VICTORIA UNIVERSITY OF WELLINGTON TE HERENGA WAKA NEW ZEALAND
Archives of Sustainable Energy Systems
https://www.wgtn.ac.nz/sustainable-energy-systems

Techno-economic assessment of integrated floating photovoltaic and small-scale pumped hydro storage systems: A case study of the Te Mārua reservoirs in Wellington

Kerry Pep, Alan Colin Brent

Abstract
The integration of floating photovoltaic (FPV) and pumped hydro storage (PHS) systems offers a promising hybrid renewable energy solution, particularly when co-located on water reservoirs. This study investigates the technical, economic, and environmental feasibility of deploying a 10 MW FPV array with a small-scale 10 MW PHS system at the Te Mārua reservoirs in Wellington, Aotearoa New Zealand. Using a multidisciplinary techno-economic framework, the analysis combined site-specific solar and hydrological data, system modelling, simulation, and financial assessment over a 60-year horizon. The results indicate annual FPV generation of 14.4 GWh and PHS storage of 100 MWh per cycle, with complementary seasonal profiles enhancing grid stability and renewable dispatch. Financial metrics show FPV offers low Levelised Cost of Energy (NZ$150/MWh) and short payback, while PHS delivers a higher Net Present Value (NZ$47.7 million) through energy arbitrage. Environmental and social considerations are addressed through conservative array coverage and stakeholder engagement. The study provides a replicable framework for hybrid FPV-PHS deployment on similar reservoirs, supporting energy resilience and decarbonisation objectives.

Keywords: Floating photovoltaic; Pumped hydro energy storage; Pumped hydro storage co-location; Hybrid renewable systems; Te Mārua reservoirs.

1. Introduction

The increasing urgency to address climate change and energy security has accelerated the global transition toward renewable energy systems. Countries are increasingly seeking integrated solutions that combine renewable generation with energy storage to manage variability and ensure system resilience. Aotearoa New Zealand (NZ), despite its already high share of renewable electricity generation, is entering a critical phase in its low-carbon transition as electrification of transport and heating places growing pressure on existing energy infrastructure (MBIE, 2023). This creates a need for flexible, scalable, and locally deployable energy storage solutions.

Among emerging renewable technologies, floating photovoltaic (FPV) systems and pumped hydro storage (PHS) represent two promising yet underutilised options within the NZ context. FPV systems enable solar electricity generation on the surface of existing water bodies, reducing land-use conflicts and offering additional benefits such as reduced evaporation and improved module efficiency (Oliveira-Pinto and Stokkermans, 2020).

The integration of FPV with PHS is particularly relevant for energy systems with increasing shares of intermittent renewable generation. Excess solar energy or surplus off-peak grid energy can be used to pump water to an upper reservoir during periods of low demand or high generation, while stored water can be released to generate electricity during peak demand periods. This is especially relevant in Wellington, where local grid constraints and price volatility create opportunities for distributed storage.

The Te Mārua reservoirs in Upper Hutt, Wellington, represent a unique and largely unexplored opportunity to examine the feasibility of integrating small-scale PHS with FPV within existing council infrastructure. As a critical drinking water supply asset located in a region with variable renewable energy availability and growing urban demand, the reservoirs provide a real-world testbed for evaluating how hybrid renewable energy systems can contribute to regional energy resilience. In addition to electricity generation and storage, co-location of FPV on water reservoirs may support water management objectives by reducing evaporation and enhancing drought resilience, while maintaining the primary function of the asset.

This research is motivated by the convergence of several challenges and opportunities, including the increasing penetration of intermittent renewables, constraints on land availability for solar deployment in urban areas, and the need to enhance the flexibility and resilience of decentralised energy systems. The study aligns with national and regional policy objectives aimed at increasing renewable energy uptake, reducing greenhouse gas emissions, and supporting energy system transformation (MfE, 2023; GRWC, 2024). By focusing on a real-world municipal asset, the research seeks to bridge the gap between theoretical system modelling and practical implementation considerations.

1.1. Objective of the paper

The objective of this paper is to assess the techno-economic feasibility of integrating a small-scale FPV and PHS system within the existing Te Mārua reservoirs infrastructure in Wellington, Aotearoa New Zealand. This study specifically aims to:

- develop a site-specific techno-economic model;
- evaluate system performance under representative operating scenarios;
- examine associated capital and operational costs; and
- identify key technical, environmental, and infrastructural constraints influencing system viability.

Through this assessment, the paper seeks to provide practical insights into the potential role of small-scale FPV-PHS systems in Aotearoa New Zealand and similar council contexts.

2. Literature review

This section reviews the theoretical foundations and key scholarly contributions related to FPV systems, PHS, and their integrated application. The review focuses on system configurations, performance characteristics, and techno-economic evaluation approaches, with particular attention to the relevance of hybrid FPV-PHS systems in site-specific and small-scale contexts. The section concludes by identifying gaps in the existing literature that motivate the present study.

2.1. Floating photovoltaic (FPV) systems

Floating photovoltaic (FPV) systems involve the deployment of photovoltaic (PV) modules on the surface of water bodies rather than on land (Mehra, 2022). FPV systems can be classified according to the type of water body and system configuration, including artificial water bodies such as man-made reservoirs, industrial or agricultural ponds; natural lakes and ponds; ocean/offshore installations; hybrid FPV-hydropower co-located systems; dual-use applications over aquaculture ponds; canal-top FPV; and small- or large-scale utility systems (Rossow, 2022; Yusuf, 2024).

FPV systems are typically mounted on buoyant platforms and anchored to the reservoir bed or shoreline to accommodate wind loading and water-level fluctuations. Most installations employ modular pontoon-based structures manufactured from high-density polyethylene (HDPE), which offer flexibility, scalability, and proven durability for inland waters, while specialised marine-grade floats and anchoring systems are used for ocean/offshore sites. Less common configurations include membrane-based FPV systems and tracking-enabled FPV designed to optimise solar capture at the expense of higher mechanical complexity and cost (Rossow, 2022; Yusuf, 2024).

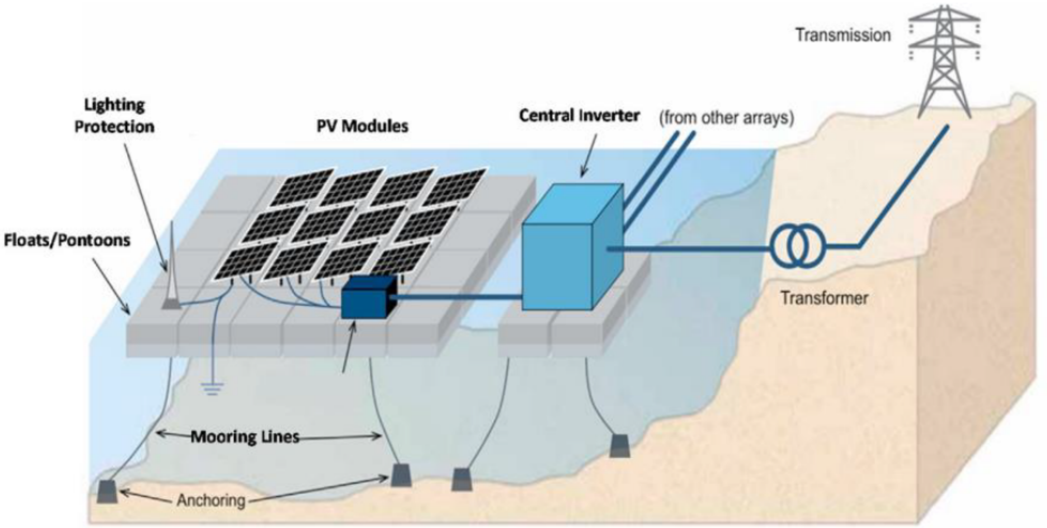

Figure 1. Schematic view of a typical FPV system and its main components
(Source: Sahu et al., 2016)

FPV systems provide an attractive alternative to land-based PV installations, particularly in regions where land availability is constrained or where competing land-use priorities exist. The benefits of FPV extend across different system types, including reduced water evaporation, improved water-use efficiency, and enhanced module performance due to the cooling effect of the underlying water body. These advantages make FPV particularly relevant for drinking water reservoirs and other managed water assets (Trapani and Redón Santafé, 2014; Oliveira-Pinto and Stokkermans, 2020).

Despite these advantages, FPV systems face a range of technical, economic, and environmental challenges. Capital costs are typically higher than ground-mounted PV due to floating structures, anchoring systems, and FPV-specific balance-of-system components (see Figure 2). Engineering complexity related to mooring design, maintenance access, and long-term structural durability must also be addressed, particularly for drinking water reservoirs where water quality and public acceptance are critical considerations. Environmental impacts on aquatic ecosystems and visual amenity remain important factors influencing FPV deployment, especially in urban and peri-urban settings (Cazzaniga et al., 2021).

