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Energy storage solutions to support the implementation of renewable electricity in Aotearoa New Zealand

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Abstract
Aotearoa New Zealand targets a 100% renewable electricity grid built off a strong renewable energy supply. Renewable energy, as a non-dispatchable form of energy generation, requires supporting energy storage to work effectively as the sole energy supplier for the national grid. A primary long-term energy storage system is required for consistent high quantity supply with a complementary short-term system that can respond quicker for lower scale needs. The objective of this paper is to identify the most suitable energy storage configuration and provide the associated cost. A literature review of energy storage technologies identified flywheels and lithium-ion batteries as short-term solutions and pumped hydro, compressed air energy storage and thermal energy storage as long-term solutions, with hydrogen able to fill both roles. Through the modelling of renewable generation and grid demand, energy storage and power output requirements for each technology were identified with key properties of each technology quantified. Data from real-world energy storage projects were used to calculate expected initial cost of each technology. This data was combined to provide the levelized cost of storage for each investigated technology which, combined with real-world information, was used to provide the recommendation. While further avenues for research to refine the conclusion were identified, the ideal configuration found was lithium-ion batteries partnered with pumped hydro.

Keywords: Energy storage; Renewable energy; Costs.

1. Introduction
Aotearoa New Zealand ratified the United Nations' Paris Climate Agreement in 2016, which took effect in 2020 (Ministry for the Environment, 2020). This document outlined the goals of an international collaborative effort to combat climate change. The single quantified target of the agreement is to prevent global average temperatures increasing more than 1.5°C above pre-industrial levels to significantly reduce the risk and impacts of climate change(UNFCCC, 2015: 3). The key tool to ensure the goals of the Agreement are reached is the limit and reduction of global greenhouse gas (GHG) emissions. In response to the obligations of this agreement, the government passed the Climate Change Response (Zero Carbon) Amendment Act 2019. This legislation states that net emissions of GHGs, other than biogenic methane, are zero by the calendar year beginning on 1 January 2050 (New Zealand Government, 2019: Sections 3 and 5Q). As of 2020, New Zealand's energy sector was responsible for 31 thousand kilotonnes of carbon dioxide equivalent (CO2e) emissions (Ministry of Business, Innovation & Employment, 2022a). This accounts for 39% of the country's 79 thousand kilotonne CO_2e gross GHG emissions (Stats NZ, 2022). Due to the significant role the energy sector plays in emissions, improving the renewability of the energy sector will play a large role in New Zealand meeting its emission targets.

In 2022, the total net electricity generation for New Zealand was 43 TWh. This included 60% from hydro, 10% from fossil fuels (coal, gas and oil) and 7% from wind and solar PV (photovoltaic) (Ministry of Business, Innovation & Employment, 2025). As New Zealand aspires to reach 100% renewable electricity generation, the substantial fossil fuel use needs to be replaced with renewable alternatives. There is significant potential for the extremely fast-growing wind and solar PV industries to fill the required electricity supply (Gibson, 2024). The importance of these resources will only increase as New Zealand becomes more reliant on them for the renewable electricity transition. Reliance on these resources raises concerns due to their inherently variable nature. These are non-dispatchable resources that do not generally match the national usage profiles. While hydroelectricity is considered somewhat dispatchable, there is potential for environmental factors to limit the water resource available for use in dry years. In the right circumstances hydro, wind and solar PV could all fail to meet generation needs simultaneously, crippling New Zealand's electricity supply. This threat to national energy security highlights the need for careful planning in the transition away from dispatchable fossil fuels.

The variability concerns of the electricity supply can be significantly reduced with adequate energy storage options. Energy storage converts extremely variable renewable resources such as wind and solar PV into more dispatchable energy resources akin to hydroelectricity. Energy storage can allow the electricity supplied by these resources to be dispatched when the demand is present and can lessen the strain on the hydro water supply. In addition to this, long-term storage options can help combat seasonal variations in electricity supply from hydro, solar PV and wind, perhaps even yearly variations including dry years with the appropriate type of storage. The New Zealand Battery Project was launched in 2020 to explore possible renewable energy storage solutions to address concerns with periods of low hydro-electricity supply. A pumped hydroelectricity storage option at Lake Onslow was the primary solution investigated (Ministry of Business, Innovation & Employment, 2024). Alternative options with significant potential include bioenergy, geothermal energy and hydrogen, while air storage and flow batteries were not recommended (WSP, 2022). The Battery Project's results and findings provide a strong base for research into the electricity storage options for Aotearoa New Zealand.

1.1. Objective of the paper

The objective of this paper is to define the viability and costs of various energy storage methods to deliver the electricity required to support a 100% renewable grid for Aotearoa New Zealand. This includes first modelling future renewable generation and national grid demands, to define the required storage capacity and power output for both short-term and long-term needs where the energy storage is the ability to hold energy while the power output is the ability to convert this energy into usable electricity for the grid. Here, long-term needs are defined as the demand in excess of generation over weeks which must be met to support a renewable grid. Short-term needs complement the long-term storage through acting as the quick dispatch energy storage required during initial demand fluctuations while the long-term systems begin operating. This research then investigates some key identified energy storage options to find expected costs and qualitatively evaluate these options to provide a meaningful recommendation to the ideal solutions.

2. Literature review

The objective of this literature review is to investigate the energy storage options available to support Aotearoa New Zealand's gird in its transition to 100% renewable electricity. Firstly, a broad search into full New Zealand national electricity grid storage solutions provides the gaps in knowledge and directs where research is necessary. Through the analysis, each system is evaluated on its potential suitability and how this has varied over time with the maturity of the technology a key. This section of the literature review is critical in determining which electricity storage systems merit consideration for this research. The literature analysis is key in discerning what type of application scale each system can be effectively utilised for.

2.1. Storage options

To evaluate the feasibility of energy storage options for the national grid, the key options must first be identified. As overviews of energy storage options for Aotearoa New Zealand are uncommon, more generalised or specialised literature had to be used. Energy storage systems can be divided into the following classifications as stated by Shabani et al (2020): mechanical energy storage, such as pumped hydro storage (PHS), compressed air energy storage (CAES) and flywheels; electrochemical energy storage, such as batteries and hydrogen fuel cells; electromagnetic energy storage, such as super-capacitors and superconducting magnetic energy storage (SMES); and thermal energy storage (TES). Flywheels, super-capacitors and SMES are suitable for short-term applications while batteries, micro-PHS, hydrogen fuel cells and micro-CAES are medium/long-term storage (Shabani et al., 2020). Supercapacitors are only applicable to very small PV systems, so for utility-scale needs, this technology does not appear appropriate (Wang et al., 2022). Research targeted towards electricity storage in New Zealand identifies standard electrochemical batteries as not viable for long-term storage needs and face practical and economic constraints. CAES, TES, flywheels and gravitational storage are identified as potential solutions (Rendel et al., 2025). MBIE indicates that pumped hydro, thermal storage, hydrogen and batteries all possess significant potential as storage options (Read, 2022).

2.1.1. Pumped Hydro Storage

Pumped hydro energy storage utilises the downward flow of water through turbines to produce electricity while also using excess electricity to pump water from the lower reservoir up to the higher reservoir where it can be stored. PHS is considered an effective energy storage solution to operate with renewable energy production due to its large energy density and ability to work with large variations in generation or supply. There is especially high potential for PHS to work very strongly with wind and solar electricity generation. The effectiveness of this storage depends on the installation capacity, location, and environmental issues (Javed et al., 2020). PHS is essential in electricity grids with a high share of renewable energy and can replace combined heat power plants to further support a national energy transition (Naval et al., 2023). PHS is considered a fully mature technology, ready for implementation (Cai et al., 2024). Grey literature has investigated the suitability of pumped hydro energy storage as an option for Aotearoa New Zealand and found it to be one of the highest potential options, if not the most promising (Read, 2022). The technology is ready and has been evaluated for an Aotearoa New Zealand context. As the Lake Onslow pumped hydro project was given serious consideration by the government due to recommendations from the New Zealand Battery Project, it is clear that it is a suitable technology for Aotearoa New Zealand (Ministry of Business, Innovation & Employment, 2024).

2.1.2. Compressed Air Energy Storage

Compressed air energy storage uses excess electricity to compress air into a confined volume, typically a tank or underground reservoir. To discharge the stored energy, the compressed air is allowed to run through turbines, like PHS, except the compressed state of the fluid is responsible for the generated force, rather than gravity. Hydrocarbon reservoirs, once depleted, can be repurposed as large compressed air storage units to the grid scale while reducing the surface footprint associated. Porous media geological energy storage (PM-GES) offers the potential to develop both long-term and large-capacity storage solutions for Aotearoa New Zealand, and, due to oil, gas and geothermal industry developments, the technology is mature and readily available (Rendel et al., 2025). Compressed Air Energy storage is very clearly a mature technology that is ready to implement. The fact that there are depleted hydrocarbon reservoirs in New Zealand supports the validity of CAES as a potential electricity storage solution for the national grid, as the conditions required for this form of storage are evidently present.

2.1.3. Gravitational Energy Storage

Gravitational energy storage stores energy by using excess grid electricity to lift a large weight with a pulley system, storing the energy as gravitational potential energy. When electricity is required from the system, the mass is lowered with the energy stored converted through a generator back into electricity through spinning the pulley system. Gravitational storage utilising is still in the development phase, although it has very good geographic adaptability, high energy density and is more flexible than alternatives such as PHS (Cai et al., 2024). Some literature considers gravitational storage to be superior to other large-scale energy storage options due to the high storage capacity, scalability, sustainability, durability, flexibility and several other factors (Kavoosi & Hagh, 2025). As there is very limited literature on the viability and maturity of gravitational storage, with sources providing conflicting arguments on its viability, the technology appears to not have yet achieved the maturity required for widespread implementation in a grid system. This leads to a conclusion that, while there is substantial future potential, this technology is not yet advanced enough to be considered as one of the key energy storage forms to support an entirely renewable electricity grid in Aotearoa New Zealand.

2.1.4. Thermal Energy Storage

Thermal energy storage systems use excess energy to heat a contained substance, commonly molten salt, within an insulated container. Electricity can then be made by using the heated substance in a heat exchanger in a standard power cycle. This form of storage can provide low-cost energy storage for renewable energy sources with various substances exhibiting the required characteristics to act as the phase change material, such as guanidinium organic salts (Matuszek et al., 2021). TES technology is established and economically feasible, where short-term systems have been in use in North America since the 1980s. High initial costs have acted as a deterrent, however, these have reduced to allow this technology to emerge with significant potential to revolutionise the renewable energy sector (Elkhatat & Al-Muhtaseb, 2023). The literature suggests that this technology is not perfect but has reached the maturity for required implementation while the prevalence of relevant literature supports this. This literature has begun to discuss more technical details of the storage, such as the specific material or temperature used, suggesting the technology to be stable and in a state of refinement. Provided the materials required for use in a thermal energy storage system are available at a reasonable cost, this technology could feasibly be implemented in Aotearoa New Zealand.

