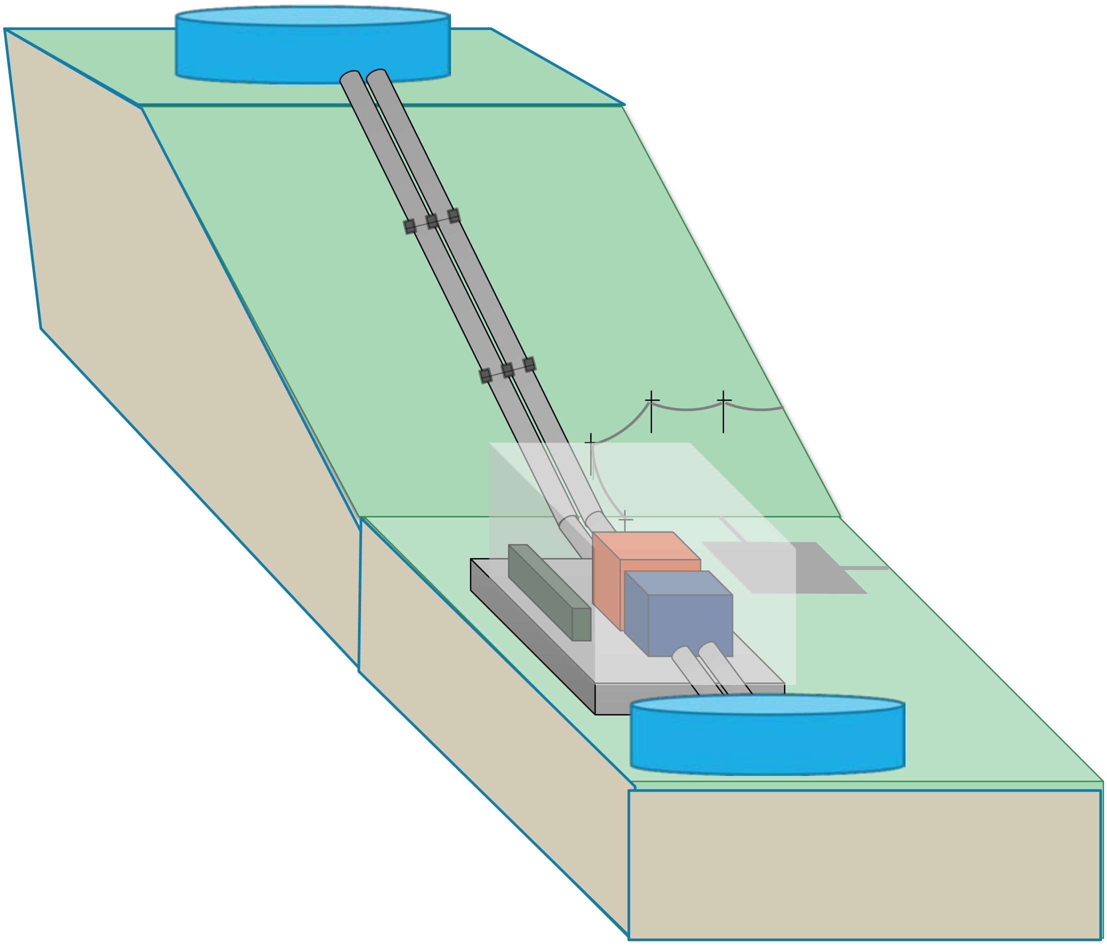
Modular Pumped Hydro Energy Storage (MPHES):

Relevance, concept design, economics and future prospect.

By Dane Fernandez



Masters of Renewable and Sustainable Energy Dissertation

School of Engineering and Science, Murdoch University

Supervisor: Dr Manickam Minakshi Sundaram

May 2019

Declaration

I declare that all work undertaken in this research topic, and presented in this dissertation is my own work, and that where data, research and conclusions from others have been used to support my findings, that these have been fairly referenced and acknowledged.

Abstract

This project gives an overview and literature review of Pumped Hydro Energy Storage (PHES) technology detailing the present context and future prospects with particular focus on Australia's National Electricity Market (NEM). Discussion that addresses present challenges and requirements to move forward with sustainable hydro power development electricity supply is explored. An overview of the fundamental system components and a technical design base for a Modular PHES (MPHES) is presented. A cost base is given for the MPHES and subsequently compared with other technologies. A concept design is proposed for a deployable, scalable MPHES system and is applied to two Case Studies. Discussion is given with respect to the relevance of such a scheme in Australia and the potential scalability and costs. The MPHES was found the be technically feasible and economically comparable to recent solar developments.

Table of Contents

By Dane Fernandez

Student No: 32945458

Abbreviations

ABC	Aerial Bundled Conductors
AEMC	Australian Energy Market Commission
AEMO	Australian Electricity Market Operator
ARENA	Australian Renewable Energy
BCA	Building Code of Australia
CAES	Compressed Air Energy Storage
COAG	Council of Australian Governments
CSIRO	Commonwealth Scientific and Industrial
DNSP	Distribution Network Service Provider
DOL	Direct Online
DFIM	Doubly Fed Induction Machine
ECNSW	Electricity Commission of NSW
EPC	Engineering, Procurement and
FCAS	Frequency Control Ancillary Services
GRP	Glass fiber reinforced polyester
GSUT	Generator Step-up Transformer
IEC	International Electrotechnical
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
LEP	Local Environmental Plans
MEI	Melbourne Energy Institute
MPHES	Modular Pumped Hydro Energy
NEM	National Electricity. Market
NER	National Electricity Rules
NPV	Net Present Value
NSW	New South Wales
NVE	Norwegian Water Resources and Energy
PHES	Pumped Hydro Energy Storage
PE	Polyethylene
PV	Photovoltaic
PVC	Polyvinyl Chloride
RET	Renewable Energy Technology
SCR	Short Circuit Ratio
SEPP	State Environmental Planning Policies
SPS	Special Protection Scheme
SRAS	System Restart Ancillary Services
SSD	State Significant Development
TNSP	Transmission Network Service Provider
VCAS	Voltage Control Ancillary Services
WAL	Water Access License

1. Introduction

1.1. Background

Australia's rapidly evolving power system is seeing a fast, and largely un-coordinated, deployment of Renewable Energy Technology (RET) energy systems. PHES is the most dominant form of energy storage in the world due to it being a reliable, established technology, economic on a cost per unit energy ($/MWh) metric over its lifecycle and provides a wide range of critical network support features to the power system.

PHES plants in Australia such as Wivenhoe, Shoalhaven and Tumut 3 schemes are effectively used to balance energy supply during low and high demand and indirectly used to compliment intermittent RET's such as wind and solar. The strategy used for dispatch is termed energy arbitrage, with PHES generally classed "peaking generation".

Although large hydro developments, both conventional and pumped storage, are long lived with known low lifecycle costs, they are extremely capital intensive. A key question forms. Is there appetite within the private sector to invest in greenfield PHES developments now and into the future?

The following is a list of complexities for large PHES development:

- Lack of policy stability from successive governments creates low market confidence in energy policy (why would a Board endorse, or foreign entity invest, significant amounts of capital in a volatile market, on a high-risk project with low rate of return?);

- Long project build times (typically 5 - 7 years for large scale);
- Land use and community issues (often located in environmentally sensitive or protected areas usually requiring large rehabilitation offsets and complex stakeholder engagements)
- High project risks and cost uncertainty (mainly around rock excavation, tunnelling and land use)
- Limited number of suitable development sites in Australia (in comparison to solar and wind)
- Limited financial recognition towards the value of sustainable energy storage in the NEM

This work differs from previous works [1] [2] as it outlines and attempts to break down PHES investment barriers whilst attempting to highlight and adopt the successful development characteristics and deployment rates of Solar PV we have seen in Australia over the last 8 years. In summation, key differences of this work include:

- The work is novel; the commercial costings of speculative technologies are often not included in majority of analysis in the literature because mass deployment of solar and wind are generally the lowest cost RET's.
- Focus on the Australian landscape and market context. Much work in the literature is based on national analysis of physically smaller countries, interconnected countries, or countries with different demand profiles such as northern countries (North Europe, North America) where there are high heating loads and less seasonality. The NEM in Australia is complex and unique system and does not compare well with international literature.
- Consideration to the value of future revenue streams stemming from the need for Ancillary Services (SRAS, FCAS, VCAS, FFR, SCR and inertial response) given

the challenge of retirement (and impending retirement) of conventional generation plant.