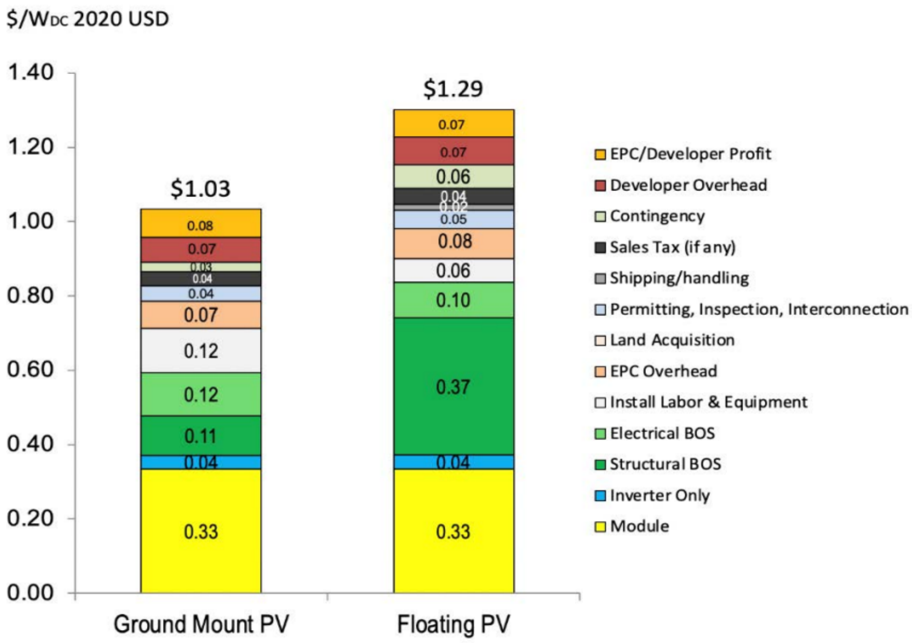

Figure 2. U.S. installed cost breakdown for a 10MW$_{DC}$ FPV system relative to ground-mounted PV system, illustrating that the structural balance-of-system (SBOS) requirements account for the majority of FPV expenditure
(Source: NREL, 2022)

International case studies demonstrate the technical feasibility and growing commercial maturity of FPV systems. Large-scale installations in countries such as China, Japan, and India have shown stable performance over multiple years. Notable examples include hybrid FPV-hydro systems in Japan and utility-scale projects in Anhui Province, China (13.7 MW), which have provided operational insights for pontoon-based designs in calm inland waters (IRENA, 2023; Rossow, 2022). In contrast, FPV deployment in Aotearoa New Zealand remains limited. To date, only one commercial FPV installation exists: a small-scale pontoon-based system at the Rosedale Water Treatment Plant in Auckland, managed by Watercare Services Limited. This project represents NZ's first application of FPV integrated into council water infrastructure.

Recent research has begun to explore the FPV potential within the NZ context. Feasibility studies at Maraetai Dam and Lake Tekapo indicate site-specific energy yields between 1,115 and 1,497 kWh/kWp, but highlight high installation costs as a barrier (Brent et al., 2023; Yusuf, 2024). These findings underscore the opportunities for FPV deployment while demonstrating the need for locally informed research to improve cost-efficiency and support broader adoption of FPV technologies.

2.2. Pumped hydro storage (PHS) systems

Pumped hydro storage (PHS) systems store energy by transferring water between two reservoirs at different elevations (U.S. Department of Energy, 2023). During periods of high electricity demand, water is released from the upper reservoir to the lower reservoir through a turbine to generate electricity. During periods of low demand or surplus generation, the system operates in reverse, pumping water back to the upper reservoir.
PHS systems are commonly classified as open-loop or closed-loop, depending on their hydraulic connection to natural waterways (see Figure 3). Open-loop systems are

connected to rivers or lakes, while closed-loop systems operate largely independently of natural hydrological flows. Beyond these primary categories, PHS technologies can also be categorised according to operational cycles and reservoir configurations. These include pump-back systems integrated with existing hydropower dams, hourly and daily PHS designed for short-term grid balancing, weekly and seasonal PHS intended for longer-duration storage, and rare pluriannual systems capable of multi-year storage (Papadakis et al., 2023). Additional specialised forms—such as underground PHS using former mines, seawater PHS utilising the ocean as a lower reservoir, and hybrid systems powered by co-located renewable energy—reflect the growing diversity of PHS applications and siting possibilities (Papadakis et al., 2023).

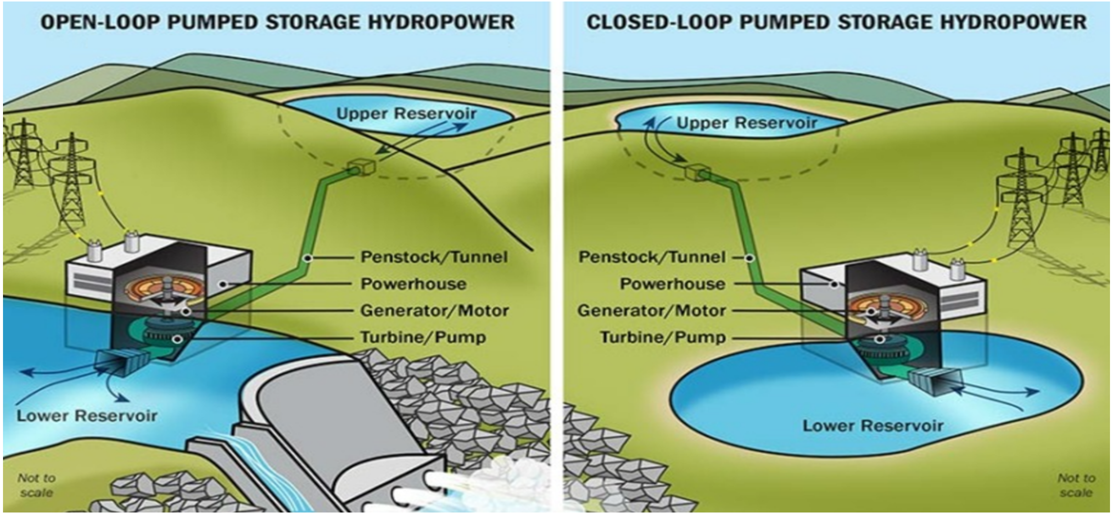

Figure 3. Two common classifications of PHS systems
(Source: National Hydropower Association, 2024).

Global hydropower growth is notable, with installed capacity rising from 1,210 GW in 2015 to 1,425 GW in 2024, highlighting its continued expansion relative to wind and solar (IRENA, 2024). While this figure does not distinguish conventional from pumped storage, it contextualises the scale of infrastructure supporting PHS deployment (see Figure 4). PHS remains the dominant form of large-scale energy storage, accounting for over 94 % of installed storage capacity when excluding conventional hydropower dams (IHA, 2025). This dominance reflects the widespread deployment of large-scale open-loop facilities in regions with favourable topography. PHS systems offer high round-trip efficiency (70-90 %), long operational lifespans, and rapid response to grid demand fluctuations (Pérez-Díaz et al., 2015), making them particularly effective for balancing variable renewable sources such as solar and wind.

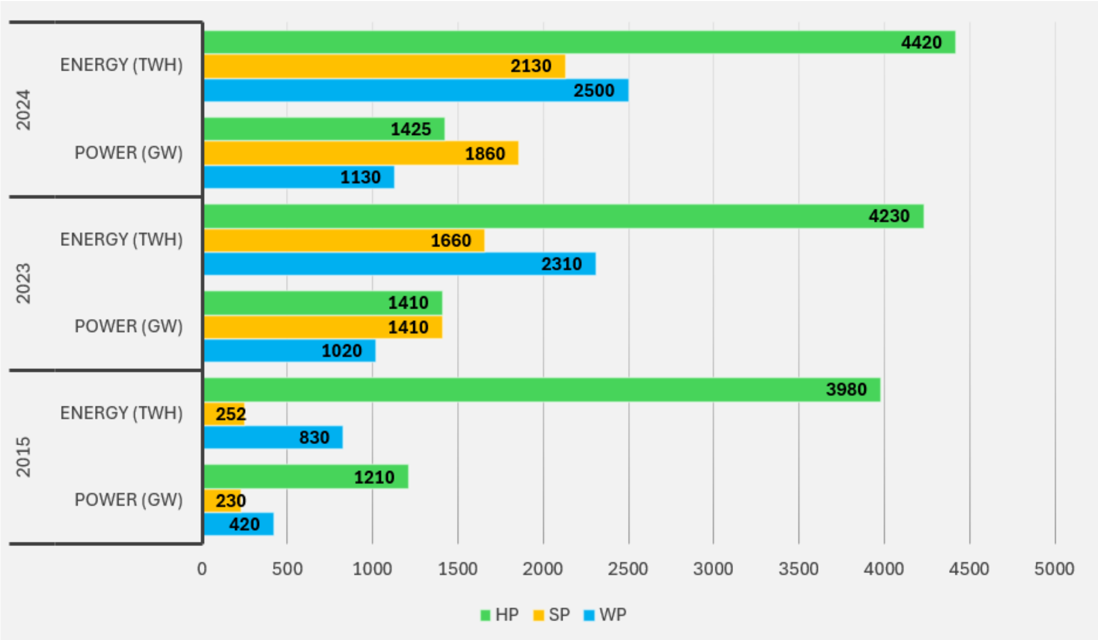

Figure 4. Global installed renewable power capacity (2015–2024) for wind, solar, and hydropower
(Source: IRENA, 2024)

However, traditional large-scale PHS systems require specific geographical conditions, including substantial elevation differences and proximity to water bodies, which have historically limited deployment. In contrast, small-scale and modular PHS systems offer greater siting flexibility and can integrate with existing infrastructure, such as municipal water reservoirs. These systems are often closed-loop, reducing environmental impact while expanding deployment potential in non-traditional settings.