2.1.5. Flywheels

Flywheels operate to store energy by using excess electricity to spin a cylinder, which is magnetically levitated to minimise friction and the resulting losses while storing energy. To produce electricity, the rotational energy of the flywheel is used to spin a generator. Flywheel energy storage systems offer high power density and instantaneous response times, making them especially effective for applications such as grid stabilisation, frequency regulation and power quality support. They also have an exceptional life cycle with round-trip efficiencies between 85% and 95%. The high-power short-duration applications of flywheels make them a strong alternative to the lithium-ion batteries, which dominate the utility-scale short-duration energy storage market (Matos et al., 2025). Flywheel technology is suitable for the direct generation of high voltages, and the systems are scalable with larger machines able to serve grid applications such as stabilisation (Bolund et al., 2007). There is a large volume of literature available on this technology over a prolonged period, indicating a mature, well understood and well-developed technology. This suggests that flywheels could fill the short-term needs for an electricity grid entirely reliant on renewable resources.

2.1.6. Batteries

Batteries store and produce energy through electrochemical reactions in battery cells. This is the most common form of energy storage, with lithium-ion batteries holding a large stake in the energy storage industry as an established technology. lithium-ion batteries have better performance than their lead-acid counterparts in combination with renewable energy systems (Ghorbanzadeh et al., 2019). Batteries are considered a typical representative of short-term electricity storage while the effective combination of batteries as a short-term energy storage option with a long-term energy storage system, such as hydrogen, would lead to a considerable reduction in energy costs. This very strongly supports the transition from conventional power plants to renewable alternatives (Adams, 2025). Batteries provide a feasible option as stand-alone energy storage systems for Aotearoa New Zealand. (Read, 2022). There is widespread literature on various battery configurations while lithium-ion batteries are considered high-performance and available for short-duration applications on a grid scale, especially with renewable energy sources. The volume of literature suggests this technology to be a very mature and even the default option for short-duration applications, a role it could fil in Aotearoa New Zealand.

2.1.7. Hydrogen

Energy can be stored in the form of hydrogen through utilising excess electricity to electrolyse water into hydrogen and oxygen. The hydrogen produced is stored in tanks or underground reservoirs and can be recombination with oxygen to release energy, which can be used directly for heat or through a fuel cell. Hydrogen can be considered a typical representative of long-term energy storage in cooperation with renewable energy. This technology, partnered with a short-term stabilising can support in the transition from conventional energy production to renewables while reducing energy costs (Adams, 2025). While hydrogen does present hurdles as an option for Aotearoa New Zealand, such as market factors, there is the potential for stand-alone hydrogen systems to be implemented (Read, 2022). The literature suggests that hydrogen, whether stored in tanks or depleted hydrocarbon reservoirs, has potential applications for Aotearoa New Zealand. The abundance of relevant literature also indicates that the technology is advanced enough to warrant targeted applications. In addition, literature suggests that hydrogen energy storage may be considered both a typical long-term form of energy storage and a grid stabilisation method, suggesting a unique versatility, uncommon in other storage technologies.

3. Research methods

The research comprised two principal components. The first involved the rigorous definition of the problem, with the objective of utilising national grid datasets to derive robust estimates of both long-term and short-term energy storage requirements for a fully renewable electricity system in Aotearoa New Zealand. This analysis was conducted under a scenario in which the minimum proportion of renewable generation is assumed to be immediately deployable, while maintaining the production distribution patterns currently observed within the electricity system.

The second component of the research employed these derived storage requirements to examine alternative energy system configurations and the associated costs. The key technologies considered were identified through the literature review, while a combination of case studies and general cost datasets was used to establish realistic estimates of initial capital expenditure and levelised costs of storage (LCOS). This approach integrates both quantitative and qualitative analyses in the evaluation of potential solutions.

3.1. Research design

Part one of the study used information taken from previous research undertaken into future grid demand and renewable electricity generation for Aotearoa New Zealand to provide reasonable expectations on the national electricity demand and supply for a national energy storage system for 2030. The data was analysed in such a way as to suggest a minimum short- and long-term electricity storage and power distribution capacity to support an entirely renewable electricity grid for three future energy use scenarios in addition to the dry year problem.

Part two of the study used the outputs of part one as the targets that must be reached. As the focus of this part is much more on the real-world aspects of this solution, figures and information on pricing and viability were taken from actual case studies and supporting resources. This aims to associate theoretical results with real-world applications.

3.2. Part one: The problem

To properly define the required long- and short-term storage capacity and power output to support an entirely renewable grid (the problem), a bathtub-style model constructed in spreadsheets was used as shown in Figure 1. This model treated the electricity required from the storage system as the output while defining the input as renewable energy generated. The key dataset used in support of the first section of this research was provided by the lead author of a research paper into the impact of 100% renewable electricity on hydropower generation in Aotearoa New Zealand (Stelling et al., 2026).

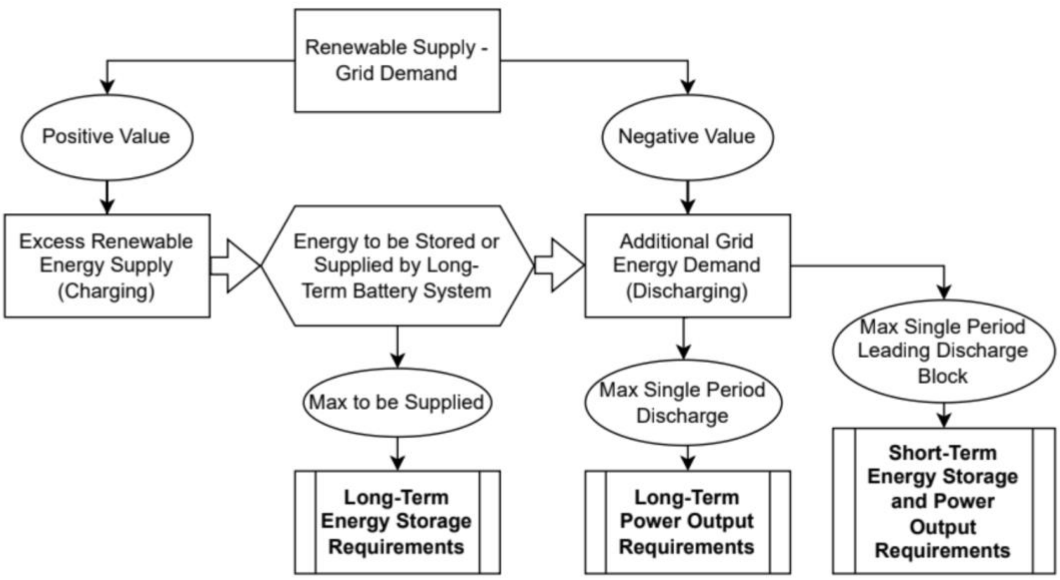

Figure 1. Method to find key requirements

The authors provide expected 2030 energy output for hourly periods in a completely renewable grid, based on the 2024 generation profiles and the generation pipeline: for biomass, geothermal, onshore wind and utility-scale solar. It is key to note that offshore wind is excluded from consideration due to the uncertainty of the completion of any projects by 2030.

The national generation pipeline indicates no committed new hydro projects, only minor improvements to existing systems, and so the hydro capacity and generation profile for the national grid was taken to be constant from 2024 to 2030 (Electricity Authority, 2024).

It was assumed that the yearly energy generation perfectly matches the yearly energy demand to allow for the storage requirements that would allow for the minimum conditions for a 100% renewable in alignment with three of the MBIE Electricity Demand and Generation Scenarios (EDGS). This included a 13% increase in national energy demand from 2024 to 2030 in the constraint scenario, a 23% increase in the growth scenario, and a 34% increase in the innovation scenario, as indicated in Stelling et al. (2026).

Assuming all excess generated energy is stored then discharged when electricity is needed, subtracting the national energy demand from the renewable supply for each period provides a positive number for periods of charging the storage system and a negative number for periods of discharging. It is key to note this part of the study operates under 100% efficiency as factoring in efficiency at this stage creates an unmanageable model. However, efficiency is factored in at a later stage.

The short-term system is intended to act over the first hour of any continuous energy deficit period in the grid, allowing the long-term storage system time to begin operation. By isolating the initial energy quantity of each discharge block, the expected energy supply to the grid over the year is found. The maximum of this dataset represents the maximum expected power output over a year, and as this is for a single hour, this also represents the required energy storage of the short-term system.

The long-term storage requirement was found by calculating a running total of the charging and discharging of the storage system starting at zero. The largest negative value represents the maximum amount of energy that will be required to be continuously supplied to ensure demand is met, while the largest positive represents the greatest energy that must be stored to ensure energy is not lost. As both numbers must be met, the larger of the two provides the minimum energy storage capacity for each scenario for the national grid. The single greatest energy deficit for a single period represents the minimum power output capacity for the long-term energy storage to ensure the system can always convert the stored energy into electricity as required.

By setting these values to be the baseline for energy storage requirements, this provided the minimum usable storage and power capacity to support an entirely renewable grid. When considering each individual storage technology, dividing the general expected storage requirement by the respective efficiencies provided the real required storage size.

3.3. Part two: The solution

The solution aspect of the research began with the gathering of supporting information for each energy storage technology identified in the literature review required to effectively calculate the LCOS. The project lifespans, round-trip efficiencies and the OPEX were found from Mongird et al. (2019) and Viswanathan et al. (2022). The OPEX was given at a rate per unit of power installed, so the dollar values were calculated for each technology and scenario and were converted from the currencies applied in the sources to 2025 New Zealand Dollars (NZD).

For each of these short- and long-term technologies, their respective real required energy storage capacities were calculated as outlined in the previous section. To ground the research in reality, the initial capital expense (CAPEX) was based on the CAPEX of various previous relevant energy storage projects. Firstly, the ratio of the CAPEX per unit of energy storage to the CAPEX per unit of power output was defined by data from Mongird et al. (2019) and Viswanathan et al. (2022). The cost per unit of energy storage, x, was divided by the cost per unit of power output, y, to provide the cost ratio, r, where:

$$r = \frac{x}{y} \tag{1}$$

This formula applied to any energy project as the ratio is assumed to hold for any scale. For each project, the cost per unit of energy storage, x, and the cost per unit of power output, y, were required. Unless the data was unavailable, each investigated real-world project had a known CAPEX, C, energy storage capacity, E, and power output capacity, P. For this research, these are the costs assumed to make up the CAPEX, where:

$$C = (E * x) + (P * y) \tag{2}$$

Solving these simultaneous equations by substituting equation 1 into equation 2 and rearranging for y, it yields:

$$y = \frac{C}{((E*r)+P)} \tag{3}$$

The application of equation 3 followed by equation 1 to the investigated projects provided the cost per unit of energy storage and the cost per unit or power output for that project, which, when multiplied by the previously obtained target values, yielded an expected cost based on real-world data.