- Holistic approach to sustainable energy supply and development in the NEM
- Proposal of a concept design and economic analysis of a novel, deployable, scalable, Modular PHES (MPHES) system

1.2. Research Objectives

The objectives of this Dissertation is to explore the following areas:

- History and present context of PHES development within Australia and internationally
- Unique characteristics and future relevance of MPHES with respect to the sustainability of Renewable Energy Technologies (RET's) in the National Electricity Market (NEM)
- Development stages and relevant challenges faced in the development of new Hydro Power generation systems in Australia
- Requirement for Ancillary Services in the NEM in the context of reliability of supply and energy security
- Economic feasibility of greenfield MPHES development in comparison to solar and wind benchmarks
- Major components and technical design requirements for MPHES
- Relevant costs in constructing a MPHES facility
- A final understanding of the technical requirements and economical window for development of a deployable, MPHES concept system

1.3. Overview

- Initial focus of the Dissertation is discussion of the relevance of PHES in Australia. This begins by reviewing some current issues in the NEM:
    - Issue 1: The NEM is undergoing rapid transformational change.
    - Issue 2: Poorly managed, large penetration and increasingly fast, low cost, deployment of intermittent RET's in the NEM. Is energy supply reliable and the mix of supply fit for purpose?
    - Issue 3: Retirement and impending retirement of conventional generation for bulk energy supply has and will further result in reduced inertia, reduced fast frequency response and low short circuit ratios creating power system stability and security concerns.
    - Issue 4: Dispatchability. The market needs to value flexible, fast ramping, dispatchable energy supply with capability to perform Ancillary Services.
- Justification of how PHES can support the transition towards making electricity more reliable, affordable and ultimately sustainable in Australia. Discussion of relevant topics such as:
    - Flexibility of generation;
    - Energy storage capacity, bulk energy supply and reliability of supply;
    - Improve power system stability and security;
    - Support further penetration of distributed, intermittent inverter fed RET's such as solar and wind;
- Overview of the costs of recent Power Generation developments. Review of recently delivered project costs both in Australia and overseas to establish a cost baseline for future reference in the Dissertation.
- Discussion of PHES development barriers and challenges

- Formulation of a set of design requirements which need to be considered to make any new PHES concept feasible
- Brief overview of main components of PHES system
- Concept design of Modular PHES
    - Fundamental calculations (head, potential energy, power, flow rate)
    - Turbine and component selections
    - Upper and lower water storage reservoir requirements
    - Waterway requirements
    - Land requirements
    - Cost base and project timeline
- Application of the concept MPHES to two Case Studies
- RETScreen financial analysis with comparison to the current status quo
- Discussion about feasibility, scalability and relevance of design in Australia
- Discussion in regard to any future works or recommendations

1.4. Methodology

Chapter 2 provides context and key background information to support the Dissertation. It defines the PHES technology, gives an overview of pumped hydro development on a world-wide context and discusses its importance and potential value it can add to the NEM in Australia. A high-level overview is also given towards the planning and development requirements including access to water. The purpose of the chapter is to highlight the value that has been generated from PHES on a local and international scale. It suggests the technology is required to be modified from conventional to a more compact and flexible form to be economically viable and sustainable in Australia.

Chapter 3 provides a target design and cost brief. The key concepts are modularity, scalability, cost competitiveness and ability to be easily deployable. It begins by outlining the technical outcomes required by the plant and cost objectives to maintain cost relevance compared to Solar PV. The MPHES concept is introduced. The main technical design requirements and key equations are presented. Calculations are performed to form the basis of design for a prototype plant. The Chapter then focuses on a cost analysis utilising both domestic costings and cost curves found in the literature. Chapter 3 finishes with analysis of potential revenue streams from the various markets available in the NEM. The purpose of the chapter is to provide a technical design base, a methodology to estimate the cost to build the design and establish potential revenue scenarios.

Chapter 4 details two case studies that uses the concepts and learnings from Chapters 2 and 3 and applies them to the real world. The case studies deliver a detailed breakdown of the capital costs to construct a MPHES and FMPHES.

Chapter 5 delivers results in the form of cost curves for MPHES and FMPHES development. The curves can be used to estimate the capital cost for scalable plants up to 30MW.

The literature review defines the problem, the concept design provides a solution and the cost curves and recommendations are the outcome of this Dissertation.

1.5. Contributions

- Overview of current PHES landscape in Australia and in the literature
- Concept design of modular, scalable, deployable PHES system
- Demonstration that a concept MPHES system:
    - is economically viable in comparison to other RET's;
    - can be sustainably mass deployed;
    - has relevance in Australia.
- Cost base for MPHES in Australia
- Financial analysis for MPHES

2. Literature Review

2.1. What is PHES?

Pumped Hydro Energy Storage (PHES) is a flexible and dynamic way to store energy and generate electricity. This is achieved by moving water between an upper and lower reservoir, such as a dam or lake. The water reservoir can be naturally occurring or man-made. During times of low electricity demand or surplus generation such as during the night or on weekends, excess generation can be used to pump water to the upper storage reservoir. Peak generation often occurs during the day and when there is a high penetration of Renewable Energy Technologies (RETs) such as solar and wind. During this time, when, typically the wholesale price of electricity is low, or during the night when demand is low, the hydro turbine operates in pump mode moving water from the lower to higher elevation. During periods of peak electricity demand or low system capacity, the stored energy in the water at the higher elevation is released to the lower reservoir via gravity. The turbine is used to generate electricity via traditional AC generators. PHES utilises similar infrastructure to conventional hydro-electric plants, with the main variance being usage of the turbine with a pump set.

PHES does not typically consume water in the process of storing energy or generating electricity. Water can be lost via evaporation, and reservoir, tunnel or pipeline leaks. Typically, there is no requirement for a continuous supply of bulk water or make-up water. Water consumption via the process is typically considered negligible. In saying this, PHES plants are quite often integrated into existing water infrastructure serving additional purposes such as critical water transfer capability and reservoir level management for drinking, irrigation and facilitate natural flow management. Schemes used for multiple purposes with multiple stakeholders typically have an active storage level for operations and a gross water storage level. Each reservoir's water level is managed via licencing.

The principal design parameters that characterise a PHES scheme include:

- Hydroelectric generation potential power defined by a water turbine rated flow and power (or mega-watt, MW) capacity
- The upper and low reservoir water volumes
- The net vertical head available which is the difference in elevation of the upper and lower water storage reservoirs
- The potential energy available which is a function of volume and head
- The energy storage time period in hours, which is a function of the potential energy and size of the turbine. The stored electrical energy often stated in mega-watt-hours (MWh) or giga-watt-hours (GWh)

Further technical detail is given in Section 3. Figure 1 shows graphically the main principle of a PHES scheme.

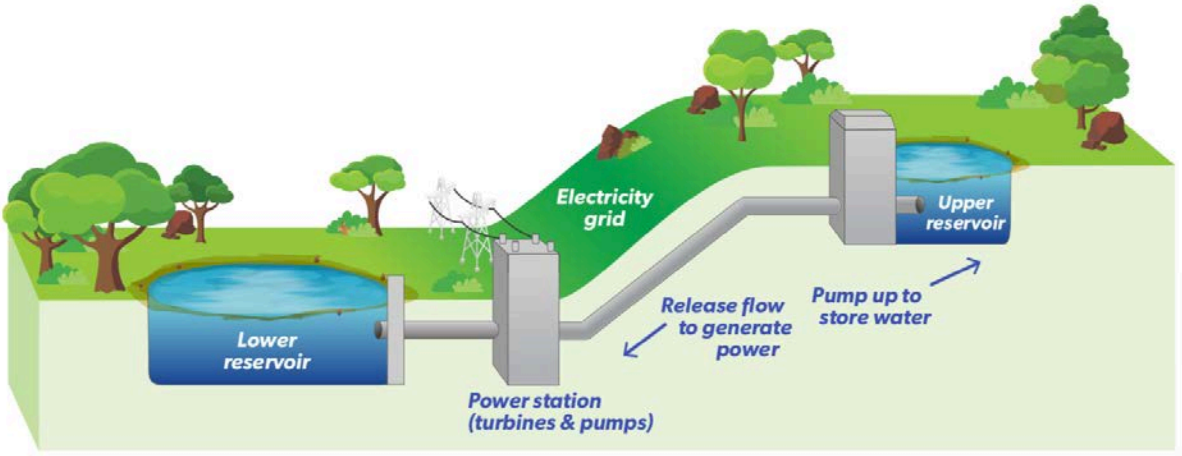


Figure 1: Pumped Hydro Energy Storage scheme overview [3]

2.2. PHES – a worldwide context

PHES is the most significant form of energy storage in the world with a total storage capacity of 153GW as of the end of 2017 [4]. Global energy storage capacity is 159GW making PHES comprise over 96% of the world electrical storage [4].

The energy storage capability of PHES has formed a foundation to many countries' energy reliability of bulk energy supply. The reliability and overall efficiency of installations make it an obvious choice when countries are seeking long term energy security in particular when coupled with geographically blessed or optimal land scapes such as high elevations. PHES storage reservoirs can store potential energy in their upper reservoir via either natural flow or via pumping. During pumping, PHES can be used to absorb surplus power or facilitate water transfer by acting as a load when RET penetration is high or power prices are low. Worldwide RET grid penetration is growing rapidly resulting in a global focus on dispatchable storage technologies. Global PHES capacity increased over 3GW by the start of 2018 with the majority of new installations located in China, Portugal and Switzerland [4].

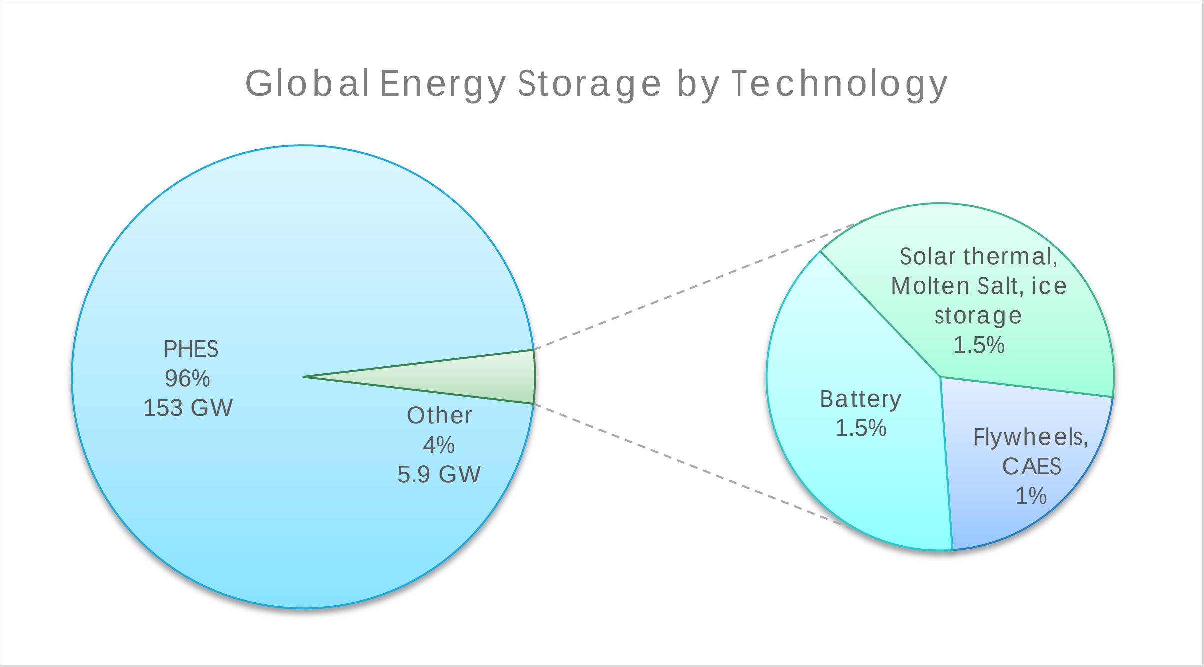


Figure 2: Global energy storage breakdown by technology type

China added 1.5GW in a facility in Liyang and completed 300MW of a 1.2GW plant in Shenzen. China's State Grid Corp have future plans in the provinces of Jilin, Hebei, Shandong and Zhejiang to build additional 6GW facilities by 2026 [5] [4]. This state backed company currently has 19GW or PHES capacity with 30GW under construction [6]. To put this in context, the 49GW total hydro capacity expected by 2026 by State Grid Corp in China is 3GW higher than the total generation capacity of the NEM in Australia. The total NEM capacity for 2018/19 YTD is 46.8GW [7].