Recent research highlights modular PHS designs using standardised electro-mechanical components and adaptable civil works, enabling sites with modest elevation differences (Dai et al., 2019). These configurations broaden viable PHS options, especially in regions without mountainous topography, underscoring the relevance of small-scale, closed-loop, and hybrid systems for municipal reservoirs. Small-scale PHS thus extends the benefits of pumped storage to contexts previously unsuitable for conventional deployment.

2.3. Integrated FPV-PHS systems

The integration of FPV and PHS systems represents a hybrid energy model that leverages the complementary strengths of both technologies. FPV systems can supply renewable electricity to power pumping operations during daylight hours, while PHS provides dispatchable energy storage to support electricity generation during peak demand or periods of low renewable output (Zhang et al., 2025). Shared use of reservoirs, electrical connections, and civil infrastructure can reduce overall project costs and environmental footprints.

Several studies have modelled the techno-economic performance of integrated FPV-PHS systems. Cazzaniga et al. (2021) conducted a simulation-based assessment of a hybrid FPV-PHS plant in southern Europe and reported LCOE values competitive with grid-connected solar and wind generation. The study also demonstrated improved energy reliability during evening and night-time periods when solar generation is unavailable.

Additional research from South Korea and India has shown that FPV-PHS hybrids can support microgrids and enhance energy resilience in remote or constrained settings (Momodu and Big-Alabo, 2024; Kumar et al., 2024).

Despite these promising results, much of the existing literature focuses on large-scale systems or assumes idealised site conditions. Small-scale FPV-PHS configurations, particularly those integrated into existing public infrastructure such as municipal water reservoirs, remain under-represented in published studies. This limits the transferability of findings to urban and peri-urban contexts where infrastructure constraints, regulatory considerations, and multi-use asset management are critical.

2.4. Techno-economic evaluation frameworks

Techno-economic evaluation plays a central role in assessing the viability of FPV-PHS hybrid systems. Common evaluation frameworks consider capital expenditure (CAPEX), operational expenditure (OPEX), system efficiency, operational lifespan, environmental impacts, and relevant policy and regulatory factors. Simulation tools such as HOMER Pro, MATLAB/Simulink, RETScreen, and Excel-based models are frequently employed to model system performance and financial outcomes.

Key performance indicators used in FPV-PHS evaluations include levelized cost of energy (LCOE), net present value (NPV), internal rate of return (IRR), payback period, and cost–benefit analysis (CBA). Sensitivity analysis is widely applied to assess the influence of key variables such as energy prices, solar irradiance, reservoir capacity, and pump–turbine efficiency on system performance and economic viability (Hernández-Callejo et al., 2019).

Recent studies emphasise the importance of electricity market structures and pricing mechanisms in determining storage system feasibility. Bamoshmoosh et al. (2024) demonstrated strong sensitivity of FPV-PHS system performance to time-of-use tariffs and wholesale price peaks, while Concept Consulting (2022) highlighted the growing role of ancillary service markets in decentralised electricity systems. In the NZ context, electricity price volatility driven by hydrological variability, renewable intermittency, and limited storage capacity further reinforces the potential value of dispatchable storage solutions.

Accurate techno-economic modelling remains challenging due to the limited availability of site-specific cost and performance data, particularly for emerging hybrid systems. Nevertheless, datasets from organisations such as Transpower, NIWA, and MBIE provide suitable proxies for system modelling within NZ (MBIE, 2023; NIWA, 2024; Transpower, 2025). Applying these frameworks to real-world sites such as the Te Mārua reservoirs offers an opportunity to generate context-specific insights into feasibility and scalability.

2.5. Identified gaps in literature

Although FPV and PHS technologies are well established individually, their integrated application at small scales remains underexplored. Existing FPV-PHS studies predominantly examine large hydropower reservoirs or theoretical configurations that do not reflect the operational constraints of local water infrastructure (Luo et al., 2015; Blakers et al., 2017). No published research evaluates FPV-PHS integration within drinking water reservoirs, despite their stable water levels, controlled access, and existing civil works. A structured summary of key international FPV-PHS studies and current pilot deployments is provided in the Supplementary Material to support this gap assessment.

Key gaps identified include:
- Limited research on small-scale (<10 MW) FPV-PHS systems;
- Absence of studies on municipal drinking water reservoirs;
- Lack of cost and performance data for small-scale PHS; and
- Minimal NZ-specific techno-economic modelling of hybrid systems.

These gaps highlight the need for site-specific assessments that consider the technical, economic, environmental, and operational constraints of municipal water assets.

3. Research method

This study applied a multidisciplinary techno-economic assessment (TEA) framework to evaluate the feasibility of integrating floating photovoltaic (FPV) systems with small-scale pumped hydro storage (PHS). The methodology combined data analysis, system design modelling, simulation, and financial analysis to capture both the technical and economic dimensions of the proposed system.

3.1. Site and data analysis

Comprehensive data collection at this site provided the foundation for both technical modelling of the integrated FPV-PHS system and its accompanying techno-economic assessment. The data encompassed multiple dimensions—technical, solar, hydrological, economic, and operational—ensuring a holistic understanding of system feasibility and performance.

3.1.1. Technical data

A site visit to the Te Mārua reservoirs (Stuart Macaskill Lakes) was conducted to capture the physical and operational characteristics relevant to system modelling. Observations were structured into qualitative and quantitative datasets.

Qualitative sbservations:
- Water surface conditions and seasonal fluctuations.
- Vegetation and biodiversity along reservoir margins.
- Environmental and social sensitivities affecting FPV deployment.
- Accessibility for construction and maintenance.
- Proximity to transmission and distribution infrastructure.
- Anchoring considerations for floating PV arrays.

Quantitative metrics:
- Combined reservoir capacity: ~3,300 ML.
- Surface area: ~14-18 ha per reservoir (~31 ha total).
- Maximum lake depth: ~16 m.
- Elevation: ~300 m above sea level, with ~160-165 m differential between upper proposed basin and the lower existing basin.
- Seasonal water-level variations, incorporated into FPV array sizing and PHS head calculations.

These site-based observations and metrics complemented secondary data from:
- Wellington Water (GWRC, 2022): this included structural details of the reservoirs, usable surface areas, and relevant constraints associated with their role in potable water storage and supply.

- Photovoltaic System Software (PVsyst.): PV simulation software used to obtain site-specific solar resource parameters, including long-term irradiance data, ambient temperature profiles, and system performance assumptions.

These inputs were essential for calibrating reservoir dynamics and evaluating the potential performance of FPV installations.

3.1.2. Solar data

High-resolution solar irradiance data were obtained from PVsyst and compared with NIWA's SolarView (NIWA, 2024) and SolarGIS (SolarGIS, 2025.), all of which provide hourly and seasonal solar radiation profiles. These datasets enabled accurate simulation of photovoltaic generation under the specific geographic and climatic conditions of the Te Mārua site, capturing both diurnal and seasonal variability.

3.1.3. Hydrological data

Hydrological datasets were provided by Wellington Water (GRWC, 2024), covering:
- Reservoir geometry and storage capacity parameters.
- Seasonal inflow and outflow patterns.
- Operational constraints linked to drinking water supply and treatment processes.
- Historical water usage profiles and drought response protocols.

These data were critical for modelling the PHS subsystem, particularly for estimating usable storage head, round-trip efficiency, and the operational limits of reservoir cycling.

3.1.4. Economic data

The economic assessment incorporated multiple national and international data sources to ensure realistic cost and revenue modelling:

1) Technology Cost Benchmarks: Capital and operational expenditure estimates for FPV and PHS technologies were sourced from the International Renewable Energy Agency (IRENA, 2012; 2025a; 2025b).
2) National and Regional Energy Pricing: Wholesale and retail electricity pricing structures were obtained from Transpower and Meridian Energy (the primary electricity retailer in the Wellington region) (Meridian Energy, 2024; Transpower, 2023; Transpower, 2024).
3) Financial and Investment Parameters: Reports from the Ministry of Business, Innovation and Employment (MBIE) provided discount rates, cost of capital, and renewable energy investment benchmarks (The Treasury, 2015; MBIE, 2024a; MBIE, 2024b).
4) Environmental Valuation: The New Zealand Emissions Trading Scheme (ETS) supplied carbon pricing values, which were incorporated into the estimation of emission offset benefits from renewable energy generation (MfE, 2024).
5) Academic and Industry Literature: Comparative case studies of FPV and PHS projects in similar geographies were reviewed to validate assumptions and benchmark financial modelling (Domakonda and Farooq 2023; Mamatha & Kulkarni 2022; Spencer et al. 2019; Liu et al., 2019).

3.2. System design modelling and simulation

3.2.1. Floating photovoltaic (FPV) array modelling

The FPV system was sized according to the usable water surface area of the lower Te Mārua reservoir, considering seasonal water level fluctuations and anchoring requirements. Solar irradiance and temperature data were sourced from PVsyst database (see Supplementary Material). These datasets were used to construct solar generation profiles, adjusted for panel efficiency, tilt orientation, and degradation rates over the project lifetime. In this way, the model reflects the long-term performance of FPV generation under real-world conditions.