In addition to the calculated results, the investigation of active energy storage projects provided the information for a nuanced qualitative evaluation of the energy storage options for Aotearoa New Zealand. For the LCOS the discount rate recommended by MBIE for ongoing OPEX as supplied by The Treasury New Zealand (2025) was used to find the net present value (NPV). This with the CAPEX and the lifetime energy supplied by the system (LE) provided the LCOS where:

$$LCOS = \frac{CAPEX+NPV(OPEX)}{LE} \tag{4}$$

3.4. Limitations

Assumptions and simplifications had to be made to develop a model. The method for factoring in inefficiency of the storage systems, as previously discussed, was required to make a model that could realistically be completed and utilised to produce usable results. Efficiencies are also taken as round-trip values and include depth of discharge. Other simplifications were necessary for the system, such as the inability to predict behavioural changes in the energy industry such as the buildup or increased use of hydro reservoirs due to the introduction of other storage and the effect of market factors on the use of a storage system. A clear assumption made is the scenario investigated, where adequate renewable energy is in place. This is required to find the minimum storage for a renewable Aotearoa New Zealand but is not a true reflection of the current electricity grid. It is also key to note that anomalies can occur in electricity demand and especially in renewable energy supply, so working with the minimums calculated harms the national energy security and can only act as a baseline with room for error. This study is designed to be a generalised look into various options to a limited level, which only allows it to be taken as a general overview, rather than an in-depth analysis. This study cannot be taken as the answer, but a tool to suggest options and provide indications of the landscape of the energy storage industry, which suggest avenues for further investigation and more targeted analysis.

4. Results

4.1. Storage needs

The base dataset for energy demand and renewable supply was provided by Stelling et al. (2026) as shown in Figure 2. To accurately scale renewable energy generation to match the demands in each scenario, the fraction of the total increase in energy generation from 2024 to 2030 provided by each technology was found where hydro was assumed to have a 0% increase. The increase in expected yearly energy generation from 2024 to 2030 for geothermal energy was 1.7TWh or 47% of the total generation increase. The increase for onshore wind energy was 0.9TWh or 25% and the increase for solar energy was 1.0TWh or 28% of the total increase. Multiplying these fractions by the required additional generation for the yearly generation to match the yearly demand in each scenario provided the required increase in each energy generation method across each scenario.

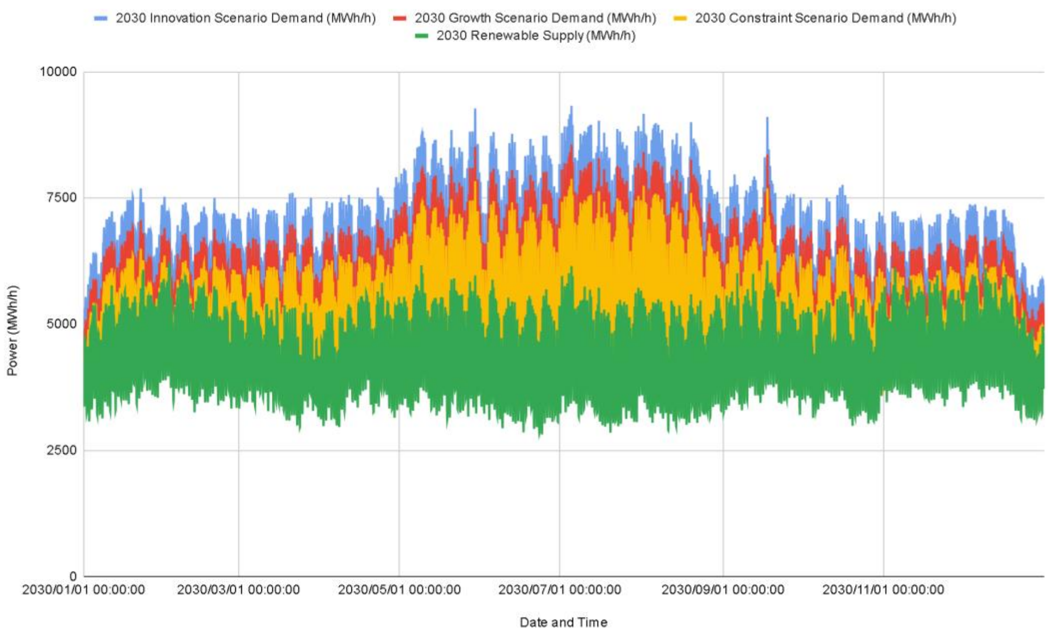

Figure 2. 2030 renewable energy supply and grid demand

A required increase factor for each generation period for each technology was found by dividing this required energy generation for the scenario by the expected value for 2030. Each generation period could then be multiplied by this increase factor for the respective technology to scale the generation while matching the previously established pattern. The energy storage requirements were then divided by the respective efficiencies to find a specific required capacity.

4.1.1. 2030 constraint scenario

The data from the 2030 constraint scenario indicated the additional energy generation required for the yearly demand to perfectly match the yearly renewable supply as 6.9TWh. The associated increase factors for this scenario were found to be to be 1.32 for geothermal, 1.37 for onshore wind 2.78 for solar which, when applied, yield the results in Figure 3.

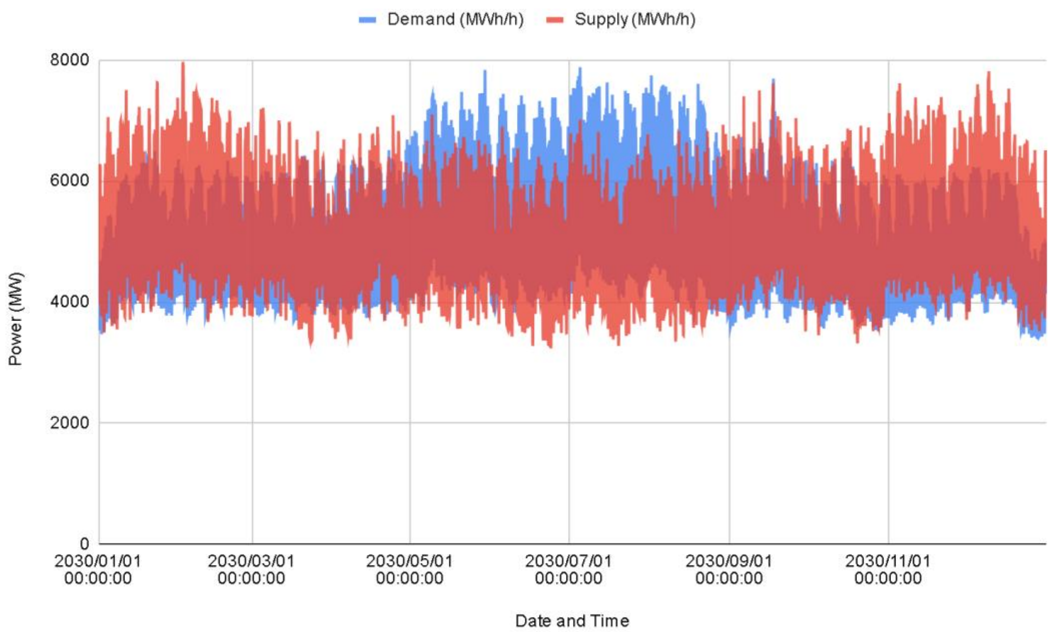

Figure 3. Constraint scenario demand and scaled renewable generation

The periods excess energy generation available for storage and the periods of energy deficit as required for energy storage power output can be seen in Figure 4. The running total of these periods of excess energy or energy deficits for the purpose of finding energy storage capacity requirements can be seen in Figure 5.

The required long-term power output capacity was found to be 1.82GW for this scenario. The long-term energy storage requirement was found to be 1.22TWh. The required power capacity of the short-term grid energy storage system was found to be 0.86GW. As this system is designed to function at this output for one hour, the required energy capacity is similarly 0.86GWh. The yearly total discharge of the short-term system for this scenario was taken to be the sum of the first discharges of each block over the year at 52.6GWh which the long-term yearly discharge was taken to be the total yearly energy discharge minus this short-term energy discharge at 2.42TWh.

