy generated during high-wind periods and its dispatch during periods of low wind or high demand (Higgs, 2024).

5. Conclusion and recommendations

In summary, while the discourse surrounding Aotearoa New Zealand's long-term energy security has historically centred on large-scale Pumped Hydro Storage – exemplified by massive projects like the Lake Onslow proposal – Compressed Air Energy Storage presents a technologically mature, sustainably advantageous, and economically competitive alternative. As the Aotearoa New Zealand grid transitions toward 100% renewable energy in the coming years, the strategic deployment of CAES offers a decentralised solution that mitigates the financial risks and environmental issues inherent in traditional PHS.

The economic argument for CAES over PHS hinges on the technology's modularity and capital efficiency. The prohibitive capital expenditure associated with PHS presents significant corporate and/or national risk, as well as extended construction times leading to increased interest costs. Large PHS projects can take 5 to 10 years to complete; A-CAES systems can be built in roughly half the amount of time – particularly when factoring in environmental compliance costs (Jankowski et al., 2024). Utilisation of existing geological formations, such as Taranaki's depleted gas fields, further optimises the cost-benefit ratio.

Aotearoa New Zealand's unique regulatory environment – the combined governance of the Resource Management Act and the principles of Kaitiakitanga, the Māori principle of holistic guardianship of the natural environment – remains a major obstacle for new PHS developments (Spittle et al., 2022). CAES, however, would experience significantly less friction to adoption. The technology requires a negligible surface footprint compared to the massive inundation zones required for PHS reservoirs. This preserves critical biodiversity and avoids the disruption of local communities and natural landscapes. Furthermore, only the adiabatic variants (no natural gas) of CAES technology are being evaluated for Aotearoa New Zealand, to ensure zero-emissions over the entire life of the project. These facilities would directly support the decarbonisation of the electricity sector without the carbon-intensive concrete requirements of mega-dam construction.

Technologically, CAES provides Aotearoa's electrical grid with critical ancillary services that chemical batteries cannot easily replicate and PHS cannot provide as flexibly. Utilising synchronous turbomachinery, CAES turbines provides physical inertia to the grid, which is essential for maintaining frequency stability as fossil-fuel generators are phased out (Olabi et al., 2021). CAES facilities have better geographical flexibility – they can be sited closer to load centres, or integrated directly near wind farms. This proximity reduces transmission losses and eases the burden on the Inter-Island High Voltage Direct Current (HVDC) link, enhancing overall system reliability.

A thorough literature review and in-depth techno-economic analysis have shown that CAES should be considered a central pillar of Aotearoa New Zealand's diversified energy storage strategy. CAES is able to store significant, utility-scale quantities of clean energy for long periods of time and continuously discharge over multi-hour timeframes. The components endure for decades with low operating and maintenance requirements. The technology aligns with the country's need for long-duration, high-capacity, emissions-free storage and is able to leverage existing and well-documented geological formations for reduced-cost, utility-scale storage of energy. Furthermore, it complements PHS, offering a comparable LCOS with a significantly lower environmental risk profile. CAES truly represents the most viable pathway for Aotearoa New Zealand to achieve its dry-year reserve requirements while maintaining fiscal and ecological responsibility.

5.1. Recommendations

Based on the evidence presented, this research recommends that the optimisation of Aotearoa New Zealand's renewable energy transition requires a strategic shift from a singular "mega-projects" focus toward a diversified long-duration energy storage portfolio. Specifically, it is recommended that A-CAES be deployed in tandem with PHS to create a multi-tiered resilience framework. A-CAES should be prioritised as a medium-duration (10–100 hour) stabiliser. While PHS (such as a revived or scaled-down Lake Onslow) is unrivalled in addressing the dry-year risk – providing the massive energy reserves needed for multi-month deficits – A-CAES provides the necessary flexibility for multi-day energy troughs and winter peak demands. This hybrid approach ensures that the high-CAPEX hydro assets are reserved for extreme seasonal events, while A-CAES manages the higher-frequency, mid-duration imbalances.

To avoid the sunk-cost and lead-time risks associated with decade-long hydro construction, Aotearoa New Zealand should adopt a modular deployment schedule for A-CAES. By commissioning 300-500 MW A-CAES facilities near North Island load centres (e.g., the Waikato or Taranaki regions), the grid can gain immediate storage capacity and physical inertia within a 3- to 5-year window. This provides a critical "bridge" while long-term PHS infrastructure is still in the consenting and construction phases. Recommended next steps include detailed, site-specific feasibility studies of depleted gas fields with high potential for compressed air storage in the Taranaki region. The cost and performance of any CAES system are highly dependent on the characteristics of the chosen reservoir, including its volume, pressure limits, and rock properties.

As Aotearoa New Zealand retires its remaining thermal peaker plants, the grid will face a significant deficit in mechanical inertia. A-CAES facilities utilise synchronous turbomachinery that, unlike chemical batteries, provides physical rotating mass. Integrating A-CAES alongside PHS allows for a geographically distributed network of virtual synchronous generators, enhancing frequency stability across both islands and reducing the reliance on the Inter-Island HVDC link for ancillary services.

The evidence supports a dual-track storage strategy: utilising the massive scale of PHS for national energy security during hydrologic dry years, while leveraging the modularity, lower environmental footprint, and rapid deployment of A-CAES to ensure localised grid reliability and economic efficiency. This integrated portfolio approach minimises Aotearoa New Zealand's sovereign financial risk and offers the most robust path toward a 100% renewable, net-zero future in the coming years.

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