In Europe, during 2017 three new PHES plants commenced service. The Veytaux facility in Switzerland added two additional 120MW units which were conventional open loop systems with pumping capability [4]. In Portugal, a 780MW PHES plant in Frades II and a 263MW plant Foz Tua commenced service in 2017 [8]. The units in Frades II were 390MW turbines which are the largest variable speed units in Europe. The Frades II units are able to respond faster to grid disturbances and load changes than conventional fixed speed units [8] [4]. An increasing number of projects in Europe are adopting variable speed turbines to yield better efficiencies over a wider operating range to complement the increased penetration of RET's. A key performance theme that is being observed worldwide is the importance of flexibility in asset owner's generation fleet to meet changing market and grid conditions.

During the developments in Portugal in 2017, there was a severe drought. The drought highlighted the important and unique role that PHES technology and water storage reservoirs play with respect to energy security, affordable electricity prices and long-term water supply. As a result of the drought, the government began to synergise PHES projects with interconnection and expansion of its existing dam and water transfer infrastructure [4].

Although PHES is overwhelmingly the largest and most mature energy storage technology globally, competing technologies have seen significant technological improvements. Electromechanical technologies such as flywheels and compressed air, electrochemical technologies such as batteries and thermal storage such as molten salt or sand and ice storage all have relevance in the application to power generation. The different storage technologies have their relative benefits and challenges. The main factors which contribute to their deployment in practice are development times, life cycle cost and more recently – project or investment risk profile. Figure 3 outlines expected costs for the most common forms of energy storage. Of interesting is to note the relatively lower costs of Compressed Air Energy Storage (CAES) although very low deployment rate globally. There are presently only two grid connected plants in the world; a 290MW plant in Germany and another in USA. Issues with this technology include low round trip efficiency, long planning, environmental constraints and financial project risk. A key challenge for this technology is high operating costs, maturity and lack of projects under development in comparison to other technologies.

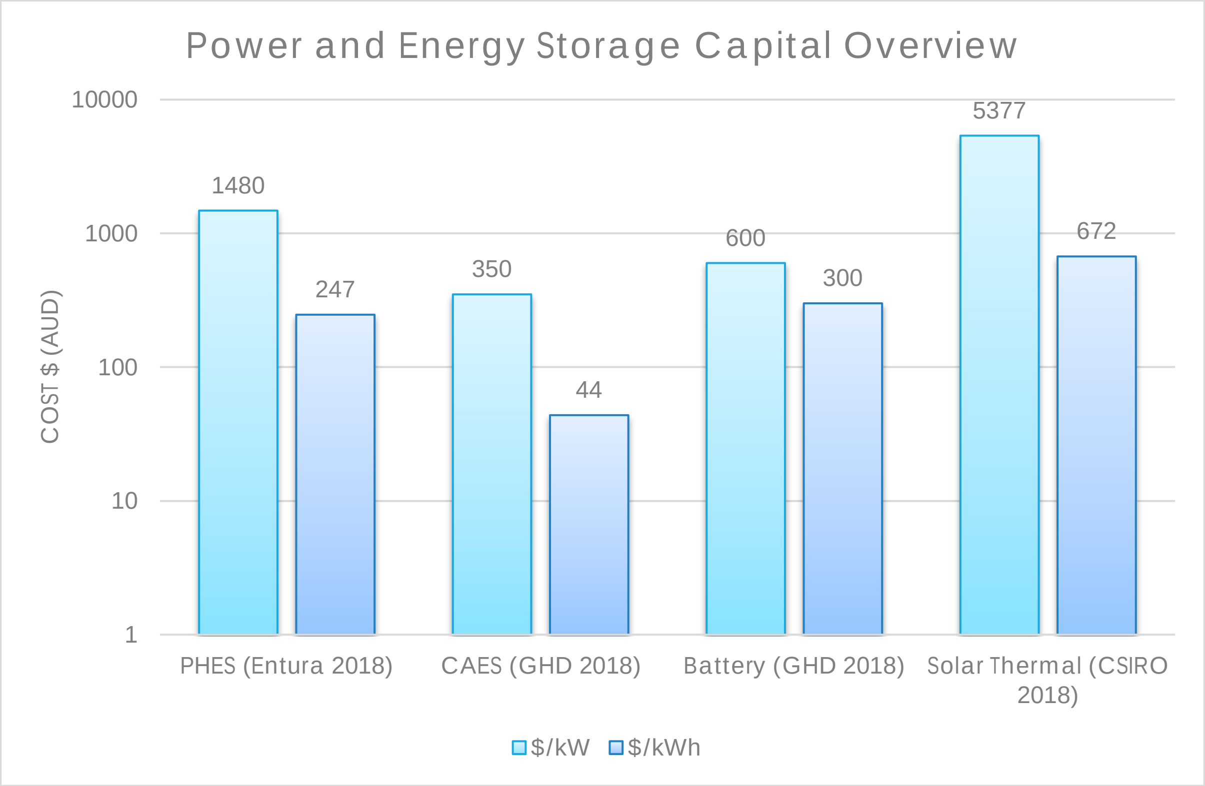


Figure 3: Power and energy storage capital costing overview of the main global storage technologies [9] [10] [11].

PHES schemes are well understood and individual plant items (dams, pipes, and electro-mechanical equipment) have decades of industry experience and local equipment manufacturers. The materials to build a conventional PHES scheme are typically concrete and steel which are all readily available worldwide. The greatest challenge is geographic potential, which is, by the most part, unequally distributed worldwide. Like some countries are blessed with coal and oil, some countries are afforded with an abundance of economical hydro potential. Countries such as Norway, Brazil and Nepal have significant potential while others have very little. Other pressure for PHES development is typically environmental restrictions and investment hesitation due to large capital requirements, long build times and electricity market confidence.

Hybrid PHES systems that incorporate other RET's such as wind for pumping have been studied [12] and proved as economically viable. An example of such a design in Germany is given in Figure 4 of a 16-32MW scheme with a 13.6MW wind farm for (nominally) pumping. The design utilises the ocean as a lower reservoir as it reduces the build requirement to only one upper storage reservoir.

Subsurface reservoirs utilising abandoned mine sites have also been explored [13] [14]. The Kidston PHES facility in North Queensland has been supported by ARENA with a grant of $4M for technical feasibility studies and a further $5M in pre-financial close activities [13]. The development is an integrated solar PHES facility which will utilise two existing gold mining pits as the upper and low reservoir to reduce construction costs.

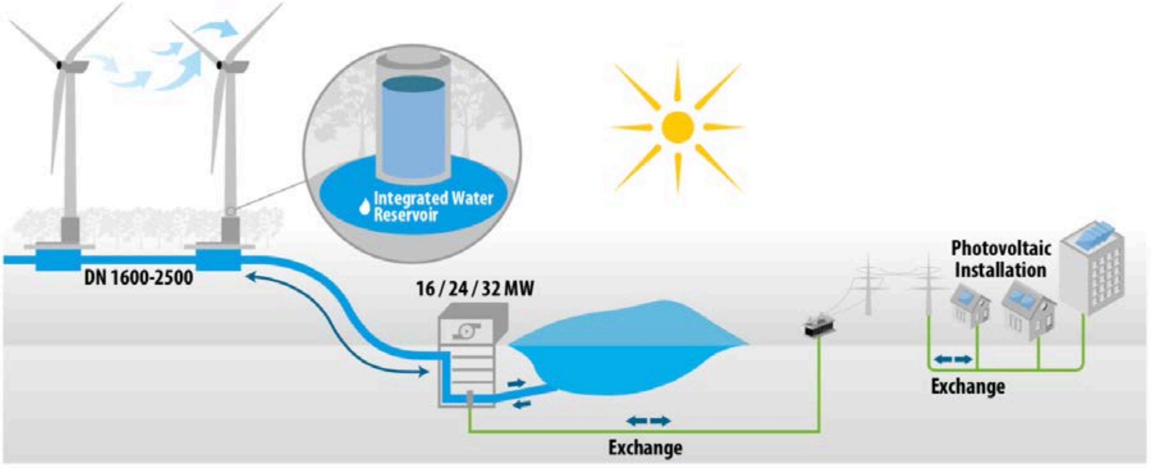


Figure 4: Implemented hybrid windfarm and integrated hydropower project in Germany [12]