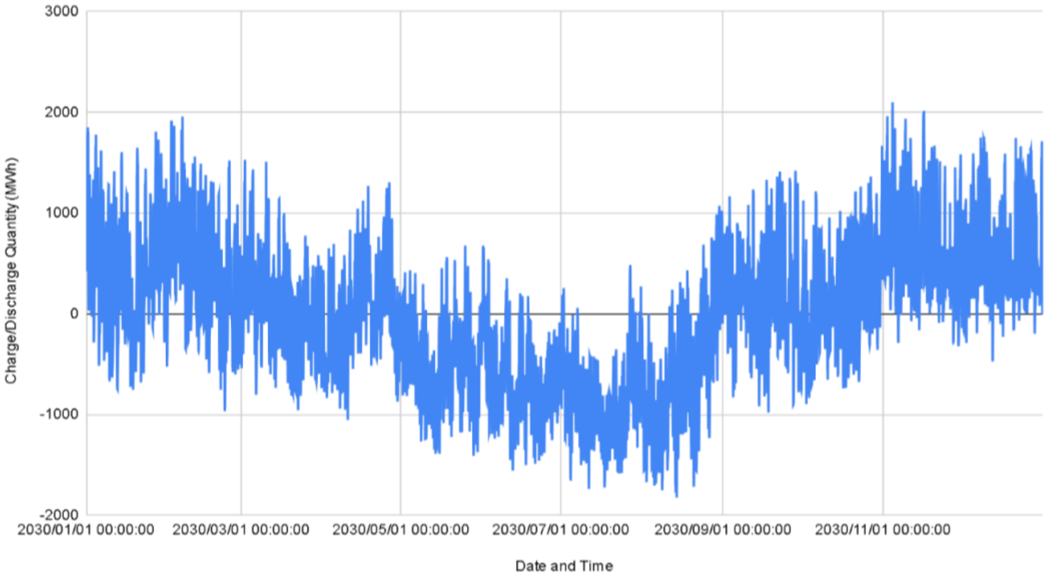

Figure 4. Constraint scenario charging/discharging

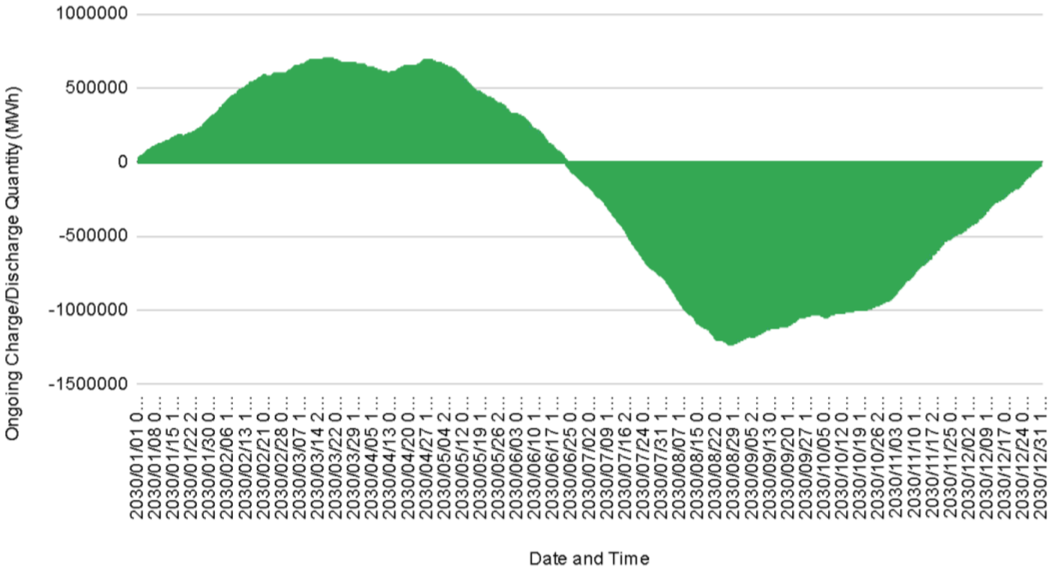

Figure 5. Constraint scenario ongoing charge/discharge requirements

4.1.2. 2030 growth scenario

The additional yearly energy generation for 2030 required to meet the yearly demand of the 2030 growth scenario was found to be 10.9 TWh. The increase factors were found to be 1.51 for geothermal energy, 1.58 for onshore wind energy and 3.82 for solar energy. Applying these values to the expected 2030 renewable generation outputs yielded renewable generation and national grid demands seen in Figure 6.

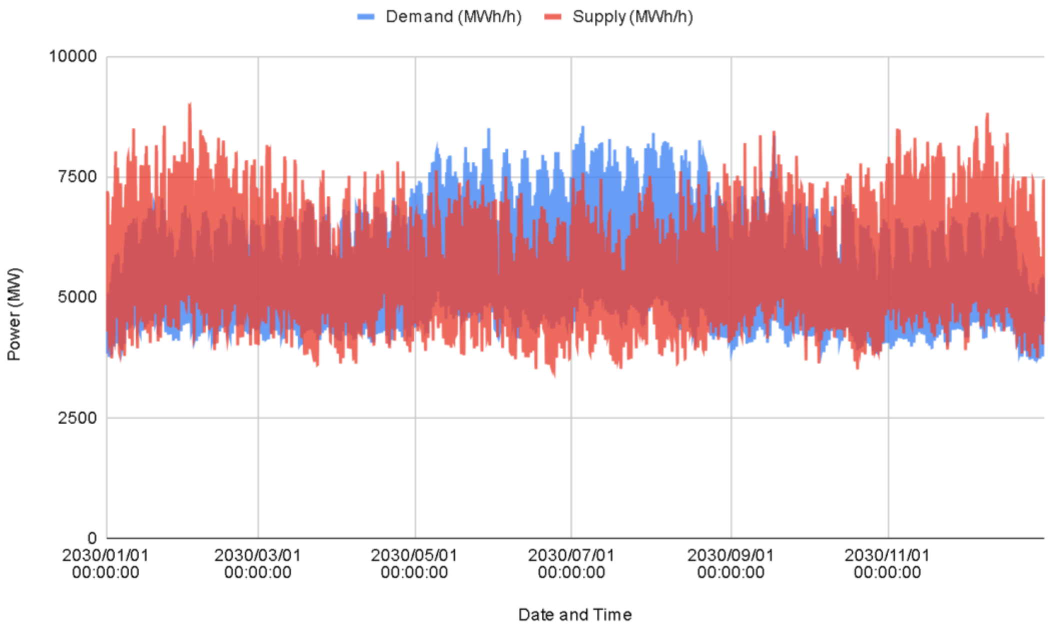

Figure 6. Growth scenario demand and scaled renewable generation

The periods excess energy generation available for storage and the periods of energy deficit as required for energy storage power output can be seen in Figure 7. The running total of these periods of excess energy or energy deficits for the purpose of finding energy storage capacity requirements can be seen in Figure 8.

The power output capacity requirement of a long-term national grid energy storage solution for this 2030 scenario is 2.14GW. The minimum energy storage capacity for the long-term system required to ensure no periods without adequate grid electricity is 1.39TWh. The required short-term power output capacity for this scenario is 1.02GW and again as this system is designed to operate at this capacity for one hour, the energy storage requirement for this system is 1.02GWh. Using the same method for the total yearly discharges, the short-term total was found to be 79.7GWh while the long-term total was found to be 2.96TWh

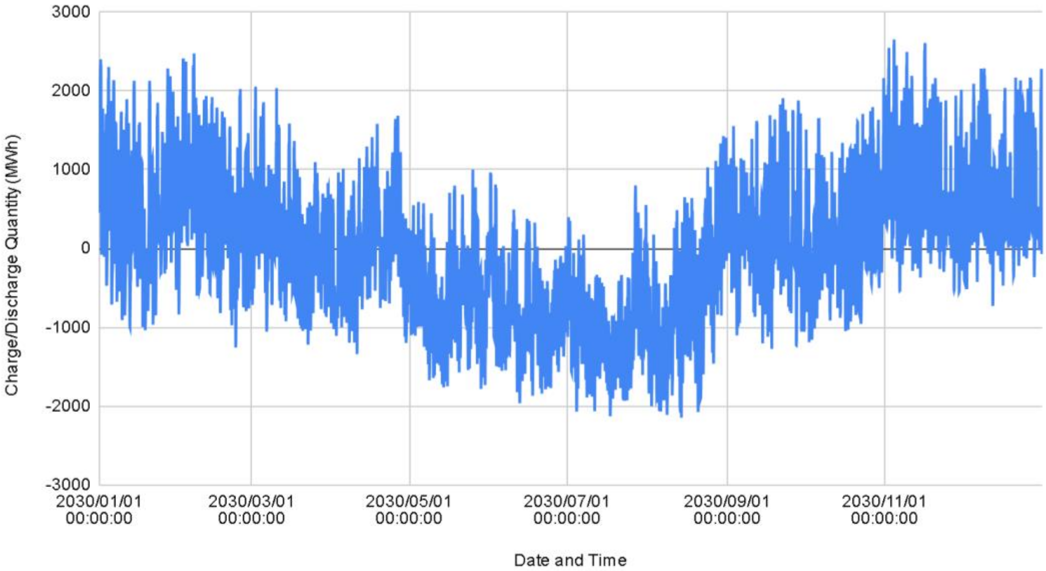

Figure 7. Growth scenario charging/discharging

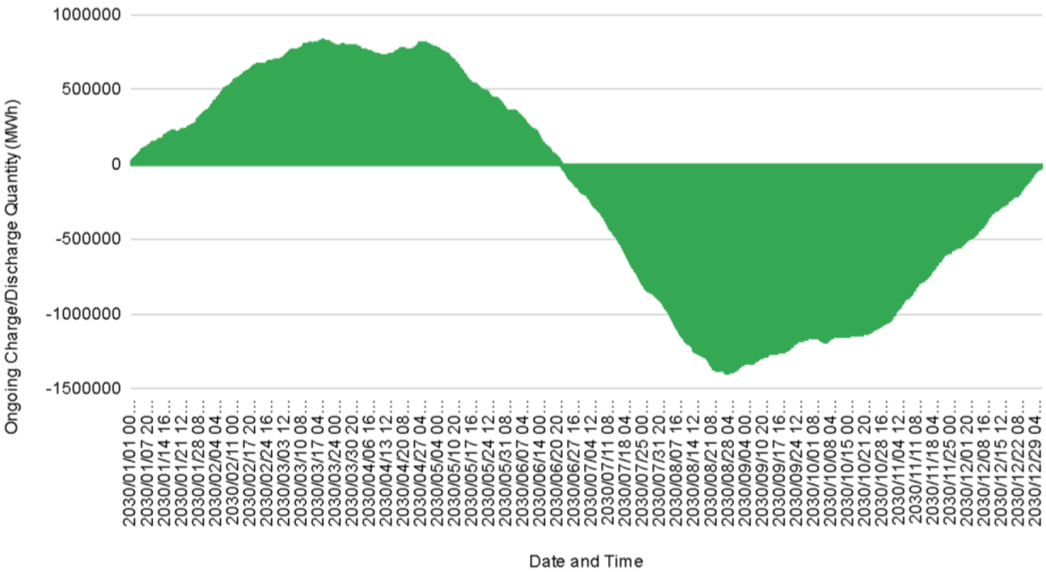

Figure 8. Growth scenario ongoing charge/discharge requirements

4.1.3. 2030 innovation scenario

The additional renewable generation for 2030 required to meet the innovation scenario demand was found to be 15.4TWh. The increase factor for geothermal energy is 1.72, onshore wind energy is 1.82 and solar is 4.98. Appling these factors to the data yields the expected renewable generation and grid demand profiles as seen in Figure 9. The periods excess energy generation available for storage and the periods of energy deficit as required for energy storage power output can be seen in Figure 10.

The running total of these periods of excess energy or energy deficits for the purpose of finding energy storage capacity requirements can be seen in Figure 11.