3.2.2. Pumped hydro storage (PHS) modelling

The PHS system was designed around the elevation gradient between the existing lower reservoirs and proposed upper reservoir. Headroom constraints and minimum ecological water levels, as specified by Wellington Water, were incorporated to ensure that the model respected operational and environmental requirements. Turbine-pump efficiency values, based on international benchmarks for small-scale PHS systems, were applied. The system was configured to operate in charging mode during daytime generation surpluses and in discharge mode during evening and morning peak demand. This dual operation captures the balancing role of PHS in enhancing renewable energy penetration.

3.3. Techno-economic analysis

3.3.1. Energy generation and storage potential

FPV generation:
The FPV array produces a modelled energy of 14,437 MWh/year, with seasonal variation driven by irradiance, tilt, and DC/AC conversion behaviour. The array configuration, with a 10° tilt angle and 0° azimuth (due north-facing), is optimised for Wellington's solar resource.

PHS storage and generation:
The PHS component provides 300 MWh of storage, corresponding with a 10-hour pumping and generation schedule. Under full-cycle operation, the PHS system can deliver 36,500 MWh/year.

3.3.2. Efficiency and performance metrics

FPV System Efficiency:
FPV performance incorporates losses from temperature derating, soiling, inverter conversion, and cabling. With a DC/AC ratio of 1.2, system losses are estimated at 8%. The expected performance ratio (PR) is 0.75-0.85, affected by panel tilt, north-facing orientation, and seasonal irradiance variation.

PHS system efficiency:
The PHS system exhibits a round-trip efficiency of 80% (Pérez-Díaz et al. 2015; Rehman et al., 2015), accounting for pump/turbine and electrical losses. Francis turbine performance varies with head, with the net head of 160 m enabling high conversion efficiency. Hydraulic losses are mitigated by the favourable 0.16 head-to-length ratio.

Seasonal and grid sensitivity:
FPV output peaks in summer while PHS contributes more significantly during winter, stabilising seasonal supply. Reservoir level variations influence PHS turbine output. Grid constraints (including curtailment and voltage limitations) affect dispatch timing and net yield.

3.3.3. Grid integration and stability

Connection and configuration:

Both FPV and PHS systems utilise shared grid-connection infrastructure, with transformer sizing aligned to 10 MW capacity. The grid-tie configuration supports bidirectional flow for PHS and unidirectional export from FPV.
Curtailment and stability risks:
Curtailment risk for FPV is low due to the moderate DC/AC ratio and the generation profile of reservoir-based deployment. Voltage stability is supported by inverter reactive power capability and the synchronous generation characteristics of the PHS turbine.

PHS grid services:
The PHS system contributes frequency regulation, spinning reserve, and peak shaving. Pumping cycles are scheduled during off-peak periods, enabling absorption of excess renewable generation.

Hybrid contribution to grid resilience:
The combined FPV-PHS system smooths renewable variability, supports grid balancing, and enhances regional reliability. Seasonal complementarity reduces reliance on fossil generation. The integration strategy aligns with Transpower operational standards and contributes to decarbonisation goals (Transpower, 2025).

3.3.4. Financial metrics

A project horizon of 60 years was adopted, reflecting both the expected lifespan of PV modules (second lifespan) and the durability of hydropower infrastructure. Three core financial metrics were used to evaluate project viability, with their general calculation methods outlined below:

- Levelized Cost of Energy (LCOE) – Calculated using Excel, as it enables simple and transparent incorporation of capital costs, operational expenses, system lifetime, and generation outputs.

$$LCOE = \frac{Initial\ Cost\ (\$) + O\&M\ (\$/year)\ \times\ PVAF}{Annual\ Energy\ Output\ (kWh/year)\ \times\ PVAF} \tag{1}$$

- Net Present Value (NPV) – Also calculated in Excel to assess investment performance over the 60-year project horizon, incorporating cash inflows, outflows, and discount rates.

$$NPV\ = \sum_{yr=1}^{yr=n} \left(\frac{Equity\ cash\ flow}{(1 + inflation\ rate)^{yr}} - CAPEX \right) \tag{2}$$

- Internal Rate of Return (IRR) – The effective internal rate of return achieved by the investment—that is, the discount rate at which project NPV equals zero and which must exceed the required return to be financially viable.

$$0 = \sum_{t=0}^{n} \frac{C_t}{(1 + r)^t} \tag{3}$$

Microsoft Excel was the most appropriate software due to its accessibility, ease of sensitivity testing, and its suitability for presenting financial outcomes clearly.

3.3.5. Sensitivity analysis

A sensitivity analysis is essential for understanding the robustness of each technology under uncertainty, identifying the parameters that most strongly influence financial performance, and assessing how seasonal and market dynamics shape long term viability. Key variables included:

- FPV degradation rate (0.05-1% annually),
- PHS round-trip efficiency (75-85%),
- Discount rate (4-7%), and
- Feed-in tariff fluctuations (±20%).

The analysis isolates one variable at a time while holding others constant, ensuring clear interpretation of each parameter's effect. **Error! Reference source not found.** provides a summary of the sensitivity drivers for the FPV and PHS components. Furthermore, FPV and PHS are compared to highlight their complementary roles within a hybrid energy system.

Table 1. Summary of sensitivity drivers for FPV and PHS

Parameter / Driver	FPV Sensitivity	PHS Sensitivity	Interpretation
Revenue Basis	Fixed PPA tariff	Arbitrage between low off-peak and high peak prices	FPV = tariff-driven; PHS = spread-driven
Most Influential Variable	PPA price	Off-peak pumping price	PHS is far more sensitive to market conditions
CAPEX	High influence	Moderate influence	FPV is dominated by upfront cost; PHS is dominated by spreads
OPEX	Moderate influence, stronger over 60 years	Low–moderate	FPV accumulates OPEX over a long life; PHS OPEX is small relative to arbitrage revenue
Energy Yield	High influence	Round-trip efficiency is embedded but less dominant	FPV yield is a primary revenue driver
Discount rate	Strong effect on NPV; IRR unchanged	Moderate effect on NPV; IRR unchanged	Long-life assets are highly exposed to discounting
Seasonal Behaviour	Summer-domina nt (irradiance)	Winter-dominant (price spreads)	Opposite seasonal profiles
Extreme Upside Case	High PPA or high yield	Summer minimum price ($0.72/MWh) → NPV $136M	PHS has rare but massive upside
Extreme Downside Case	Low PPA or high CAPEX	Stress case ($100/MWh off-peak) → NPV –$50M	PHS can become uneconomic under tight supply
Overall Robustness	Stable under long-term assumptions	Highly sensitive to market dynamics	FPV = predictable; PHS = high-risk/high-reward

3.3.6. Evaluation metrics

The integrated system was assessed against the following performance indicators:

- Annual Energy Yield (kWh/year): Total FPV electricity generation and PHES discharge.
- Storage Utilisation Rate (%): The ratio of actual PHS use to its theoretical storage capacity.
- Levelized Cost of Energy ($/kWh): The average cost of electricity generated over the project's lifetime.
- Payback Period (years): The time required to recover initial investment.
- CO_2 Offset Potential (tCO_2/year): The estimated emissions avoided by displacing grid-supplied electricity.

4. Results and discussion

4.1. Case study: Te Mārua reservoirs

4.1.1. Site characteristics

The Te Mārua reservoirs, located in Wellington, Aotearoa New Zealand (NZ), were selected as the case study site due to their dual-reservoir configuration, favourable elevation gradient, proximity to urban energy demand, and existing water management infrastructure, making them suitable for investigating FPV-PHS integration under real-world constraints.

The lower reservoirs (existing Te Mārua twin lakes) sit at elevations of approximately 300 m above sea level, while the upper proposed reservoir is located at an elevation approximately 160-165 m above the lower basin, with head-to-length ratio of 0.16 required for feasibility (see Supplementary Material). The existing lower reservoirs have a combined surface area of approximately 31.4 ha and maximum depths of 16 m, while the proposed upper reservoir would cover approximately 6.1 ha with a capacity of 860.1 ML. Hydraulic modelling assumes a discharge volume of 143.35 ML for 10-hour generation cycles (see Supplementary Material).

FPV system:

- Deployed across approximately 5 ha of the lower reservoirs, with 16,667 JinKO 600 W modules (2.7 m^2 each), providing 10 MWp DC capacity.
- North-facing orientation, fixed 10° tilt, supported by Zimmerman (ZIM) PV Floating and Ciel & Terre pontoons.
- Two SMA Skid inverters rated at 4.4 MVA each, yielding a system DC/AC ratio of 1.2. Energy yield was modelled in PVsyst based on Te Mārua irradiance conditions.

PHS system:

- 1 km penstock producing a net generation head of 160 m.
- 10 MW reversible Francis turbine with 11 MW pumping draw at HV terminals.
- Configured for 10-hour pumping and 10-hour generation cycles.
- Shared use of lower reservoirs with FPV (~10% of total volume, ~1 m drawdown).
- Upper reservoir operation is limited to >33% volume, except in emergency conditions prioritising potable water. Seasonal synergy and shared infrastructure are embedded in dispatch logic.