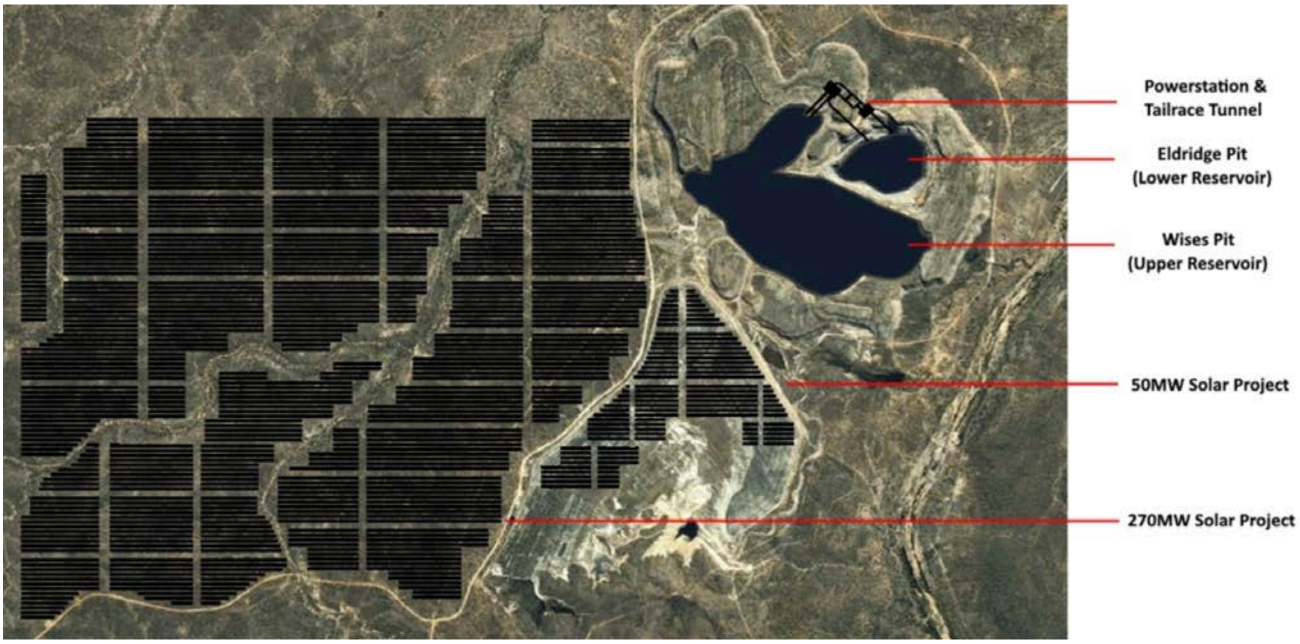


Figure 5: Aerial view of the Kidston 250MW PHES scheme re-purposing existing mine pits as water storage reservoirs. The site also has 330MW of Solar PV generation [14].

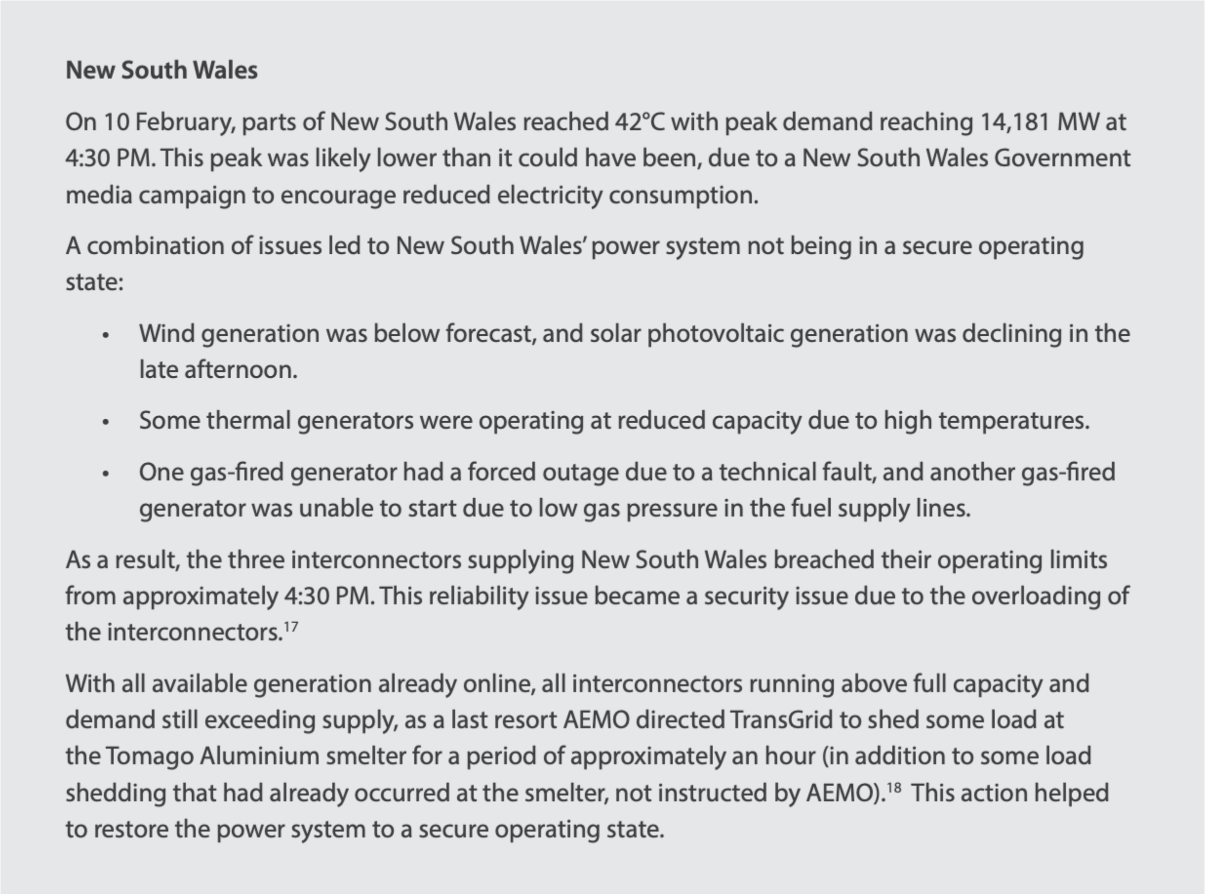
2.3. Relevance of PHES in the NEM and NSW

The NEM is an electricity wholesale spot market consisting of over 300 participating generators across New South Wales, Australian Capital Territory, Queensland, Victoria, South Australia and Tasmania bidding to sell electricity [15]. The market facilitates the exchange of electricity between generator and retailer whereby the generator gets paid for the power they produce, and retailers pay for the power their customers consume. AEMO dispatches generation in five-minute intervals and the price is averaged and settled over 30-minute intervals [16]. In 2021 the pricing settlement is expected to change from 30 minute to 5 minutes intervals [17]. Changes in demand and capacity are main factors which determine the spot price on the market. AEMO schedules generation based on the lowest cost to serve to meet market demand in five-minute intervals. The NEM's transmission and distribution network transfers power between power generation facilities and end users. In NSW, Transgrid operates for the most part the 500kV and 330kV Transmission network. Ausgrid, Endeavour Energy, and Essential Energy operate the distribution network in separate geographic regions across NSW.

NSW has the fastest population growth rate of approximately 106,000 people per annum [18]. It also has the highest population of any state and by virtue has the largest generation installed capacity in the NEM. Unfortunately, due to high fuel costs of its generation portfolio, this makes NSW typically a net importer of electricity across state interconnectors. Closure of thermal stations such as Munmorah (1400MW) and Wallerawang (1240MW) has resulted in a resurgence of maximum demand and one of the highest wholesale electricity prices in Australia [18]. In 2015, AGL released a revised greenhouse gas policy which communicated the closure of Liddell (2000MW) in 2022 [19].

In 2016, energy ministers of the COAG called for an independent review of the NEM. The goal was to take control of future energy security and reliability and provide advice to government to manage the transition.

In February 2017, the Australian Eastern states suffered an extreme heatwave resulting in conditions that led to South Australia and New South Wales operating in an unsecure state in the NEM [20]. AEMO was required to intervene by directing Transmission Network Service Providers (TNSP) to load shed to restore system security. A summary [17] is given below on the NSW sequence of events that unfolded on the 10th of February.



New South Wales

On 10 February, parts of New South Wales reached 42°C with peak demand reaching 14,181 MW at 4:30 PM. This peak was likely lower than it could have been, due to a New South Wales Government media campaign to encourage reduced electricity consumption.

A combination of issues led to New South Wales' power system not being in a secure operating state:

- Wind generation was below forecast, and solar photovoltaic generation was declining in the late afternoon.
- Some thermal generators were operating at reduced capacity due to high temperatures.
- One gas-fired generator had a forced outage due to a technical fault, and another gas-fired generator was unable to start due to low gas pressure in the fuel supply lines.

As a result, the three interconnectors supplying New South Wales breached their operating limits from approximately 4:30 PM. This reliability issue became a security issue due to the overloading of the interconnectors.[17]

With all available generation already online, all interconnectors running above full capacity and demand still exceeding supply, as a last resort AEMO directed TransGrid to shed some load at the Tomago Aluminium smelter for a period of approximately an hour (in addition to some load shedding that had already occurred at the smelter, not instructed by AEMO).[18] This action helped to restore the power system to a secure operating state.

In June 2017, a final report named the "Independent review into the future security of the National Electricity Market: Blueprint for the future" referred to as the *Finkel Review*, was released [17]. It set out the need for four key outcomes. These outcomes specifically; Increased security; Future reliability; Rewarding consumers and lowering emissions. This outcome was to be underpinned by three key pillars. Namely, orderly transition, system planning and stronger governance. The blueprint details how security and reliability of supply has been compromised by poorly integrated solar and wind technologies coupled with the unplanned withdrawal of thermal generating plants.

The Finkel Review explicitly lists ways to increase power system security and future reliability in the NEM.

System security is a function of various technical parameters including frequency stability, voltage stability, fault levels and operating plant within its nominal design envelope. Ways to increase system security consist of:

- Obligations on new generator connections to provide essential system security services that aid fast frequency response and system strength. This practically means greater physical inertia and higher short circuit ratios imposed and enforced upon new grid connections.
- More conservative market operation in each NEM region by maintaining minimum system inertia levels and more stringent frequency control permitting time for frequency control mechanisms to respond, ride through generator forced outages and interconnector faults.