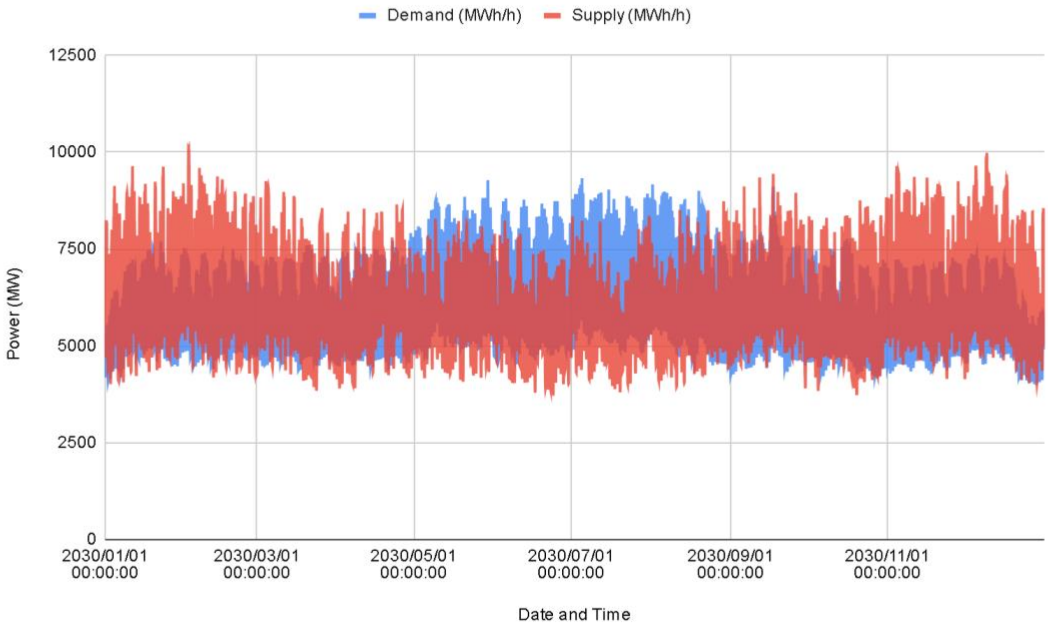

Figure 9. Innovation scenario demand and scaled renewable generation

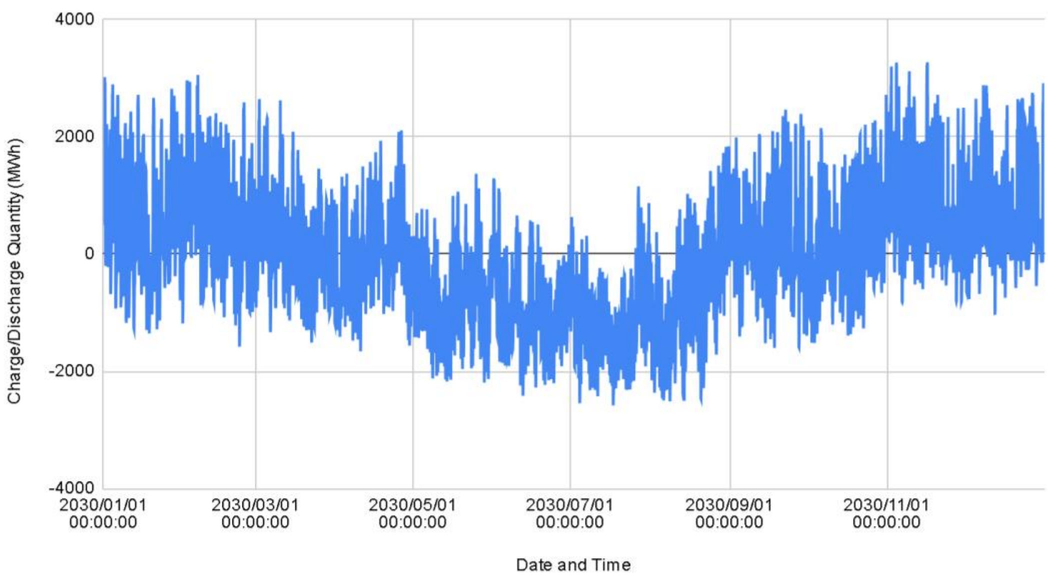

Figure 10. Innovation scenario charging/discharging

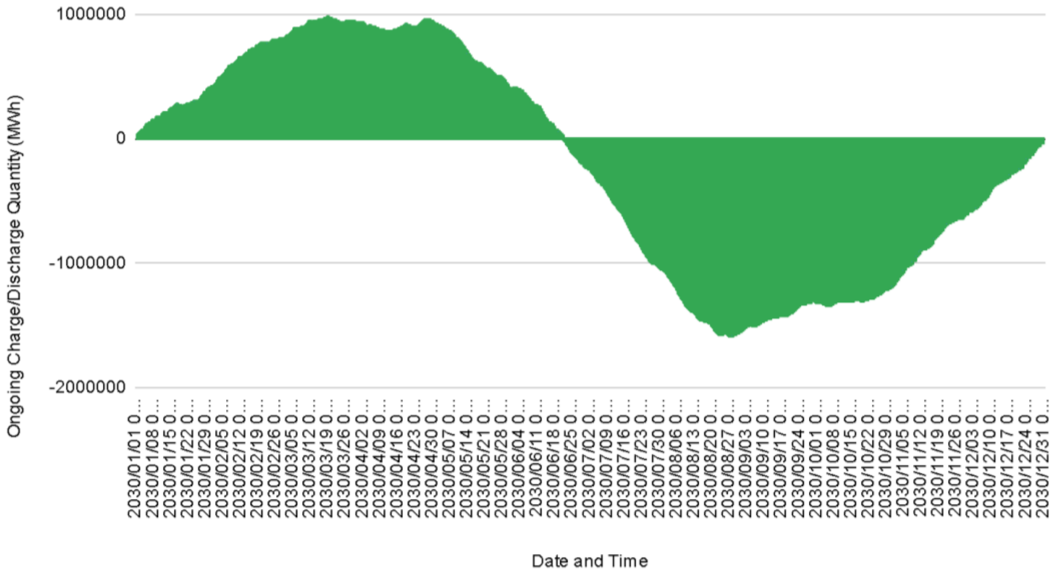

Figure 11. Innovation scenario ongoing charge/discharge requirements

The required power capacity of the long-term national grid energy storage system for this scenario is 2.58GW. The energy storage capacity that must be supplied by the long-term grid energy storage system for this scenario is 1.58TWh. The short-term power requirements is found to be 1.45GW and again, as this is required to operate at this level for one hour, the required energy capacity of this short-term system is 1.45GWh. Again, using the same method for the total yearly discharges, the short-term total was found to be 113.7GWh while the long-term total was found to be 3.59TWh.

4.1.4. Dry year problem

The energy storage requirements for the dry year problem were not explicitly modelled. However, the total national hydro storage is equivalent to approximately 4.5TWh (Electricity Authority, 2025). Assuming a dry year scenario of no national hydro storage, the required energy storage capacity of 4.5TWh is used. As there is no available demand or renewable supply profile, this research assumes a similar pattern of use to the 2030 innovation scenario. This means that the required power capacity and expected yearly energy supply for this dry year solution will be taken to match that of the 2030 innovation scenario. The dry year does not have a unique short-term energy storage solution as the short-term energy storage requirements are dictated by the specific grid demand and renewable supply profiles which are not present in this scenario's information.

4.2. Short-term solutions

The short-term grid energy storage options identified in the literature review include flywheels, lithium-ion batteries and hydrogen. To calculate the net present value (NPV) of the ongoing maintenance costs for all projects investigated, a discount rate of 2% for years 1-30 which drops to 1.5% until year 100 is used as recommended by The Treasury New Zealand (The Treasury New Zealand, 2025). All currency values obtained were converted into 2025 NZ$ with data from Trading Economics (n.d.) with the exception of the older Beacon Power Flywheel Energy Storage Plant.

4.2.1. Flywheels

Mongird et al. (2019) indicate that the round-trip efficiency for flywheel energy storage systems is expected to be 86% while the expected lifespan is greater than 20 years, so 20 years is taken as the lifespan to ensure a worst-case scenario. The OPEX rate from this source was combined with the calculated data to find the OPEX for this technology and converted into 2025 NZ with the results seen in Table 1.

The first flywheel project investigated was the Dinglun Flywheel Energy Storage Power Station in Changzhi, China. This system is cited as having a power output capacity of 30MW at an initial CAPEX of 340 million 2023 Chinese Yuan with no published storage capacity (Murray, 2024). The second flywheel project investigated was the Beacon Power Flywheel Energy Storage Plant in Stephentown, USA. The power capacity for this project is reported as 20MW while the CAPEX is reported as 3.45 million 2010 United States Dollars (Clarion Energy Content Directors, 2010).

The standard process to calculate the cost per unit of energy storage and power capacity relies on access to information on the energy storage capacity. However, as this is unavailable across all flywheel projects, a different method was employed where scaling is linearly based on the power capacity. The resulting cost rate was applied to Aotearoa New Zealand's needs and converted to 2025 NZ$. In the Beacon case, due to the age of the project, data from Federal Reserve Bank of Minneapolis (n.d.) was used for inflation data. A CAPEX for each case for each scenario is found as seen in Table 1. This data was used with the yearly expected energy output and stated discount rate with the characteristics of the technology to find the LCOS for this case for each scenario as seen in Table 1.

Table 1. Flywheel costs

Scenario	13% Constraint	23% Growth	34% Innovation
Dinglun CAPEX (2025 NZ$)	$2,441,350,188	$2,915,285,619	$4,141,706,933
Beacon CAPEX (2025 NZ$)	$7,599,436,187	$9,074,702,652	$12,892,307,583
OPEX (2025 NZ$/year)	$10,713,896	$12,793,768	$18,175,933
Dinglun LCOS (2025 NZ$/kWh)	$2.94	$2.34	$2.33
Beacon LCOS (2025 NZ$/kWh)	$7.39	$5.83	$5.80

4.2.2. Lithium-ion Batteries

Mongird et al. (2019) indicates that the round-trip efficiency for lithium-ion battery storage systems is expected to be 80% while the expected lifespan is 10 years. Viswanathan et al. (2022) cites this expected efficiency as 85% with a lifespan of 13-16 years. Combining these two sources allows for a best and worst-case basis for the lifespan, efficiency and OPEX for each scenario. The OPEX produced by these two sources act as the two scenarios as seen in Table 2. Viswanathan et al. (2022) is also used to provide the cost ratio between the energy storage and power output which has two values, 0.037 and 0.047, which is again used to give a best and worst-case scenario in the calculations of the CAPEX.

The first lithium-ion system investigated was the Ruakākā Energy Park in Northland, New Zealand. This system was reported to have an energy storage capacity of 200MWh with a power output capacity of 100MW, coming in at a CAPEX of 186 million 2025 NZ$ (Meridian Energy, 2025). The second lithium-ion system investigated was the Waratah

Super Battery System in New South Wales, Australia. This system was reported to have an energy storage capacity of 1680MWh with a power output capacity of 850MW at a cost of 1 billion 2022 Australian Dollars (Infrastructure Partnerships Australia, n.d.). The third lithium-ion system investigated was the Thorpe Marsh Green Energy Hub in the United Kingdom. This system was reported to have an energy storage capacity of 3100MWh with a power output capacity of 1400MWh at a CAPEX of 1.039 billion 2025 Great British Pounds (Fidra Energy, 2025).