Hydrological inflows and outflows are driven by the Hutt River at Kaitoke Weir, which supplies a 9,000 ha bush-clad catchment in the southern Tararua Ranges; summer abstraction limits, water-quality constraints, and bypass flows that refill the lakes before returning to the river shape reservoir operations (GWRC, 2022).

Site access is via State Highway 2, supporting construction and maintenance of FPV-PHS infrastructure. Climate conditions—annual rainfall of 1,203 mm (NIWA, 2024), mean temperature 9-13.6°C (NIWA, 2024), and generally high wind speeds typical of Wellington (NIWA, 2025)—affect both solar generation potential and hydrological dynamics. The Te Mārua reservoirs serve approximately 40-45% of the Wellington metropolitan population (Water New Zealand, 2024), covering around 177,638 properties in Upper Hutt with an average annual electricity consumption of 6,982 kWh per property (Powershop, 2025). Electricity is supplied via the national generation grid and local sources, with distribution maintained by Wellington Electricity, including substations such as the one at Birchville.

Overall, the site provides a strategic setting for this assessment, combining hydrological capacity, geographical configuration, accessibility, and proximity to energy demand.

Figure 5. Aerial view of the Te Marua reservoirs (Stuart Macaskill Lakes)
(Source: Bing Maps (Microsoft), 2025).

4.1.2. Energy need and potential

Electricity use associated with pumping, water transfer, and treatment is continuous and predictable, providing an opportunity for partial offset through on-site renewable generation. Solar resource assessments obtained from PVsyst show mean irradiance levels of 4.1-5.0 kWh/m^2/day (125 kWh/m^2/month), while reservoir surface conditions provide stable areas suitable for FPV deployment. Pumped hydro operation is enabled by the existing elevation difference of approximately 165 m offering potential for energy arbitrage and peak-load support. Together, these characteristics indicate significant technical potential for an integrated FPV-PHS system to reduce operational expenditure and contribute to regional energy resilience.

4.1.3. Existing infrastructure

The site includes two interconnected reservoirs linked by controlled intake structures and existing pumping assets. The electrical infrastructure includes proximity to local distribution lines and existing grid interconnection used for current pumping operations. Reservoir access roads, embankments, and operational control facilities offer suitable platforms for FPV deployment and PHS integration with minimal new civil works. This existing asset base reduces capital requirements and supports efficient implementation of an FPV-PHS hybrid configuration.

4.1.4. Proposed FPV-PHS integration approach

The proposed system involves deploying FPV arrays on 15% of existing available reservoir surface area to maximise solar generation while maintaining water supply functions. Generated electricity would power reversible pumps transferring water between upper (proposed) and existing lower reservoirs during periods of surplus solar output.

During peak demand or low-generation periods, stored water would be released to produce electricity via turbines installed within the proposed conveyance system. System operation would be coordinated through a centralised control strategy integrating solar forecasting, reservoir operating limits, and hydropower dispatch rules.

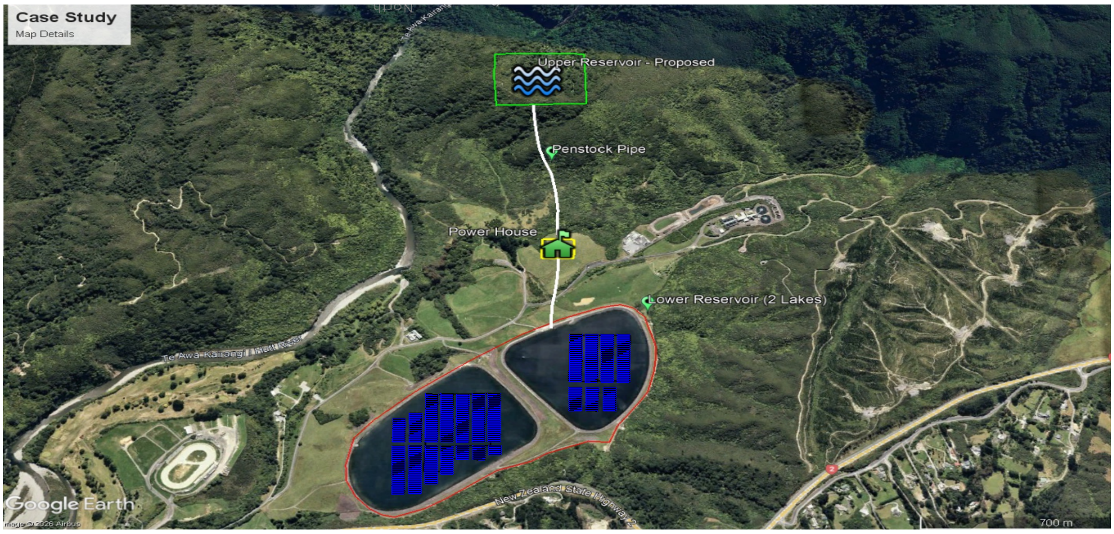

Figure 6. Layout of the proposed FPV-PHS system
(Source: PVsyst, 2025).

This approach aims to enhance operational flexibility, reduce grid reliance, and increase overall system efficiency with minimal disruption to existing water management activities.

4.2. Economic analysis

This section evaluates the economic performance of the FPV and PHS systems, comparing financial metrics under two PHS charging scenarios. FPV costs and financial outcomes remain constant in both cases; only PHS economics change because they depend on the source of pumping energy:

- Scenario 1 – Grid-charged PHS: FPV and PHS operate as independent projects with separate business models, and
- Scenario 2 – FPV-supported PHS: FPV remains a standalone generation asset, but PHS purchases 50% of its pumping energy from the co-located FPV system, creating a combined operational model for PHS.

Capital expenditure, operational costs, revenue potential, and financial indicators are all in New Zealand (NZ) context. The scenario modelling considers 30- and 60-year FPV lifetimes and a 60-year PHS project horizon, aligned with typical asset lifespans and international practice. All financial calculations, cost decomposition, and long-term cash-flow modelling are provided in the Supplementary Material.

4.2.1. Capital costs and investment requirements (CAPEX)

FPV systems require moderate capital investment (Joshi, 2023).

- FPV 30-year system: $21.59 million.
- FPV 60-year system: $24.25 million ($21.59 million in year 0, and $16.19 million for extending the 2nd life of FPV system).

PHS system demands significantly higher upfront investment (NREL, 2024):

- PHS 60-year system: $51.00 million.

These figures reflect the infrastructure intensity of PHS compared to modular FPV deployment.

4.2.2. Operational and maintenance cost (OPEX)

FPV OPEX (Joshi, 2023):

- 30 years: $5.89 million.
- 60 years: $8.31 million.

PHS OPEX (NREL, 2024):

- 60 years: $9.31 million.

PHS pumping energy cost:

- Scenario 1: $87.44 million, based on 736,628 MWh purchased at an assumed off-peak rate of $70/MWh (average off-peak grid price over the 2025 year).
- Scenario 2: Total cost is $136.68 million, based on 736,628 MWh purchased at $70/MWh (grid) and $149/MWh (FPV LCOE-based PPA).

While FPV incurs lower maintenance costs, PHS's operational profile includes substantial energy input costs—highly dependent on whether energy is sourced from the grid or the FPV system—which dominate its lifetime expenditure.

4.2.3. Revenue streams and financial feasibility

FPV revenues, based on its LCOE as its purchase power agreement (PPA) of $149/MWh escalating with inflation:

- 30 years: $38.04 million.
- 60 years: $54.60 million.

PHS revenues, based on an average grid peak price of $200/MWh escalating with inflation:

- 60 years: $195.49 million.

Net Present Value (NPV):

- FPV (30 years): $10.56 million.
- FPV (60 years): $22.05 million.
- Scenario 1 (60 years): $47.74 million.

- Scenario 2 (60 years): -$1.50 million

Internal Rate of Return (IRR):
- FPV (30 years): 4.5%.
- FPV (60 years): 5.0%.
- Scenario 1 (60 years): 10.0%.
- Scenario 2 (60 years): 5.0%

FPV remains financially positive across both lifetimes. Despite higher costs, Scenario 1 demonstrates superior financial feasibility, with stronger NPV and IRR performance, indicating robust long-term returns.

4.2.4. Payback period and levelized cost of energy (LCOE)

Payback Period:
- FPV: 10.7 years.
- Scenario 1: 11.7 years.
- Scenario 2: 21.13 years

LCOE:
- FPV: $0.15/kWh.
- Scenario 1: $0.25/kWh.
- Scenario 2: $0.34/kWh

Cost of Stored Energy (COSE) for PHS:
- Scenario 1: $254.44/MWh.
- Scenario 2: $339.24/MWh

FPV offers a shorter payback and lower LCOE, making it attractive for near-term deployment. Scenario 1 carries lower LCOE, shorter payback, and contributes strategic value through energy storage and grid support, while Scenario 2 increases costs further.