System reliability is primarily centred around having sufficient generation supply and transmission capacity to match demand throughout all times of the year. Ways to increase future system reliability consist of:

- Obligations on new generator connections to ensure adequate dispatchability of supply throughout all NEM regions. This can practically be achieved by diversification of electricity supply namely synergy through conventional and RET partnership.
- Incentivising the development of new dispatchable, emerging technologies to enter the NEM with promotion of distributed generation sources rather than centrally dispatched.

Dispatchable, utility scale PHES and batteries in strategic locations about the NEM are expected to be key enabling technologies. This is required to achieve future security and reliability whilst promoting competition in the NEM. Competition in the NEM places downward pressure on wholesale electricity prices and increases energy affordability.

WaterNSW, a state-owned Corporation, who operates over 40 dams across NSW and supplies approximately two thirds of the state's water to regional towns, irrigators, Sydney Water Corporation and local water utilities [21]. WaterNSW is NSW's bulk water supplier and river operator. In 2018, WaterNSW released and Expression of Interest on 38 of its water assets to investigate opportunity for private investment to develop its existing dam infrastructure for the purpose of power generation [3]. The government supports [3] developments on WaterNSW assets to support a more secure, reliable and affordable energy mix.

2.4. How can PHES provide value?

Ancillary Services are expected to become more highly valued in future energy markets and any new proposed Hydro Unit will need to be designed to maximize opportunities for Ancillary Services revenue and improve power system security in the deployed region.

PHES systems by design are based on well-established synchronous, rotating machine technology. Synchronous machines have a long history, and relevant future, to continue to provide critical ancillary services to the grid. It achieves this through provision of inertia, frequency, voltage, and fault level support.

1. Inertia – Synchronous Hydro Units have a turbine connected to a motor/generator the same as conventional thermal (coal and gas) units and provide inertia in both generating, pumping and synchronous condenser modes. This provides frequency support to reduce the rate of change of frequency during grid disturbances, such as large load step changes for example from intermittent renewable penetration or transmission line contingency events.

2. Spinning reserve – Hydro Units can provide rapid power response to changes in demand with change from 0-100% power possible in approximately 1min with the newly procured units and typically less than 90 seconds with the existing older generation PHES Units. Asynchronous units can also provide this support when pumping. Such response times are very well suited to the variations in power from inverter fed renewable technologies such as wind or PV systems, rapid changes in demand and meeting peak load demands.

3. System strength – The power system must maintain a minimum Short Circuit Ratio (SCR) to maintain effective and coordinated protection systems. The SCR is used to quantify the system strength (voltage stiffness) at a generator point of connection and is used to understand any reliability implications and to evaluate risk pertaining to high penetration levels of inverter fed technologies. The future power system must maintain minimum fault levels in order to assure the protection system can control and maintain the system within its design envelope. As hydro units are rotating synchronous machines or induction machines, they are a major source of short circuit contribution in the NEM. This will likely be valued in future markets. A drop in node SCR as a result of a new market participate may evoke "causer pays" type payment approach in the future NEM [17]. Once payments are enforced for reduced SCR it is likely there will be opportunities for short circuit current provision at that node to maintain SCR performance requirements of the NER. This performance requirement will be challenging for inverter fed generation technology owners to maintain in particular on consideration of impending retirements of existing conventional thermal generators which may be located nearby to a previously approved RET connection point. The AEMC's approach to this is to modify the NER to ensure newly connected generators "meet all their performance standards at the minimum short circuit ratio expected at their location in the future" [17].

4. Voltage Control Ancillary Services (VCAS) - When Hydro Units are not pumping or generating, they can be dewatered and able to operate in synchronous condenser mode for voltage or reactive power support. This increases power system security via inertia and reactive power support. Presently in the NSW south region there has been discontinued long standing reactive power support contracts with other Hydro Generators in the area. This has created network issues in the form of excess voltage levels on Lines 18 Dapto to Kangaroo Valley and 3W Capitol to Kangaroo Valley. The excess voltages occur at times of low demand in both Victoria and NSW (usually in the

early mornings), and during low interconnector flows from Victoria to NSW. Loss of these Reactive Support Contracts has resulted in the introduction of Special Protection Schemes (SPS) which isolate multiple lines under certain contingencies and redirect power flow. The impacts of such a scheme (as opposed to Voltage support from synchronous machines) increases system losses, increases the likelihood of system failure due to having one less transmission line, increased loading in other lines and an overall weaker transmission network. PHES has the ability to provide significant Reactive Power Support to the local node increasing power system security and reliability of supply to the area. It also has the capability to change quickly between generator, pump and synchronous condenser mode.

5. System Restart Ancillary Services (SRAS) – Hydro Units can provide black start capabilities requiring very little external power support. As hydro plants have minimal auxiliary plant and use water and gravity as a fuel source, the only requirements are for basic control and protection auxiliary power. It is the intention for any new hydro installation to also be able to restore the system locally through use of a procured small (~250kVA) diesel generators and/or small battery systems.

6. Frequency Control Ancillary Services (FCAS) – There are currently eight separate real-time spot markets in the NEM. Two are for the delivery of regulation (raise and lower), and six are for the delivery of contingency services (raise and lower for 6 second, 60 second and 5 minute response times). Any of these services can be provided by any generator or large interruptible load (eg. Hydro Pump) appropriately registered with AEMO and may be spinning (currently operating) or non-spinning, as long as they can deliver the service to the prescribed standard. The 6 second and 60 second contingency services are usually operated by governor response (or load shedding), triggered by system frequency (measured locally) moving outside of the normal operating band. Any new Hydro Unit must utilize an Electronic governor which fulfils

and surpasses all FCAS and furthermore IEC requirements in speed, load regulation and responses. Generally, the hydro turbine design should allow for a 10% power raise and lower capability for the FCAS fast 6 and slow 60 second markets, and an additional 5% for the delayed 5 minute market. Subject to specific machine requirements, it may be feasible to achieve higher outputs. Any proposed new PHES unit must be designed with the capability to participate in all FCAS markets to ensure maximum value is generated from the asset.

7. Ramp Rates - Hydro Units typically have ramp rates of in the order of 100 – 200 MW/min and ramp up and ramp down times of 30 - 90 seconds. This is above the minimum ramp rate required by AEMO in NSW of 3MW/min. The new PHES units are proposed to have similar capability and exceed the minimum requirements.

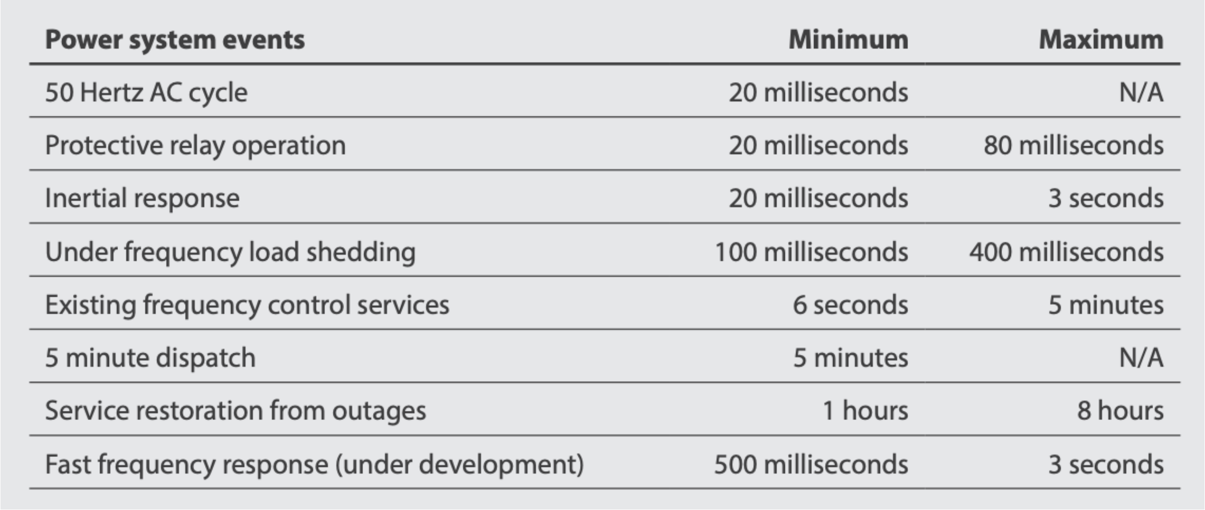
8. Hydro Units can help maintain regional stability as well as help to reduce the cost of interconnection between the states to manage variable generation and demand. Due to their design, they also aid to maintain transient and oscillatory stability within the power system following major power system events.

9. Peak shaving – PHES are able to reduce the peak off wholesale electricity prices due to its on demand capability given the system is charged (upper reservoir full). This reduces stresses on power infrastructure and promotes economy of operation of the NEM.

10. Fast Frequency Response (FFR) – Future versions of the NER may likely require new generators to have FFR capability in order to increase power system security. The Finkel Reviews states “A future move towards a market-based mechanism for procuring fast frequency response should only occur if there is a demonstrated benefit” [17]. This future market would at first aim for non-synchronous machines (utility scale solar, wind

and battery technologies) to have capability to provide FFR services. PHES may be able to provide synergy with this requirement by providing physical inertia instead, at inverter fed plants.

Turbine, generator, governor and excitation control systems must be procured to suit the functional requirements of the scheme. This includes the ability to provide power system Ancillary Services to embed the flexibility of the site to maximize future revenue streams. Box 1 outlines the time response required of the plant to support the different power system events. In summation, the value of fully dispatchable renewable generation from hydropower can play a significant role in supporting a diverse generation mix in NSW.