Applying the simultaneous equations and the desired energy storage and power output capacities to these numbers yields a best and worst-case CAPEX for each case for each scenario which was converted to 2025 NZ$ and can be seen in Table 2. Applying the standard lithium-ion characteristics of lifespan, round-trip efficiency, expected OPEX with the expected short-term yearly energy supply and the recommended discount rate and best and worst-case CAPEX yields a best and worst case LCOS as seen in Table 2.

Table 2. Lithium-ion battery costs

Scenario	13% Constraint	23% Growth	34% Innovation
Ruakākā CAPEX (2025 NZ$)	$1,550,775,079 - $1,566,976,644	$1,851,824,580 - $1,871,171,329	$2,630,862,187 - $2,658,347,853
Waratah CAPEX (2025 NZ$)	$880,926,192 - $889,937,108	$1,051,938,993 - $1,062,699,184	$1,494,475,530 - $1,509,762,388
Thorpe Marsh CAPEX (2025 NZ$)	$1,421,577,817 - $1,439,237,187	$1,697,546,459 - $1,718,634,014	$2,411,681,343 - $2,441,640,149
OPEX (2025 NZ$/year)	$15,305,566 - $37,606,831	$18,276,811 - $44,907,385	$25,965,619 - $63,799,316
Ruakākā LCOS (2025 NZ$/kWh)	$2.09 - $4.03	$1.65 - $2.87	$1.64 - $2.85
Waratah LCOS (2025 NZ$/kWh)	$1.30 - $2.61	$1.02 - $1.85	$1.02 - $1.84
Thorpe Marsh LCOS (2025 NZ$/kWh)	$1.94 - $3.39	$1.53 - $2.67	$1.52 - $2.66

4.2.3. Hydrogen

Viswanathan et al. (2022) indicated the lifespan for hydrogen energy storage systems are expected to be 30 years while the round-trip efficiency is 31%. The cost rate from this source provides the OPEX which was converted to 2025 NZ$ and can be seen in Table 3. It is key to note that both the lifespan and round-trip efficiency are properties of hydrogen systems, so these same values apply to long-term hydrogen use as well. The cost ratio of energy to power is again produced with information from Viswanathan et al. (2022) and is 0.042, which is again, a property of hydrogen in general, so applies to long-term, however, here it is used to find an expected CAPEX.

The first hydrogen system investigated was the HYFLEX – Flexible Hydrogen Storage for Power-to-X and Grid Optimization system in Denmark. This system is reported to have an energy storage capacity of 500MWh, a power output capacity of 10MW and a CAPEX of 72.6 million 2025 Danish Krone (Erhvervsstyrelsen, n.d.). The second hydrogen energy storage system investigated was the ACES Delta hydrogen storage site in Utah, USA. This system was reports to have an energy storage capacity of 300GWh, a power capacity of 220MW at a CAPEX of 1 billion 2023 United States Dollars (Martin, 2023).

Applying the simultaneous equations and scaling to the required capacities and converting to 2025 NZ$ provided the CAPEX results seen in Table 3. Again, using the previously obtained lifespan, round-trip efficiency, OPEX, discount rate and yearly energy output, the LCOS for each scenario is found as seen in Table 3.

Table 3. Short-term hydrogen costs

Scenario	13% Constraint	23% Growth	34% Innovation
HYFLEX CAPEX (2025 NZ$)	$628,250,930	$750,212,284	$1,065,816,467
ACES CAPEX (2025 NZ$)	$7,615,781,473	$9,094,221,022	$12,920,037,068
OPEX (2025 NZ$/year)	$15,282,852	$18,249,687	$25,927,085
HYFLEX LCOS (2025 NZ$/kWh)	$0.62	$0.49	$0.49
ACES LCOS (2025 NZ$/kWh)	$5.04	$3.98	$3.96

4.3. Long-term solutions

The long-term solutions investigated include hydrogen, pumped hydro energy storage, compressed air energy storage and thermal energy storage. The same discount rates are applied for these calculations.

4.3.1. Hydrogen

The data for short-term hydrogen storage can also be applied to long-term hydrogen storage, where the same characteristics such as lifespan are consistent, and the same costing rates for aspects such as OPEX and CAPEX can be used, scaled to the long-term requirements. Using the previously obtained data and results for short-term hydrogen energy storage, the CAPEX for each long-term scenario can be seen in Table 4. The LCOS is similarly based off the short-term data, but applied to a long-term, higher output system, yielding LCOS for each scenario, seen in Table 4.

Table 4. Long-term hydrogen costs

Scenarios	13% Constraint	23% Growth	34% Innovation	Dry Year
HYFLEX CAPEX (2025 NZ$)	$107,522,259,347	$122,456,259,408	$139,319,778,920	$392,996,453,459
ACES CAPEX (2025 NZ$)	$1,303,402,213,405	$1,484,434,578,594	$1,688,856,892,768	$4,763,966,446,765
OPEX (2025 NZ$/year)	$32,550,007	$38,253,786	$46,046,171	$46,046,172
HYFLEX LCOS (2025 NZ$/kWh)	$1.49	$1.39	$1.30	$3.66
ACES LCOS (2025 NZ$/kWh)	$17.97	$16.73	$15.68	$44.21

4.3.2. Pumped Hydro Storage

Mongird et al. (2019) cites the round-trip efficiency of pumped hydro systems as 80% with a lifespan of more than 25 years. Viswanathan et al. (2022) similarly states the efficiency of pumped hydro to be 80%, however, they state a lifespan of 60 years. As two lifespans were provided, they were treated as a best and worst case. Viswanathan et al. (2022) also provided the data required to calculate the cost ratio between the energy storage and power output which was found to be 0.10. Both sources also provided differing OPEX cost rates, which allowed for a best and worst-case OPEX result to be found, both of which were converted to 2025 NZ$ (see Table 5).

The first pumped hydro energy system investigated was the proposed Lake Onslow pumped hydro scheme in New Zealand. This project is cited as having an energy storage capacity of 5500GWh and a power output capacity of 1000MW according to Herron (2022) with a CAPEX of 15.7 billion 2023 NZ$ according to RNZ (2023). The second pumped hydro project investigated was the Saurdal Pumped Hydro Plant in Norway. This system is cited as having an energy storage capacity of 3331GWh, a power output capacity of 640MW and a CAPEX of 995 million 2020 Euros (Pitorac et al. 2020). The third system investigated was the Snowy 2.0 pumped hydro project in New South Wales, Australia. This system is reported to have an energy storage capacity of 350GWh, a power output capacity of 2200MW by Snowy Hydro (n.d.) with a CAPEX expected to be 12 billion 2023 Australian Dolars according to Snowy Hydro (2024).

Applying the simultaneous equations, scaling the results appropriately and converting to 2025 NZ$ yields a CAPEX from each case for each scenario as seen in Table 5. As there are two values for the lifespan and OPEX available, a best and worst-case LCOS was found for each investigated case for each scenario. The resulting LCOS values can be seen in Table 5.

Table 5. Pumped Hydro Storage costs

Scenario	13% Constraint	23% Growth	34% Innovation	Dry Year
Onslow CAPEX (2025 NZ$)	$21,493,746,093	$25,199,042,977	$30,205,820,580	$34,171,370,675
Saurdal CAPEX (2025 NZ$)	$5,012,058,251	$5,876,084,686	$7,043,599,327	$7,968,310,337
Snowy 2.0 CAPEX (2025 NZ$)	$9,045,415,773	$10,604,750,774	$12,711,800,157	$14,380,660,844
OPEX (2025 NZ$/year)	$58,869,444 - $64,789,290	$69,185,211 - $76,142,400	$83,278,400 - $91,652,784	$83,278,400 - $91,652,785
Onslow LCOS (2025 NZ$/kWh)	$0.18 - $0.19	$0.19	$0.19	$0.21
Saurdal LCOS (2025 NZ$/kWh)	$0.05	$0.05	$0.05	$0.05
Snowy 2.0 LCOS (2025 NZ$/kWh)	$0.06	$0.06	$0.06	$0.06

4.3.3. Compressed Air Energy Storage

Mongird et al. (2019) indicated the efficiency of compressed air energy storage to be 52% with a lifespan of 25 years. Viswanathan et al. (2022) similarly states the efficiency to be 52%, however, a lifespan of 60 years is stated, again creating a best and worst-case for this technology. The OPEX rates cited by these two sources also differ, meaning that after converting to 2025 NZ$, there is again a best and worst-case OPEX, both of which can be seen in Table 6. Viswanathan et al. (2022) again provides the data to calculate the cost ratio for the energy storage and power output which is found to be 0.01 for this technology.

The first system investigates was the McIntosh CAES plant in Alabama, United States. This system is reported to have an energy storage capacity of 2640MWh and a power output capacity of 110MW as reported by Zhang et al. (2023) with a CAPEX of 148.28 million 2020 United States Dollars found with data from Mongird et al. (2020). The second project investigated was the Xinyang CAES project in China. This project was reported to have an energy storage capacity of 1200MWh, a power output capacity of 300MW and a CAPEX of 2.15 billion 2025 Chinese Yuan (Shaw, 2025).

Applying the simultaneous equations, scaling to the national needs and converting to 2025 NZ$ yields a CAPEX from each case for each scenario as seen in Table 6. As there are two OPEX and two lifespan values, a best-case and worst-case LCOS is formed based on these values and previous data for each case for each scenario as seen in Table 6.

Table 6. Compressed Air Energy Storage costs

Scenario	13% Constraint	23% Growth	34% Innovation	Dry Year
McIntosh CAPEX (2025 NZ$)	$59,731,698,434	$68,161,800,000	$77,834,035,310	$210,069,461,021
Xinyang CAPEX (2025 NZ$)	$43,747,545,193	$49,921,759,234	$57,005,713,944	$153,855,003,265
OPEX (2025 NZ$/year)	$37,912,073 - $68,049,129	$44,555,454 - $79,973,464	$53,631,504 - $96,264,245	$53,631,504 - $96,264,246
McIntosh LCOS (2025 NZ$/kWh)	$0.42 - $0.84	$0.39 - $0.79	$0.37 - $0.74	$0.98 - $1.97
Xinyang LCOS (2025 NZ$/kWh)	$0.31 - $0.62	$0.29 - $0.58	$0.27 - $0.55	$0.72 - $1.45

4.3.4. Thermal Energy Storage

Viswanathan et al. (2022) states the round-trip efficiency for thermal energy storage is 80% while the lifespan is 60 years. This resource also provides the data to calculate the OPEX which was converted to 2025 NZ$ and can be seen in Table 7. This source also provided the data required to calculate the energy storage to power capacity cost ratio which came to 0.042 for this technology.