4.2.5. Economic performance of the FPV base case

The 60-year (2nd life inclusive) FPV base case produces an NPV of $22.05M and an IRR of 5.0%, with a payback period of 10.7 years. The system generates 218,754 MWh over its lifetime, supported by a CAPEX of $24.25M and OPEX of $8.31M. Compared with the 30-year case (NPV $10.56M, IRR 4.5%), the extended lifetime nearly doubles the NPV for only a modest increase in cost, demonstrating that FPV benefits significantly from long term operation. However, the IRR remains modest, indicating that FPV viability depends on stable tariffs, predictable energy yield, and disciplined cost management.

4.2.6. FPV: Sensitivity results

A one-at-a-time sensitivity analysis was conducted on the 60-year FPV case, varying PPA price, CAPEX, OPEX, energy yield, and discount rate.
- PPA price: A 10% increase raises NPV to $27.5M and IRR to 7%, while a 10% decrease lowers NPV to $16.5M and IRR to 3%. FPV is therefore highly sensitive to tariff structure.
- CAPEX: A ±20% variation produces substantial shifts in NPV and IRR, reflecting the importance of EPC cost certainty.
- OPEX: Changes in OPEX have a moderate influence, with long-term effects more pronounced in the 60-year case.

- Energy yield: ±10% variation directly affects revenue and therefore NPV and IRR.
- Discount rate: Lower discount rates significantly increase NPV, while higher rates reduce it, though IRR remains unchanged.

Compared with the 30-year case, the 60-year FPV system is more exposed to long term variables such as discount rate and OPEX, while the 30-year case is more dominated by upfront CAPEX and tariff assumptions.

Overall, FPV behaves like a conventional generation asset. Its financial performance is driven primarily by tariff certainty, energy yield, and capital cost. It is relatively insulated from short-term market volatility because revenue is tied to a fixed PPA rather than wholesale price spreads. This makes FPV stable but moderately sensitive to long-term financial assumptions.

4.2.7. Economic performance of the PHS base case

The 60-year PHS base case yields an NPV of $47.74M and an IRR of 10%, with a payback period of 11.7 years. Pumping energy is purchased at $70/MWh and sold at $200/MWh, giving a spread of $130/MWh. The system consumes 736,628 MWh for pumping and generates 580,697 MWh for sale, resulting in a pumping cost of $87.44M. Compared with FPV, PHS is more capital-intensive but also significantly more profitable, driven by its ability to arbitrage between low-price and high-price periods.

4.2.8. Nodal price spread sensitivity

A nodal price sensitivity analysis was undertaken to evaluate the impact of off-peak pumping electricity prices on PHS economic viability. The base case assumes a national average off-peak price of $70/MWh, but Haywards nodal data (EA, 2025) show substantial seasonal variation.
Seasonal off-peak prices used:

- Winter minimum: $67.37/MWh.
- Summer minimum: $0.72/MWh.
- Stress case: $100/MWh.

The results show:

- Winter minimum ($67.37/MWh): NPV increases to $51M, IRR remains at 10%. Winter spreads are stable and favourable.
- Summer minimum ($0.72/MWh): NPV rises dramatically to $136.3M and IRR to 16%. These conditions represent rare but extremely profitable surplus generation events.
- Stress case ($100/MWh): NPV falls to $10.26M, demonstrating that PHS becomes marginally viable economically if off-peak prices remain elevated.

PHS economics are dominated by the spread between charging and discharging prices. Unlike FPV, which depends on stable tariffs and energy yield, PHS thrives when it can access very low-cost surplus energy and sell into high value peak periods. Seasonal dynamics therefore play a critical role.

4.2.9. Seasonal dynamics and cross-technology insights

The seasonal analysis reveals a clear pattern. PHS value is winter dominant, with summer conditions offering limited but occasionally extreme arbitrage opportunities. Winter provides the most reliable profitability because peak prices remain high while off-peak prices stay moderate, ensuring a stable and favourable spread. Summer, by contrast, can produce very low nodal prices during surplus solar periods, creating rare but highly lucrative opportunities, but also periods of flatter spreads.

FPV exhibits the opposite seasonal profile. FPV performs best in summer due to higher irradiance but does not directly benefit from price volatility. Its revenue is stable and tariff driven, not spread driven.

Together, FPV and PHS form a complementary pair:

- FPV generates low-cost energy, especially in summer.
- PHS absorbs surplus energy and shifts it into high value winter and peak demand periods.
- FPV depresses summer prices, creating ideal pumping conditions for PHS.
- PHS stabilises winter supply, converting stored energy into firm capacity.

This seasonal complementarity strengthens system resilience and enhances the economic performance of both technologies when deployed together.

4.3. Discussion

4.3.1. Technical performance

The PVsyst simulations indicate an annual global horizontal irradiation of approximately 1,500 kWh/m^2 at Te Mārua. The FPV system achieves a high specific yield of 1,445 kWh/kWp/yr, producing 14.437 GWh annually when panels are north-facing. This aligns with performance expectations for high latitude FPV installations, where the cooling effect of the water surface typically improves module efficiency by 3 to 5% (ref). The system configuration—16,667 Jinko 600 W modules mounted on Xiamen Mibet pontoons and supported by 8.3 MVA of inverter capacity—provides stable generation across seasonal conditions.

The PHS component, comprising a 10 MW reversible Francis turbine, offers 100 MWh of storage with a 10-hour discharge duration. With an 80% round trip efficiency, the system consumes approximately 45.6 GWh annually for pumping and generates 36.5 GWh, consistent with expected losses for medium head reversible units (ref). The hybrid operation shifts 15 to 25% of daily energy into evening peaks by exporting FPV output directly to the grid and using off-peak electricity for pumping. The 10-hour discharge capability also enables the system to supply critical loads during grid outages, providing a resilience function that FPV alone cannot deliver.

High summer excess generation conditions substantially increase pumping opportunities, enabling the PHS system to complete full charge-discharge cycles more frequently. In contrast, reduced winter solar output limits the amount of surplus energy available for pumping; however, the system continues to maintain a high level of storage readiness by drawing on low-cost off-peak grid imports. Under winter peak price conditions, the system achieves noticeably higher dispatch value, demonstrating the hybrid configuration's ability to adapt effectively to both seasonal variability and market-driven operating conditions.

4.3.2. Economic feasibility

The long-term economic modelling over a 60-year horizon indicates favourable financial performance for both the FPV and PHS components, with detailed financial metrics summarised in Table 2. The techno-economic model incorporates Te Mārua-specific hydrological, solar, and operational data, including reservoir geometry, seasonal irradiation profiles, hourly price curves, and pumping-generation constraints to ensure that all financial outputs reflected actual operating conditions of the site.

Table 2. Te Mārua hybrid energy system economic feasibility summary

Costings	FPV	PHS (Scenario 1)	PHS (Scenario 2)
CAPEX	2.2 million/MW	5.1 million/MW	5.1 million/MW
OPEX	0.031 million/MW	0.034 million/MW	0.034 million/MW
Pumping Cost	-	$87.44 million	$136.68 million
LCOE	$0.15/kWh	$0.25/kWh	$0.34/kWh
NPV	$22.0 million	$47.7 million	-$1.50 million
IRR	5%	10%	5%
Discount Rate	6%	6%	6%
Payback Period	10.7 Years	11.7 Years	21.1 Years

The FPV achieves low CAPEX and OPEX, resulting in competitive LCOE, while PHS requires higher upfront and operational costs but provides strategic value through energy storage and grid stability. The scenario 2 system, however, is less economically attractive under current assumptions. These values compare competitively with other small-scale renewable plus storage systems, particularly when resilience benefits are considered.

The sensitivity analysis identifies three dominant economic drivers:

- FPV CAPEX reductions: a 20% decrease improves IRR and NPV and reduces LCOE by 13%.
- PHS node minimum summer price: higher summer prices significantly improve IRR and NPV and reduce LCOE by 44%.
- Winter peak avoided cost values: grid import prices of 0.21-0.35/kWh substantially enhances revenue streams.

Overall, Scenario 1 demonstrate economic viability, while Scenario 2 model substantially reduces profitability, doubles the payback period, and increases the cost of stored energy by approximately 33 to 36%, thereby demonstrating limited economic feasibility under current assumptions.

4.3.3. Carbon emission implications

The hybrid system contributes 43.64 GWh of renewable electricity annually and reduces emissions by approximately 3.18 kt CO_2e per year (MfE, 2024) equivalent to around 0.1% of emissions from national electricity generation. While modest at the national scale, this reduction is meaningful for local decarbonisation and aligns with Wellington's broader climate resilience strategy. Importantly, the project demonstrates a replicable model for other municipal reservoirs across Aotearoa New Zealand, many of which share similar hydrological and infrastructural characteristics. Integrating FPV and PHS within existing water supply assets offers a pathway to expand renewable generation without competing for land, while simultaneously strengthening community-level resilience.

The combination of moderate solar irradiance, existing hydropower infrastructure, and proximity to the grid positions Te Mārua as an ideal pilot site, with FPV-PHS offering both seasonal renewable balancing and water-management co-benefits (GWRC, 2022; Transpower, 2023).