Power system events	Minimum	Maximum
50 Hertz AC cycle	20 milliseconds	N/A
Protective relay operation	20 milliseconds	80 milliseconds
Inertial response	20 milliseconds	3 seconds
Under frequency load shedding	100 milliseconds	400 milliseconds
Existing frequency control services	6 seconds	5 minutes
5 minute dispatch	5 minutes	N/A
Service restoration from outages	1 hours	8 hours
Fast frequency response (under development)	500 milliseconds	3 seconds

Box 1: Overview of the different time responses required for various power system events [17]

2.5. Development Context

Both globally and in Australia, power systems are undergoing rapid transformation as generation portfolios diversify to extend beyond traditional thermal technologies. Immergence of new innovative generation systems and new user technologies are changing the way we generate, transform and consume electricity. NSW has not seen any significant electricity structure change since before the 1980's when the bulk of the coal fired power stations were constructed by the Electricity Commission of NSW (ECNSW) and the Snowy Mountains Hydro Scheme was built. The conventional energy supply system has quickly transitioned into a dynamic model with new energy inputs, feedback mechanisms and a range of new stakeholders and energy markets. The interactions of conventional and modern energy systems are contrasted in Figure 6.

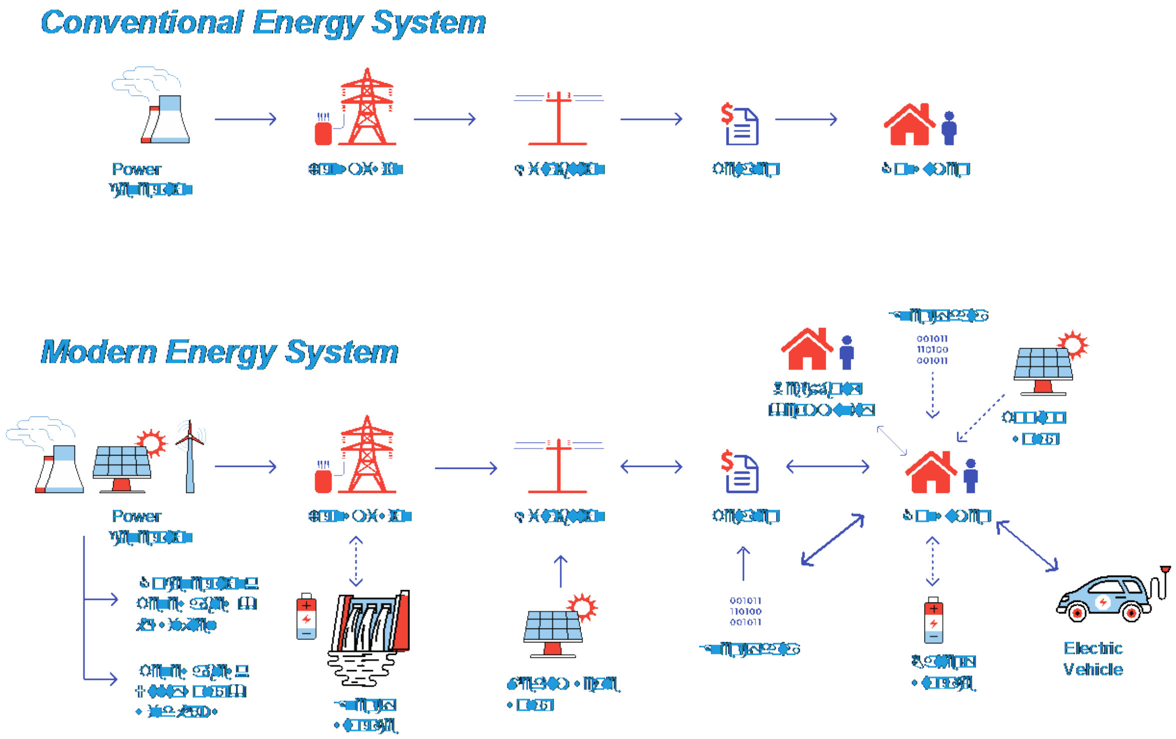


Figure 6: The linear relationship of a conventional energy system compared to the modern, dynamic system showing increased connectivity and interactions. Concept adapted from [3].

NSW has two large scale PHES schemes: Tumut 3 part of the Snowy Hydro Scheme and the Shoalhaven Scheme (Kangaroo Valley and Bendeela). There is also one additional PHES scheme in Australia located at Wivenhoe, Queensland. Currently Australia has 1410MW of significant pumped hydro capacity [22]. Table 1 overviews the current PHES sites in operation in Australia including their relevant capabilities.

There are currently six Arena funded feasibility and market studies. These are presented in Table 2.

Power Station	Year	Capacity (MW)	Units	NEM Gen (MW)	NEM Pump (MW)	Storage (GWh)
Wivenhoe (QLD)	1984	570	2 x 285MW	624	490	5
Shoalhaven (NSW)	1977	240	2 x 80MW (KV), 2 x 40MW (BN)	240	240	4.7
Tumut 3 (NSW)	1973	600	3 x 200MW	900	600	15

Table 1: Large scale PHES schemes currently in operation in Australia [23] [24]

Development Name	Owner	Capacity (MW)	Development Stage
Cultana (SA)	Energy Australia	225	Expected 2021
Kidston (QLD)	Genex	250	Expected 2021
Battery of the Nation (TAS)	Hydro Tas	250	Pre-feasibility
Iron Duchass North (SA)	One Steel	90	Pre-feasibility
Snowy 2.0 (NSW)	Snowy Hydro	2000	Feasibility
Shoalhaven Expansion (NSW)	Origin Energy	235	Feasibility

Table 2: Listing of current ARENA funded PHES feasibility and market studies in Australia

PHES projects funded by the private sector are subject to the following barriers:

1. PHES are capital intensive, have long development lead times, high engineering costs, construction costs and complex approval processes. These combined add to a perceived high investment risk and actual project (time and cost) risk.
2. Low market confidence due to political instability and lack of long-term commitment to energy policy
3. Lack of local knowledge and construction expertise as hydro projects have not been developed for almost 40 years in Australia.
4. Site selection, land access, environmental impacts and offsets are highly complex
5. Direct competition with Solar, Wind, Battery and Open Cycle Gas Turbine projects
6. Subject to long term investment and long payback periods

Future PHES development and expansion is supported by the Finkel Review, the NSW Energy Security task force Final Report [25] and the AEMO Integrated System Plan (ISP) [26]. It is currently an excellent time to invest in the development of innovating PHES technologies in NSW if the previous mentioned risks can be managed. The NSW Government states *"The government is working to support the next generation of pumped hydro projects by inviting energy and storage proposals that make use of the state's water infrastructure to support a more secure, affordable and reliable energy mix"* [27].

2.6. Cost overview

Prior to exploring the costs of developing potential PHES systems, it is first interesting to review the history around the development of the Snowy Mountains Hydro Scheme to establish context and appreciate its immensity. The scheme began construction in 1949 and comprises of 16 major dams, seven power stations and two pumping stations. Key statistics [28] [29] of note include:

- 25 years construction time
- Over 100,000 (two-thirds) immigrant labour force from over 30 countries
- 225km of tunnels and pipelines developed
- 1,600km of roads were constructed
- 220km of 330kV transmission infrastructure
- 7 townships were built and over 100 temporary camps
- 2% of the construction works are visible above ground
- Entire scheme (over 5000 square kilometres) developed almost entirely in Kosciuszko National Park
- Death toll of workers during construction was 121
- Total project cost of A$820 million in 1974 dollars

In terms of estimating the cost of building the Snowy Scheme in today's dollars, it can offer insight by reflecting on the expected cost of constructing the Snowy 2.0 expansion project. This project utilises existing water infrastructure assets but adds 27km of new tunnels and includes the construction of an 800m underground power station. The cost of this project is estimated at $4.5 billion and due online 2024/25 [30]. The only commentary offered is that the original Snowy Mountains Scheme civil construction and excavation works was completed at an order of magnitude larger scale and at an order of magnitude less cost than Snowy 2.0 when reviewed in a present-day feasibility context.

Its relevant to note that the Snowy Scheme was constructed as a result of decisive, post-war, financial and political commitment of the Commonwealth Government.

Almost 50 years on, Australia is once again planning significant Hydro Power development. Table 3 outlines large scale PHES projects and their expected capital costs. In terms of water reservoir construction - Snowy 2.0 utilises existing Scheme dams Tantangara and Talbingo, Shoalhaven expansion utilises the existing Bendeela pondage and Talowa Dam, Kidston is re-purposing two mine sites, Oven Mountain is developing two naturally occurring granite basins and finally Cultana is building a new turkeys nest type dam in combination with the sea.

PHES Project	Power (MW)	Storage (hrs)	Capital Cost ($M)	Energy Cost ($/kWh)
Snowy 2.0	2000	175	4500	13
Shoalhaven Expansion	235	6	300	213
Kidston	330	8	282	107
Oven Mountain	600	6	1000	278
Cultana	225	8	477	265

Table 3: Outline of large scale PHES projects detailing their power, storage capacities and expected capital costs [31] [32] [33] [34] [35].

From an international context, the costs in the literature vary quite significantly in range. Five separate studies are compared with the upcoming Australian projects. These are shown in Table 4 and Table 5. Reasons why the Australian projects are at the lower end of the capital costing range in both power and also stored energy is the necessary exploitation of existing infrastructure to realise value. Competition from other generating technologies alongside private sector optimisation has forced these lower than typical figures to maintain relevance. As these projects are not built yet, it is possible the costs may exceed the budgeted costs. This is not uncommon in large-scale hydro projects.

Of equal importance to capital costs are the levelized costs that consider the total life cycle of the installation. Projects that have high operating, maintenance and fuel costs may not be sustainable over the long term. The advantage of Hydro power is the absence of a consumable fossil fuel source coupled with a long expected useful life.