The first thermal energy storage project investigated was the Pit Thermal Energy Storage system in Høje Taastrup, Denmark. This project was reported to have an energy storage capacity of 3300MWh, a power capacity of 30MW and a CAPEX of 10.7 million 2022 Euros (Global District Energy Climate Awards, n.d.). The second project investigated was the Mustikkamaa Rock Caverns in Finland. The project is reported to have a thermal energy storage capacity of 11.6GWh, a power output capacity of 120MW and a CAPEX of 15 million 2018 Euros (Helen, 2018).

Applying the simultaneous equations to these projects, scaling for the national grid needs of Aotearoa New Zealand and converting into 2025 NZ$ yields CAPEX values from each case for each scenario as seen in Table 7. Using this with the previously obtained data for thermal energy systems, LCOS values were also found based on both cases for each scenario, as seen in Table 7.

Table 7. Thermal Energy Storage costs

Scenario	13% Constraint	23% Growth	34% Innovation	Dry Year
Høje Taastrup CAPEX (2025 NZ$)	$13,788,080,579	$15,706,832,297	$17,877,715,409	$50,167,944,930
Mustikkamaa CAPEX (2025 NZ$)	$31,470,086,436	$35,849,470,927	$40,804,325,448	$114,503,834,213
OPEX (2025 NZ$/year)	$115,397,704	$135,618,990	$163,244,895	$163,244,896
Høje Taastrup LCOS (2025 NZ$/kWh)	$0.20	$0.19	$0.18	$0.44
Mustikkamaa LCOS (2025 NZ$/kWh)	$0.42	$0.39	$0.37	$0.97

4.4. Comparison

For each energy storage technology, the maximum and minimum LCOS found across the investigated projects were used to indicate the LCOS range in each scenario. The resulting LCOS range for each technology can be seen for each scenario in Figures 12 to 15.

Comparing the LCOS for the short-term grid energy storage options, flywheels, lithium-ion batteries and hydrogen, flywheels appear to have the greatest LCOS indicating they may be unsuitable for Aotearoa New Zealand's needs. While hydrogen and lithium-ion batteries appear to have a similar LCOS across the investigated scenarios, the LCOS range for hydrogen completely encompasses that of lithium-ion batteries. This suggests that, while LCOS may be similar, lithium-ion is a more stable and consistently least expensive short-term storage option. Purely on a cost basis, lithium-ion appears as the best short-term option for Aotearoa New Zealand as taking a risk on the grid storage cost with hydrogen is unnecessary.

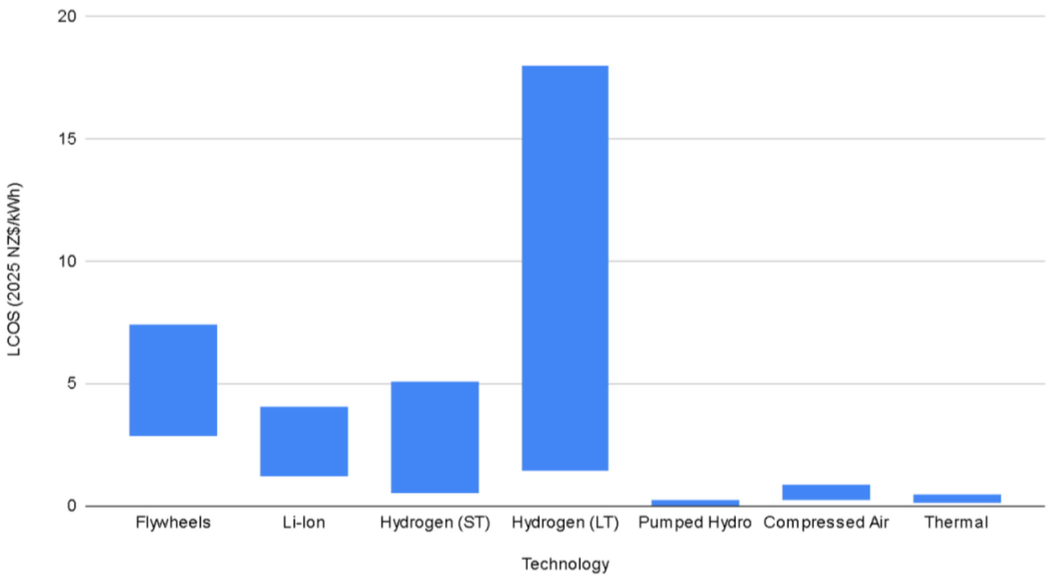

Figure 12. Constraint scenario LCOS

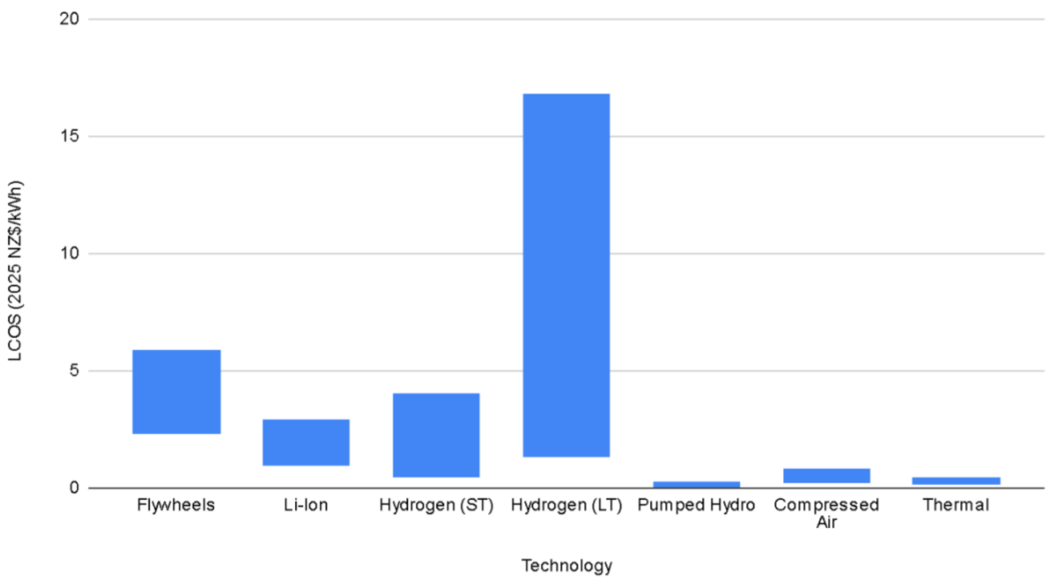

Figure 13. Growth scenario LCOS

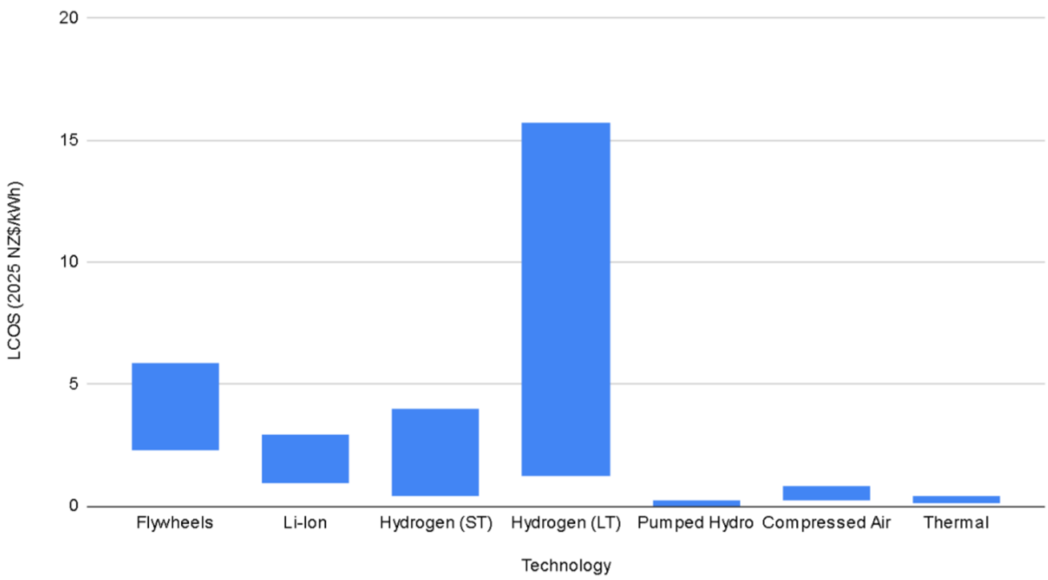

Figure 14. Innovation scenario LCOS

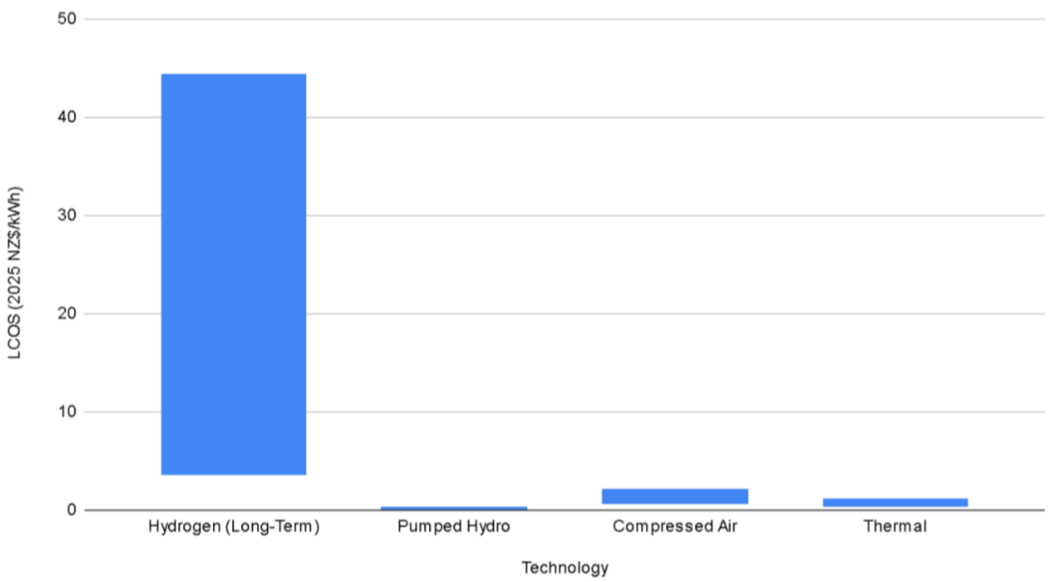

Figure 15. Dry year LCOS

Considering the LCOS for the long-term options, the costs for hydrogen as a long-term option are immense with the larger capacity to an extremely unrealistic cost, meaning this is not a suitable long-term option for the national long-term grid needs. Each of pumped hydro, compressed air and thermal energy storage have a reasonable LCOS so any would appear to be a reasonable option. The least expensive of these options is clearly pumped hydro storage options, so, on this LCOS basis, pumped hydro appears as the best option for the long-term grid needs of Aotearoa New Zealand. It is key to note that while the LCOS suggests the best option, other qualitative factors must be considered when deciding on the best long-term storage option.