4.3.4. Limitations of the study

This study has several limitations arising from site specificity, modelling assumptions, and data availability:

- Site-Specific Constraints: The analysis is based exclusively on the Te Mārua reservoirs, which limits generalisability. Reservoir geometry, seasonal water-level fluctuations, and existing infrastructure strongly influence both FPV placement and PHS design. Other reservoirs with different hydrology, topography, or environmental sensitivities may exhibit significantly different performance or operational constraints.
- Modelling Assumptions: FPV performance assumes static tilt, orientation, and module efficiency, while PHS modelling relies on constant head and full-cycle pumping and generation. Real-world variability, including weather extremes, inflow uncertainty, and grid curtailment, could reduce actual energy yield and round-trip efficiency.
- Economic Uncertainties: Financial analyses depend on projected CAPEX, OPEX, electricity tariffs, and nodal price spreads. Deviations in off-peak electricity prices, unexpected maintenance costs, or changes in regulatory incentives may alter NPV, IRR, and payback estimates, particularly for the PHS component.
- Environmental and Social Scope: While the study considers conservative FPV coverage and PHS operational limits, detailed environmental monitoring, ecological modelling, and stakeholder engagement are not fully implemented. Long-term impacts on water quality, aquatic ecology, or recreational use remain uncertain.
- Temporal Scale: The study relies on historical hydrological and solar data to model annual and seasonal energy yields. Climate change and evolving water demand could affect future performance, highlighting the need for adaptive management.
- Policy and Regulatory Context: Consents, permitting timelines, and local stakeholder negotiations are not accounted for in the analysis. These could influence project feasibility and implementation timelines.

Overall, the results provide a robust case study for Te Mārua but should be interpreted as indicative rather than universally applicable. Future work should expand site coverage, incorporate dynamic environmental monitoring, and include real-world operational data to validate model assumptions.

5. Conclusions

This study investigated the technical, economic, and environmental feasibility of integrating floating photovoltaic (FPV) arrays with a small-scale pumped hydro storage (PHS) system at the Te Mārua reservoirs in Wellington, Aotearoa New Zealand. The hybrid FPV-PHS configuration was assessed for energy generation potential, storage performance, grid integration, financial viability, and site-specific environmental and social considerations.

The findings indicate that the FPV system can produce approximately 14.4 GWh of renewable electricity annually, while the PHS component provides 100 MWh of storage per cycle with an 80% round-trip efficiency, enabling strategic energy dispatch during peak demand and enhancing local grid resilience. Economically, FPV exhibits a lower

LCOE ($0.15/kWh) and shorter payback period (10.7 years), whereas PHS, though more capital-intensive, delivers stronger financial returns (NPV $47.7 million, IRR 10%) due to arbitrage opportunities between off-peak and peak electricity prices. The complementary seasonal profiles of FPV and PHS further enhance system reliability, stabilise renewable supply, and contribute to municipal decarbonisation, reducing approximately 3.18 kt CO_2e annually.

While the FPV-PHS configuration is technically capable of operating either as an integrated system or as two hybrid subsystems that support each other and function independently, the economic analysis indicates that neither configuration is financially viable as a fully standalone system. As a result, grid connection becomes essential to ensure revenue stability, enable energy arbitrage, and make the project financeable from an investor perspective.

Collectively, these results demonstrate that co-located FPV-PHS systems can offer a replicable, low-land-impact approach to expand renewable energy capacity, improve energy resilience, and support regional decarbonisation goals. The study contributes to both knowledge and practice by providing a site-specific framework for hybrid renewable deployment in mid-latitude drinking water reservoirs.

5.1. Recommendations

Integrated insights from the Te Mārua case study highlight practical pathways for stakeholders, opportunities for future research, and considerations for wider implementation of FPV-PHS systems across Aotearoa New Zealand.

5.1.1. Recommendations for stakeholders

For utility operators and municipal water authorities:

- Generalisable: Municipal reservoirs with dual-basin configurations and moderate solar exposure can benefit from co-located FPV-PHS systems to enhance energy resilience, seasonal renewable balancing, and grid support.
- Site-specific: At Te Mārua, deploying a 1 × 10 MW reversible Francis turbine is recommended due to reduced civil complexity, lower O&M cost, and alignment with potable water management priorities, while ensuring minimal disruption to reservoir operations.
- Engage early with local communities and mana whenua to address social and cultural concerns, particularly regarding visual impact, recreational access, and water quality protection.
- Coordinate operational scheduling with regional grid operators to optimise dispatch of stored energy, peak-shaving services, and frequency regulation.

For policymakers and regulators:

- Generalise across similar reservoirs: Establish clear guidelines on FPV surface coverage for drinking-water reservoirs, balancing renewable deployment with water quality and ecological protection.
- Support pilot FPV-PHS projects via targeted financial incentives, such as green infrastructure bonds or public-private partnerships, to reduce perceived investment risk.
- Align planning frameworks with the Resource Management Act and Te Mana o te Wai principles to ensure energy development complements water governance and environmental conservation.

5.1.2. Recommendations for future research

- Validation and monitoring: Long-term performance monitoring at Te Mārua and comparable sites is essential to verify modelled energy yields, PHS efficiency, and FPV module performance under local climatic conditions.
- Hydro-solar interactions: Investigate dynamic interactions between FPV shading, evaporation reduction, and PHS drawdown/refill cycles to refine operational strategies and maximise co-benefits.
- Economic and market analysis: Explore sensitivity to variable electricity-market pricing, PPA structures, and policy incentives, particularly under evolving renewable energy frameworks.
- Replication potential: Assess transferability of FPV-PHS configurations to other council reservoirs with similar hydrological and infrastructural characteristics, identifying design modifications for differing head heights, surface areas, and water-use priorities.

References

Bamoshmoosh A, Catania M, Dipierro V, Ficili M, Fusco A, Gioffrè D, Parolin F, Pilotti L, Zelaschi A, Vincenti F, 2024. Techno-economic optimization of pumped hydro storage plants integrated with floating photovoltaic. Renewable Energy, 223, doi.org/10.1016/j.apenergy.2024.125268.

Blakers A, Lu B, Stocks M, 2017. 100% renewable electricity in Australia. Energy, 133, 471–482, doi.org/10.1016/j.energy.2017.05.168.

Brent AC, Crossland A, Ranusa D, 2023. An assessment of the economic feasibility of the floating PV technology in Aotearoa–New Zealand. Sustainable Energy Technologies and Assessments, 57, 103284, doi:10.1016/j.seta.2023.103284.

Cazzaniga R, Cicu M, Rosa-Clot M, Rosa-Clot P, Tina G M, Ventura C, 2021. Floating photovoltaic plants: Performance analysis and design criteria. Progress in Photovoltaics: Research and Applications, 29(4), 426–437, doi.org/10.1016/j.rser.2017.05.269.

Concept Consulting, 2022. Electricity price forecast. Wellington, accessed 2 August 2025 from: https://www.concept.co.nz/electricity-price-forecasts.html.

Dai J, Zhang C, Lim H V, Ang K K, Qian X, Wong J L H, Tan S T, Wang C L, 2019. Design and construction of floating modular photovoltaic system for water reservoirs. Singapore, accessed 2 August 2025 from: https://doi.org/10.1016/j.energy.2019.116549.

Domakonda V, Farooq S, 2023. Sustainable developments of hybrid floating solar power plants. In: Human Agro-Energy Systems and Sustainable Development. IGI Global, Hershey, PA, 251-276, accessed 2 August 2025 from: https://www.igi-global.com/chapter/sustainable-developments-of-hybrid-floating-solar-power-plants/317767.

Electricity Authority (EA), 2025. Nodal Prices and Volumes. Wellington, accessed 8 December 2025 from: https://www.emi.ea.govt.nz/Wholesale/Datasets/DispatchAndPricing/NodalPricesAndVolumes.

Greater Wellington Regional Council (GWRC), 2022. Te Mārua Water Treatment and Storage System – Asset Overview. Wellington, accessed 14 October 2025 from: https://www.gw.govt.nz/te-marua-asset-overview.

Greater Wellington Regional Council (GWRC), 2024. Te Mārua Water Treatment Plant Public Info Brochure. Wellington, accessed 31 May 2025 from: https://www.gw.govt.nz/document/111/te-marua-water-treatment-plant/.