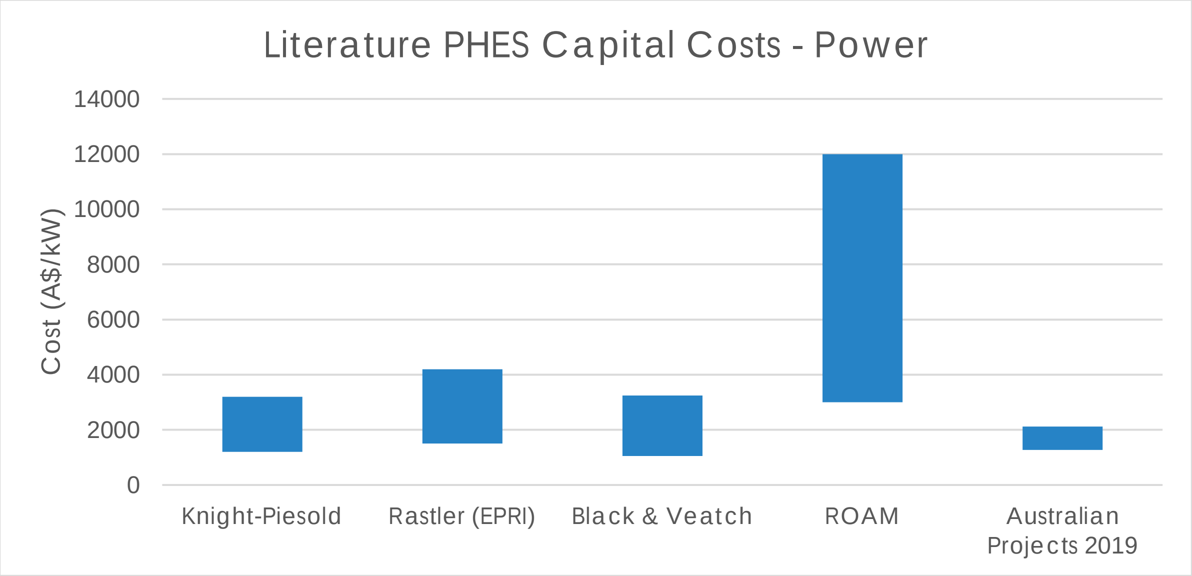


Table 4: Literature PHES power capital cost comparison against the upcoming Australian 2019 proposed projects [36] [37] [38].

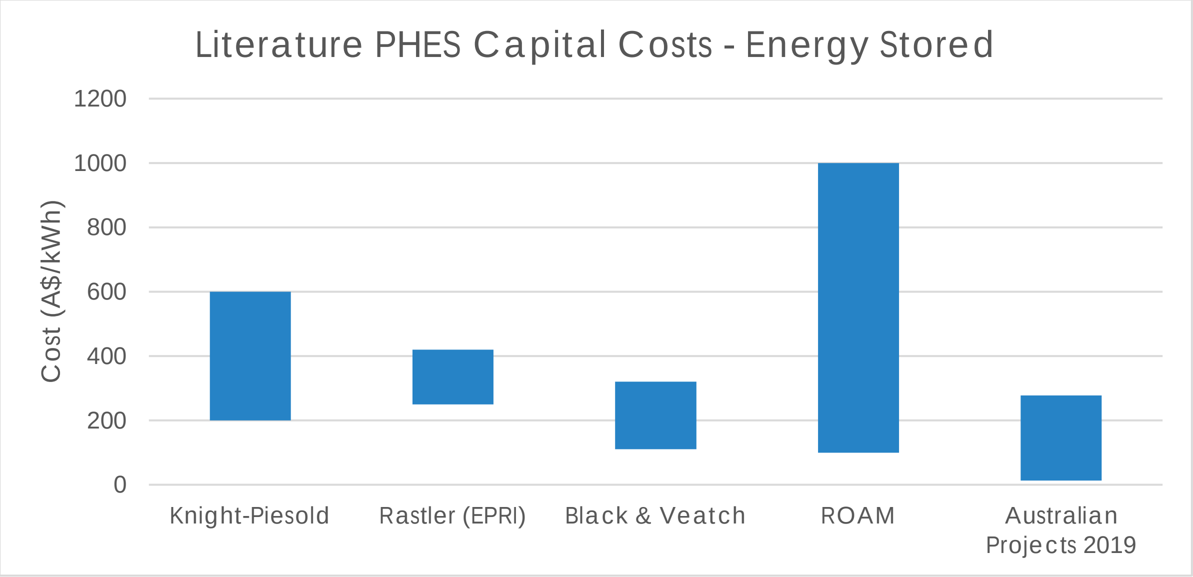


Table 5: Literature PHES energy stored capital cost comparison against the upcoming Australian 2019 proposed projects [36] [37] [38].

The CSIRO performed an energy storage cost prediction study in 2012 to support AEMO’s modelling of 100% Renewable Energy forecast scenarios. The study estimated the LCOE of different energy storage technologies and projected them to the year 2030 [39]. The results from the CSIRO cost projections are adapted to 2019 dollars and presented in Figure 7.

The LCOE values for conventional large scale PHES are projected to be $154 - $169/MWh for storage times of 2.4 - 25.7 hours respectively for year 2030 [10]. The projections indicate it is a more economically competitive method to store energy in comparison to lithium ion and advanced lead acid battery technology. It is noted however that batteries have a key performance advantage at shorter discharge cycles over PHES. Solar thermal with molten salt technology is predicted to be more cost efficient than PHES by 2030 with biomass and biogas being the least cost option for longer term storage in the order of months. It is noted all these options have their associated barriers which can limit their roll out in practice.

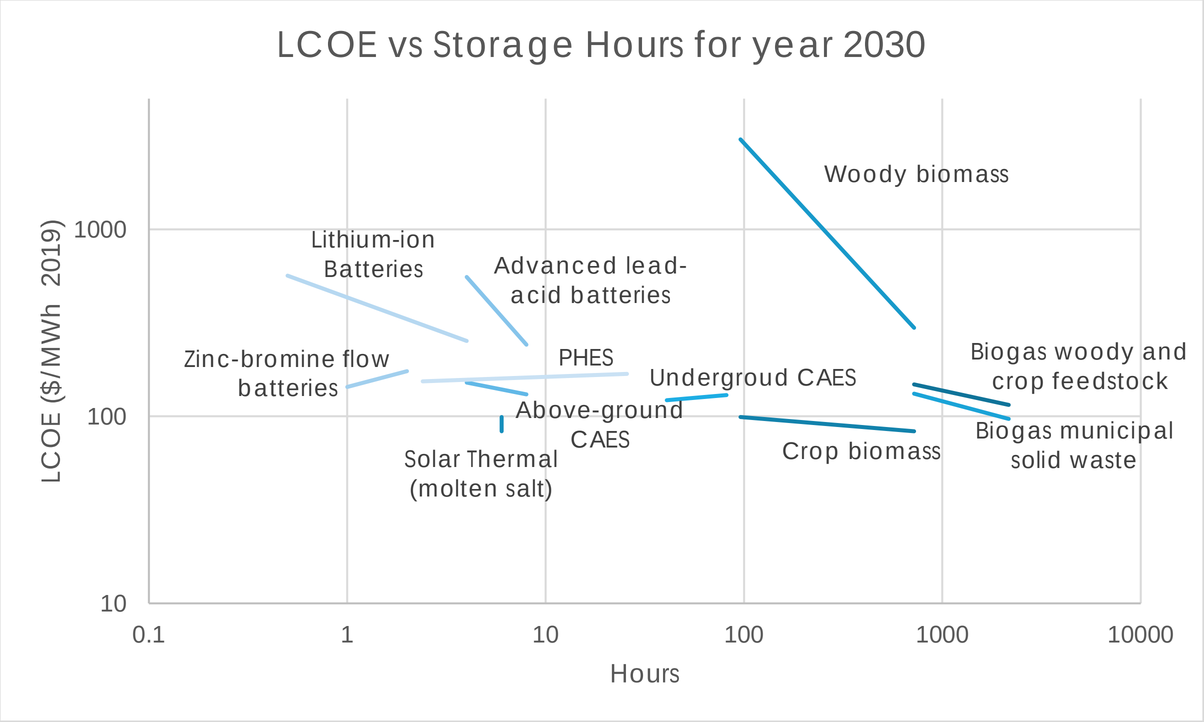


Figure 7: CSIRO modelling of LCOE vs energy storage hours projected to the year 2030. Adapted from [39].

2.7. Relevant Legislation

PHES developments in NSW are governed by both state and federal law. Other regulations such as Environmental Planning Instruments (EPI's) also must be considered [40]. EPI's reference Local Environmental Plans (LEP's) and State Environmental Planning Policies (SEPP's) which is the process by which State and Local Government can manage any proposed development to standard [41].

Below summarises a list of the key legislation which are likely to be considered during project feasibility stage.

- Environmental Planning and Assessment Act 1979 No 203
- Native Title Act 1993
- Aboriginal Land Rights Act 1983 No 42
- Crown Land Management Act 2016 No 58
- Water Management Act 2000 No 92
- Water Act 1912 No 44
- Water Act 2007
- Basin Plan 2012
- Biodiversity Conservation Act 2016 No 63
- Environment Protection and Biodiversity Conservation Act 1999
- Fisheries Management Act 1994 No 38
- Dams Safety Act 1978 No 96
- Protection of the Environment Operations Act 1997 No 156

- National Parks and Wildlife Act 1974 No 80
- Heritage Act 1977 No 136

2.8. Planning

Private proponents of large-scale pumped hydro projects will generally need to obtain development consent under Part 4 of the EP&A Act through the State Significant Development (SSD) assessment process. Projects subject to the SSD assessment pathway are assessed by the Department and approved by either the Department or the Independent Planning Commission [40].

In NSW the key legislation that regulates land use planning is the *Environmental Planning and Assessment Act 1979* (EP&A Act) and the *Environmental Planning and Assessment Regulation 2000* (EP&A Regulation).