5. Conclusion and recommendations

5.1. Main outcomes

This research has identified the expected costs associated with a range of grid-scale energy storage technologies relevant to Aotearoa New Zealand. However, a comprehensive assessment of each technology, and the formulation of an informed recommendation, requires consideration of qualitative factors in addition to quantitative cost metrics. Incorporating such qualitative analysis enables the identification of energy storage solutions that are most appropriate for both short-term and long-term grid requirements.

Flywheel energy storage was evaluated as a short-term storage option. The findings clearly indicate that flywheels are unsuitable for storing the quantities of energy required for grid-scale short-term energy storage. Flywheels represent the most expensive short-term storage technology considered. Furthermore, energy storage capacity data were unavailable for the projects investigated, strongly suggesting that this technology is not intended for large-scale energy storage applications. As flywheels were the only technology for which storage capacity information was absent, the costing model necessarily required substantial simplification, implying that actual costs may be higher than those estimated. In addition, due to the scarcity of large-scale projects, case studies from China and the United States were used, although these are unlikely to translate well to the context of Aotearoa New Zealand and remain considerably smaller in scale than would be required. While flywheels may have niche applications in Aotearoa New Zealand, such as grid stabilisation services, they are demonstrably unsuitable for energy storage at scale.

Hydrogen was also considered as a short-term energy storage technology. Although the calculated levelised cost of storage (LCOS) suggests that hydrogen could be a viable option in principle, qualitative considerations raise substantial concerns. While the LCOS appears comparable to that of lithium-ion batteries, the wide range of reported cost values indicates significant uncertainty, rendering hydrogen systems more difficult to cost accurately and thereby increasing financial risk. A further concern is the limited number of grid-connected hydrogen storage systems globally, particularly those powered entirely by renewable energy at the scale required by Aotearoa New Zealand. For example, the HYFLEX (Flexible Hydrogen Storage for Power-to-X) system relies on a methanol-based power supply (Erhvervsstyrelsen, n.d.). Moreover, storage configurations vary considerably, with projects such as ACES Delta (Martin, 2023) and UKEn (2026) utilising subterranean salt caverns to reduce the cost of hydrogen storage infrastructure.

Within Aotearoa New Zealand, hydrogen projects are predominantly focused on small-scale applications, particularly in the transport sector, and are typically limited to pilot-stage developments (New Zealand Hydrogen Council, 2025). Consequently, hydrogen presents a high-risk option for short-term grid energy storage due to the absence of established grid-integrated systems and the substantial cost uncertainty. As such, hydrogen is unsuitable as a primary storage investment where alternative short-term options are available. Nevertheless, hydrogen may have a potential supporting role under extreme energy supply conditions, for instance through the temporary redirection of hydrogen produced for transport or industrial uses to support grid demand.

Lithium-ion batteries emerge as the industry standard for short-term grid-scale energy storage. They represent the lowest-cost short-term option identified in this research and have been widely deployed at scale internationally. Case studies from Australia and the United Kingdom were used and are considered reasonably representative of the costs likely to be incurred in Aotearoa New Zealand, supplemented by analysis of a domestic project. The Ruakākā lithium-ion battery energy storage system provides a particularly robust indication of likely costs and demonstrates the technical suitability of such systems for the national grid. The existence of this project also indicates prior experience in installation and operation, which enhances the feasibility of further deployment. Additional battery energy storage systems are already operational at Rotohiko, with further projects under construction at Huntly and Glenbrook–Ohurua, further reinforcing the suitability of lithium-ion batteries for Aotearoa New Zealand (Concept Consulting, 2026). While lithium-ion batteries are clearly the most cost-effective and viable option assessed, other battery technologies, such as flow batteries, warrant further investigation prior to final investment decisions.

Hydrogen is clearly unsuitable as the long-term grid energy storage solution for Aotearoa New Zealand as supported by the NZ Battery Project finding the risks associated with the technical and commercial maturity a barrier to widespread implementation in Aotearoa New Zealand at this time (Ministry of Business, Innovation and Employment, 2022b). The cost data produced in this research indicate extremely variable capital costs, resulting in an LCOS that is both more uncertain and substantially higher than that of any other technology considered, including short-term storage options. In addition to these cost disadvantages, the qualitative concerns identified for short-term applications are magnified in a long-term context. Reliance on a technology with minimal global experience in grid-scale integration for long-term national energy storage would introduce unnecessary risk, particularly given the availability of more mature and proven alternatives.

The cost data examined in this research suggest that thermal energy storage could be a potentially viable option, with costs comparable to pumped hydro and compressed air energy storage. However, standalone thermal energy storage has not yet been demonstrated at the scale required to function as the sole long-term storage solution for Aotearoa New Zealand (to generate electricity). The two projects analysed, located in Denmark and Finland, represent relatively strong international analogues; however, both are limited to capacities on the order of gigawatt-hours, whereas national requirements are on the terawatt-hour scale. A further limitation is that the Mustikkamaa system converts electricity into heat that is used directly, rather than reconverting it to electricity, meaning that the costs associated with reconversion infrastructure are absent from this case study.

A key limitation of this research is its focus on standalone thermal energy storage, which remains uncommon and is largely confined to pilot-scale projects, such as those examined here or the MGA Thermal Energy Storage Project in Australia (Australian Renewable Energy Agency, 2025a). In practice, thermal energy storage is more commonly deployed in conjunction with concentrating solar power plants, such as the Ouarzazate Solar Power Station in Morocco, which utilises molten salt storage with a central tower configuration (PAREMA, 2025). Although such systems were not examined in this research, they may form part of future solar capacity expansion scenarios. At present, however, standalone thermal energy storage lacks evidence of operation at the scale required by Aotearoa New Zealand, and therefore cannot be considered a viable long-term solution relative to more established alternatives.

Compressed air energy storage (CAES) was found to offer relatively competitive costs, higher than those of thermal energy storage but supported by a longer operational history. CAES systems have been in operation since the commissioning of the Huntorf plant in Germany in 1976 (SSS Gears, n.d.), indicating a mature and technically proven technology. Nevertheless, the characteristics of early systems raise additional considerations. The Huntorf facility relies on salt caverns for air storage, a requirement that, as with hydrogen storage, may affect feasibility and costs in the context of Aotearoa New Zealand.

Despite its long development history, CAES has not been widely deployed globally. In countries analogous to Aotearoa New Zealand, such as Australia, projects have largely remained at the demonstration stage, including the Broken Hill Advanced CAES Demonstration (Australian Renewable Energy Agency, 2025b). As a result, this research relied on case studies from China and the United States, which may not accurately reflect costs in the Aotearoa New Zealand context and may underestimate site-specific challenges. Nonetheless, CAES represents a credible long-term storage option, as it has demonstrated technical feasibility and benefits from a more established track record than hydrogen or standalone thermal energy storage. While costs may increase once site-specific details are accounted for, CAES remains a stronger and more realistic long-term option, albeit not without limitations.

Pumped hydro energy storage emerges as the most suitable long-term energy storage solution for the national grid of Aotearoa New Zealand. It was identified as having the lowest LCOS of all technologies assessed, making it the most cost-effective option available. A substantial body of international projects was available for analysis, enabling the selection of examples from countries with comparable conditions, including Australia and Norway, whose costs are likely to translate well to the New Zealand context. The case for pumped hydro is further strengthened by the extensive investigation of the Lake Onslow pumped hydro scheme. This project provides cost estimates tailored specifically to Aotearoa New Zealand and has been described as a potential 'game changer' in reducing reliance on fossil fuels through improved utilisation of renewable resources (Herron, 2022). The Lake Onslow scheme has been thoroughly assessed as a dry-year mitigation measure and has been identified as a high-potential solution through the New Zealand Battery Project (Ministry of Business, Innovation and Employment, 2023). As a low-risk, mature, and cost-effective technology with detailed domestic analysis, pumped hydro energy storage represents the most compelling long-term option for meeting Aotearoa New Zealand's national grid energy storage requirements.

5.2. Recommendation

To establish an effective energy storage system capable of supporting a 100% renewable electricity grid in Aotearoa New Zealand, it is likely that a portfolio of complementary storage technologies would be deployed in combination. However, the objective of this research was to identify the most suitable storage options and to estimate their associated costs. On the basis of the quantitative results, supplemented by qualitative analysis, lithium-ion battery energy storage systems, such as the Ruakākā installation, emerge as the most appropriate option for short-term storage. The expected cumulative capital costs for such systems are estimated to range from NZ$881 million to NZ$2.66 billion, depending on the projected future electricity demand scenario.

For long-term energy storage, pumped hydro energy storage appears to be the most suitable solution, exemplified by the proposed Lake Onslow scheme. The estimated costs for this option range from NZ$5.01 billion to NZ$34.2 billion, again contingent on the assumed future energy use scenario.

5.3. Ongoing and further research

There are significant opportunities for further research to strengthen the conclusions regarding both short-term and long-term energy storage solutions. Although lithium-ion batteries were identified as the most suitable short-term storage option, they were employed in this research as a proxy for battery energy storage systems more generally. Further investigation into alternative battery technologies, including flow batteries and other emerging battery chemistries, would enable a more comprehensive evaluation of short-term storage options. Given that both compressed air energy storage and pumped hydro energy storage were identified as viable long-term solutions, site-specific studies examining geological, environmental, and economic conditions would allow for more precise cost estimates and a more robust comparison between these two high-potential technologies. Such analyses would support more informed decision-making regarding the most appropriate long-term storage pathway. Finally, given the rapid pace of technological development within the energy sector, continued assessment of emerging energy storage technologies is essential to ensure that future planning remains aligned with the most effective, reliable, and economically viable solutions for supporting a fully renewable electricity system.

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