Hernández-Callejo L, Gallardo-Saavedra S, Alonso-Gómez V, 2019. A review of photovoltaic systems: Design, operation and maintenance. Solar Energy, 188, 426–440, doi:10.1016/j.solener.2019.06.017.
International Energy Agency (IEA), 2022. Africa energy outlook 2022. Paris, accessed 3 August 2025 from: https://www.iea.org/reports/africa-energy-outlook-2022.
International Hydropower Association (IHA), 2025. 2025 World Hydropower Outlook. Accessed 8 December 2025 from: https://www.hydropower.org/publications/2025-world-hydropower-outlook.
International Renewable Energy Agency (IRENA), 2012. Renewable energy technologies: Cost analysis series – Hydropower. Volume 1: Power sector, Issue 3/5. Germany, accessed 14 October 2025 from: https://pdf4pro.com/view/renewable-energy-cost-analysis-hydropower-665f66.html.
International Renewable Energy Agency (IRENA), 2023. Renewable power generation costs in 2022. China, accessed 14 October 2025 from: https://www.irena.org/publications/2023/Jan/Renewable-Power-Generation-Costs-in-2022.
International Renewable Energy Agency (IRENA). (2024). Renewable capacity statistics 2024. Accessed 3 August 2025 from: http://www.irena.org/publications/2024/Mar/Renewable-Capacity-Statistics-2024.
International Renewable Energy Agency (IRENA), 2025a. Renewable power generation costs in 2024. United Arab Emirates, accessed 14 October 2025 from: https://www.irena.org/Publications/2025/Jun/Renewable-Power-Generation-Costs-in-2024.
International Renewable Energy Agency (IRENA), 2025b. Global landscape of energy transition finance. United Arab Emirates, accessed 14 October 2025 from: https://www.irena.org/Publications/2025/Nov/Global-landscape-of-energy-transition-finance-2025.
Joshi P, 2023. Overview of NREL's Research on Floating Solar Photovoltaics (FPV), including Technical Potential Assessments. National Renewable Energy Laboratory (NREL), Colorado, USA, accessed 8 December 2025 from: https://docs.nrel.gov/docs/fy24osti/87698.pdf.
Kumar P, Channi H K, Kumar R, Prakash C, Bhowmik A, Pandey S, Singh A K, Ali M M, Soudagar M E M, 2024. Efficient integration of photovoltaic and hydro energy technologies for sustainable power generation in rural areas: A case study. Materials Science for Energy Technologies, 7, 297–308, doi:10.1016/j.mset.2024.04.002.
Liu L, Sun Q, Li H, Yin H, Ren X, Wennersten R, 2019. Evaluating the benefits of integrating floating photovoltaic and pumped storage power systems. Renewable Energy, 141, 498-511, doi:10.1016/j.renene.2019.04.096.
Luo X, Wang J, Dooner M, Clarke J, 2015. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy, 137, 511–536, doi:10.1016/j.apenergy.2014.09.081.
Mamatha G, Kulkarni PS, 2022. Assessment of floating solar photovoltaic potential in India's existing hydropower reservoirs. Energy for Sustainable Development, 69, 64-76, doi:10.1016/j.esd.2022.05.011.
Mehra A, 2022. Floating solar panels (floatovoltaics): What to know. Energysage, accessed 2 August 2025 from: https://www.energysage.com/community-solar/floating-solar-what-you-need-to-know/.
Meridian Energy, 2024. Pricing and rates. Wellington, accessed 14 October 2025 from: https://www.meridianenergy.co.nz/for-home/pricing-rates.

Ministry of Business, Innovation and Employment (MBIE), 2023. New Zealand Energy Strategy to 2050: Powering Our Future. Wellington, accessed 14 October 2025 from: https://www.mbie.govt.nz/energy-strategy-2050.
Ministry of Business, Innovation and Employment (MBIE), 2024a. Electricity demand and generation scenarios: Results summary. Wellington, accessed 14 October 2025 from: https://www.mbie.govt.nz/assets/electricity-demand-and-generation-scenarios-report-2024.pdf.
Ministry of Business, Innovation and Employment (MBIE), 2024b. Energy in New Zealand 2024. Wellington, accessed 14 October 2025 from: https://www.mbie.govt.nz/dmsdocument/29395-energy-in-new-zealand-2024.
Ministry for the Environment (MfE), 2024a. Essential Freshwater – Te Mana o te Wai Implementation Guidance. Wellington, accessed 14 October 2025 from: https://environment.govt.nz/freshwater-te-mana-o-te-wai-guidance.
Ministry for the Environment (MfE), 2024b. Measuring emissions: A guide for organisations: 2024 detailed guide. ME 1829, Wellington, accessed 14 October 2025 from: https://environment.govt.nz/publications/measuring-emissions-a-guide-for-organisations-2024-detailed-guide/.
Momodu A-A, Big-Alabo A, 2024. Design optimization of a hybrid solar PV panel and pumped hydro energy supply system. Journal of Computational Mechanics, Power System and Control, 7(2), 53–62, doi:10.46253/jcmps.v7i2.a5.
National Hydropower Association, 2024. Pumped storage hydropower illustration. Hydro Review. Washington, D.C., USA, accessed 14 October 2025 from: https://hydro.org/wp-content/uploads/2024/05/basics-hydro-pumped-storage-hydropower-illustration-768x512.jpg.
National Institute of Water and Atmospheric Research (NIWA), 2024. Annual climate summary 2024. Wellington, accessed 12 February 2026 from: https://niwa.co.nz/climate-and-weather/annual/annual-climate-summary-2024.
National Institute of Water and Atmospheric Research (NIWA), 2025. Monthly climate summary – December 2025. Wellington, accessed 8 December 2025 from: https://niwa.co.nz/climate-and-weather/monthly/climate-summary-december-2025.
National Renewable Energy Laboratory (NREL), 2024. Pumped Storage Hydropower. Colorado, USA, accessed 8 December 2025 from: https://atb.nrel.gov/electricity/2024/pumped_storage_hydropower.
Oliveira-Pinto S, Stokkermans J, 2020. Assessment of the potential of different floating solar technologies: Overview and analysis of different case studies. Energy Conversion and Management, 211, doi:10.1016/j.enconman.2020.112747.
Papadakis C N, Fafalakis M, Katsaprakakis D, 2023. A Review of Pumped Hydro Storage Systems. Energies, 16(11), p.4516, doi:10.3390/en16114516.
Pérez-Díaz J I, Chazarra M, García-González J, Cavazzini G, Stoppato A, 2015. Trends and challenges in the operation of pumped-storage hydropower plants. Renewable and Sustainable Energy Reviews, 44, 767–784, doi:10.1016/j.rser.2015.01.029.
Powershop, 2026. Power in Upper Hutt – local electricity supply, consumption, and network. Wellington, accessed 8 December 2025 from: https://www.powershop.co.nz/regions/power-company-upper-hutt/.
Ramasamy V, Margolis R, 2021. Floating Photovoltaic System Cost Benchmark: Q1 2021 Installations on Artificial Water Bodies. National Renewable Energy Laboratory, NREL/TP-7A40-80695, accessed 8 December 2025 from: https://www.nrel.gov/docs/fy22osti/80695.pdf.

Rehman S, Al-Hadhrami LM, Alam MM, 2015. Pumped hydro energy storage system: A technological review. Renewable and Sustainable Energy Reviews, 44, 586–598, doi:10.1016/j.rser.2014.12.040.
Rossow M, 2022. Floating Photovoltaic Systems. Course No: R01-014, 1 PDH. Continuing Education and Development Engineering, accessed 14 October 2025 from: https://www.cedengineering.com/courses/floating-photovoltaic-systems.
Sahu A, Yadav N, Sudhakar K, 2016. Floating photovoltaic power plant: A review. Renewable and Sustainable Energy Reviews, 66, 815-24, doi:10.1016/j.rser.2016.08.051.
SolarGIS, 2025. Evaluate: Solar resource and PV potential assessment tool. Slovakia, accessed 14 October 2025 from: https://solargis.com/products/evaluate.
Spencer RS, Macknick J, Aznar A, Warren A, Reese MO, 2019. Floating photovoltaic systems: Assessing the technical potential of photovoltaic systems on man-made water bodies in the continental United States. Environmental Science Technology, 53 (3), 1680-1689, doi:10.1021/acs.est.8b04735.
The Treasury, 2015. Guide to social cost benefit analysis. Wellington, accessed 14 October 2025 from: https://www.treasury.govt.nz/sites/default/files/2015-07/cba-guide-jul15.pdf.
Transpower, 2023. Transmission Planning Report 2023. Wellington, accessed 14 October 2025 from: https://www.transpower.co.nz/plan/transmission-planning-2023.
Transpower, 2024. Transmission Planning Report 2024. Wellington, accessed 14 October 2025 from: https://www.transpower.co.nz/plan/transmission-planning-2024.
Transpower, 2025. Live system and market power: Empowering our energy future. Wellington, accessed 8 December 2025 from: https://www.transpower.co.nz/system-operator/live-system-and-market-data.
Trapani K, Redón Santafé M, 2014. A review of floating photovoltaic installations: 2007 - 2013. Progress in Photovoltaics: Research and Applications, 22(6), 681–691, doi:10.1002/pip.2466.
United States (U.S.) Department of Energy, 2023. Pumped storage hydropower. Washington, U.S.A, accessed 2 August 2025 from: https://www.energy.gov/eere/water/pumped-storage-hydropower.
Water New Zealand, 2024. Cyanobacteria Workshop: Macaskill Lakes Case Study. Wellington, accessed 14 October 2025 from: https://www.waternz.org.nz/Attachment?Action=Download&Attachment_id=6664.
Yusuf, AY, 2024. A comprehensive review of floating photovoltaic technology (FPVT) and its applications to improved efficiency. Journal of Research in Technology and Engineering, 5(3), accessed 8 December 2025 from: https://www.jrte.org/wp-content/uploads/2024/07/A-Comprehensive-Review-of-Floating-Photovoltaic-Technology-FPVT-and-Its-Applications-to-Improved-Efficiency.pdf.
Zhang D, Goh HH, Liang Q, Xie H, Liang X, Dai W, Kurniawan T A, Wong S Y, Goh K C, Teo KTK, 2025. Maximizing eco-energetic and economic synergies: Floating photovoltaic engaged pumped-hydro energy storage for water scarcity alleviation, carbon emission reduction, and cost efficiency. Process Safety and Environmental Protection, 197, doi.:10.1016/j.psep.2025.107082.