When proposing to develop greenfield or brownfield large-scale hydro projects, the following are essential considerations emerging from the EP&A Act [42]:

- Who is responsible for the development and planning approvals?
- Is the proponent a private company or public authority?
- Who will own, operate and maintain the project?
- Where is the project location and what is the history of that site?
- Does the proponent already have access to the land?
- Is access to other land required for items such as transmission lines, penstocks, access roads etc.?
- What is the design of the plant?

- What construction methods will be adopted?
- What are the development stages and life cycle stages?
- What is the proposed planning, development and assessment pathway that should be followed?

These factors influence critical considerations including whether the project is permissible with or without consent and the specific planning pathway that the project must follow.

2.9. Land and Water Access

Securing land access can be a challenge in particular for PHES developments due to their proximity to large water bodies resulting often in high value or government owned land. If the land is privately owned, access can be obtained by private treaty with the land owner. Additional complexities and cost can be expected when the development site is located in a national park, on crown land, a disused mining site or land owned by WaterNSW, the Forestry Corporation of NSW or the Commonwealth [40].

Much like thermal plants need coal or gas for fuel, PHES sites utilise large volumes of water to generate electricity. The water required initially to fill reservoir and penstock is often large and there is an additional small make up requirement to account for any losses due to evaporation and any leaks. A Water Access Licence (WAL) is required to take water from a water source [43]. A water broker can be used to facilitate this [40]. If large infrastructure is to be installed at a water source, additional licencing may be required.

3. Concept Design

3.1. Basis of Design

Design target:

- Expandable
- Deployable
- Design life at least 20 years
- Economically competitive with Solar and Wind installations
- Well known life cycle costs
- Well established project risk profile

Specifically:

- Modular design
- Minimise capital and operational costs whilst maintaining safety
- Minimise legislative and regulatory licencing, compliance and approval requirements
- Minimise rock excavation and all geotechnical works
- Minimise site footprint (land area)
- Minimise project delivery time
- Minimise on site work and maximise usage of pre-built components
- Minimise impact to environment
- Minimise technical complexity for asset owner
- Minimise water usage

- Maximise opportunity to integrate with other RETs
- Maximise traditional landowner and community engagement
- Maximise stakeholder awareness
- Institutional framework and administrative procedures to attain efficient authorisations
- Solution to maximise financing potential
- Equipment selection to maximise alternate revenue streams such as Ancillary Services and also future markets
- Site selection – Proximity to established sub-transmission infrastructure (nominally 11, 33 or 66kV)
- Usage of optimal reservoir storage size
- Design to maximise the number of available hydropower potential Sites in terms of net effective head (geographic elevation differences)

3.2. Technical Base

3.2.1. Classification of Small Hydropower

The size of a small hydro plant is approximately 10MW or less across the literature although many countries define schemes differently. In Spain, Ireland, Greece and Belgium they define 10MW as an upper limit for installed capacity whereas in Italy it is 3MW [44]. France was set at 8MW and the UK 5MW. Albeit an arbitrary figure generally speaking, in Australia the Clean Energy Councils defines Large Scale Generation as above 5MW [45]. Furthermore, AEMO dictate considerably reduced network performance standards for installations < 5MW [46]. Classification in a market sense, is thus an important item for consideration when developing a business model.

A system between 30kW – 5MW is classified as small-medium embedded generation and has a significantly simplified grid connection process as dictated by the NER [47]. Exemptions can apply also for systems under 30MW with annual exports below 20GWh [48]. Lastly a generator with an aggregated capacity of approximately 30MW can be classified by AEMO as scheduled, non-scheduled or semi-scheduled giving the asset owner flexibility to align with a particular market classification which can maximise their investment.

For the purpose of this modular PHES conceptual design, the target single unit power size, P, is proposed to be in the range 1MW < P < 5MW. For aggregated units at a single location (connection point), initially the plant size should be limited to < 30MW. Energy exports per site are to be limited to 20GWh per annum, initially.

3.2.2. Head

The power of a hydro scheme is proportional to flow and head. A scheme can be classified into three categories according to its available head [44] [49] [50]. Specifically:

- High head: > 100m
- Medium head: 30 – 100m;
- Low head: < 30m

These groupings are given mostly to categorise sites. Figure 8 shows graphically the definitions of hydraulic head. To maximise potential Site opportunities and power output capability, a design target is selected to build a high head scheme. That is, a plant with a net or effective head of at least 100m.

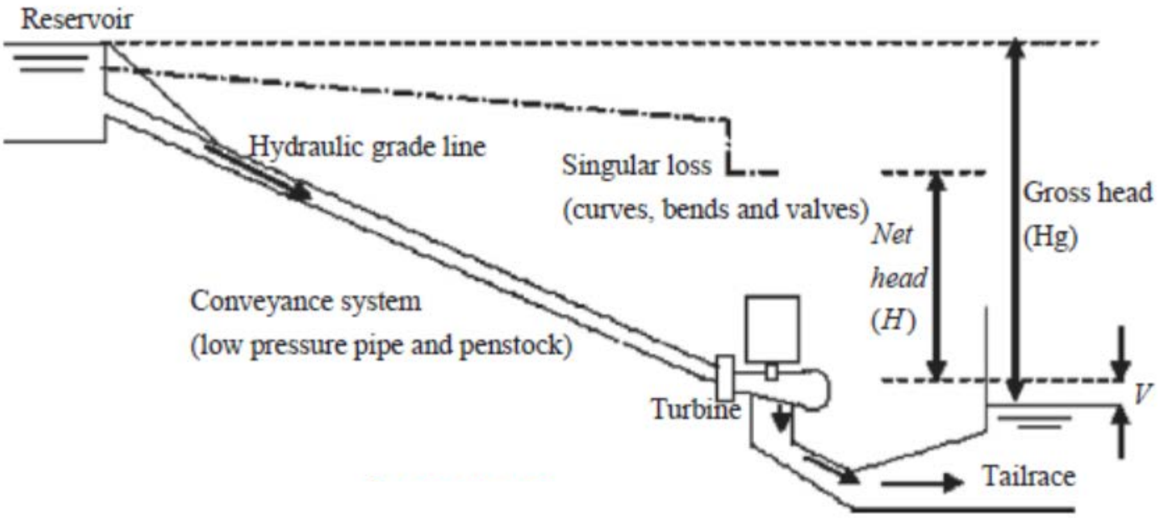


Figure 8: Definition of hydraulic head showing gross head and net head [44].

3.2.3. Hydraulic Power and Energy

The relationship between water pressure and mechanical power is the fundamental base for operation of a PHES system. The mechanical power of the turbine is used to drive an electrical AC generator. Head pressure and volumetric flow are the two principal design components of the generated power. The relationships between hydraulic power and energy are given in Equations 1 & 2 [50]:

$$P_0 = n\rho QgH \qquad \text{Equation 1}$$

$$E_0 = n\rho QgH\Delta t \qquad \text{Equation 2}$$

Where P_0 (Watts) and E_0 (Watt-hours) over a time interval Δt (hours) is the hydraulic power and corresponding energy respectively. Effective pressure head and volumetric flow rate are given, H (m) and Q (m^3/s), respectively. Water density and acceleration due to gravity are ρ (kg/m^3) and g (m/s^2), respectively.

The overall system efficiency [50] of a PHES scheme is considered as the ratio of the output power to the input power. The overall efficiency takes into consideration hydraulic (runner/waterway), mechanical (turbine/runner) and electrical (generator, cables, transformer) efficiency.

$$n = \frac{P_{out}}{P_{in}}$$

$$n_h = \frac{P_{runner}}{P_{waterway}}$$

$$n_m = \frac{P_{shaft}}{P_{runner}}$$

$$n_e = n_{generator} \times n_{cables} \times n_{transformer}$$

Considering n as the overall efficiency of the system, the total power and energy is:

$$n = n_h \times n_m \times n_e \qquad \text{Equation 3}$$

$$P = nP_0 \qquad \text{Equation 4}$$

$$E = nE_0 \qquad \text{Equation 5}$$

Hydropower is one of the most efficient technologies to generate electricity. Modern hydro turbines convert approximately 90% of the available energy into electricity while the efficiency of the best fossil fuel plants is approximately 50% [51].

Small modern hydro systems above 500kW have a typical energy conversion efficiency of 90% [50]. For design purposes, an overall efficiency of 90% is to be assumed.

3.2.4. Pump and Turbine Configuration

Hydropower is a technically mature and well-established technology. The electromechanical components of a PHES system are virtually the same as a conventional hydropower system. The principle differences lie in the pump-turbine and electrical machine designs.

PHES designs comprise of three main solutions to facilitate a pumping and turbine operational set in the one installation. These configurations [50] [52]are:

- Binary set: one pump-turbine and one motor-generator
- Ternary set: one pump, one turbine, and one motor-generator
- Quaternary set: one pump, motor, turbine and generator

Binary sets are the most typical configuration in most modern deployed PHES systems. They consist of a single reversible pump-turbine coupled to a single motor-generator. The rotation of the shaft is opposite when either in pumping or generating mode meaning that its slower in changing modes as compared to a ternary or quaternary unit. During pump start-up, the pump-turbine runner needs to be dewatered with the motor bringing the pump to speed and in synchronism with the external grid prior to pumping water.

Ternary sets have the pump, turbine and motor-generator on a single shaft and always rotate in the same direction regardless of pumping or generator mode. The pump is connected to the shaft via clutch. An advantage of this configuration is that each turbine and pump can be designed for optimum performance. This design was popular in the 1920 – 1960’s [53].

Quaternary sets are the most common type of design pre-1920's. The configuration consists of two separate sets whereby the pump is driven by a dedicated motor and the turbine drives a generator. The advantage of the design is its high efficiency and ability to design the pump and turbine to optimise the individual decoupled sets performance. In large scale projects, quaternary sets are cost prohibitive due to the inclusion of additional large plant items creating inefficiency.

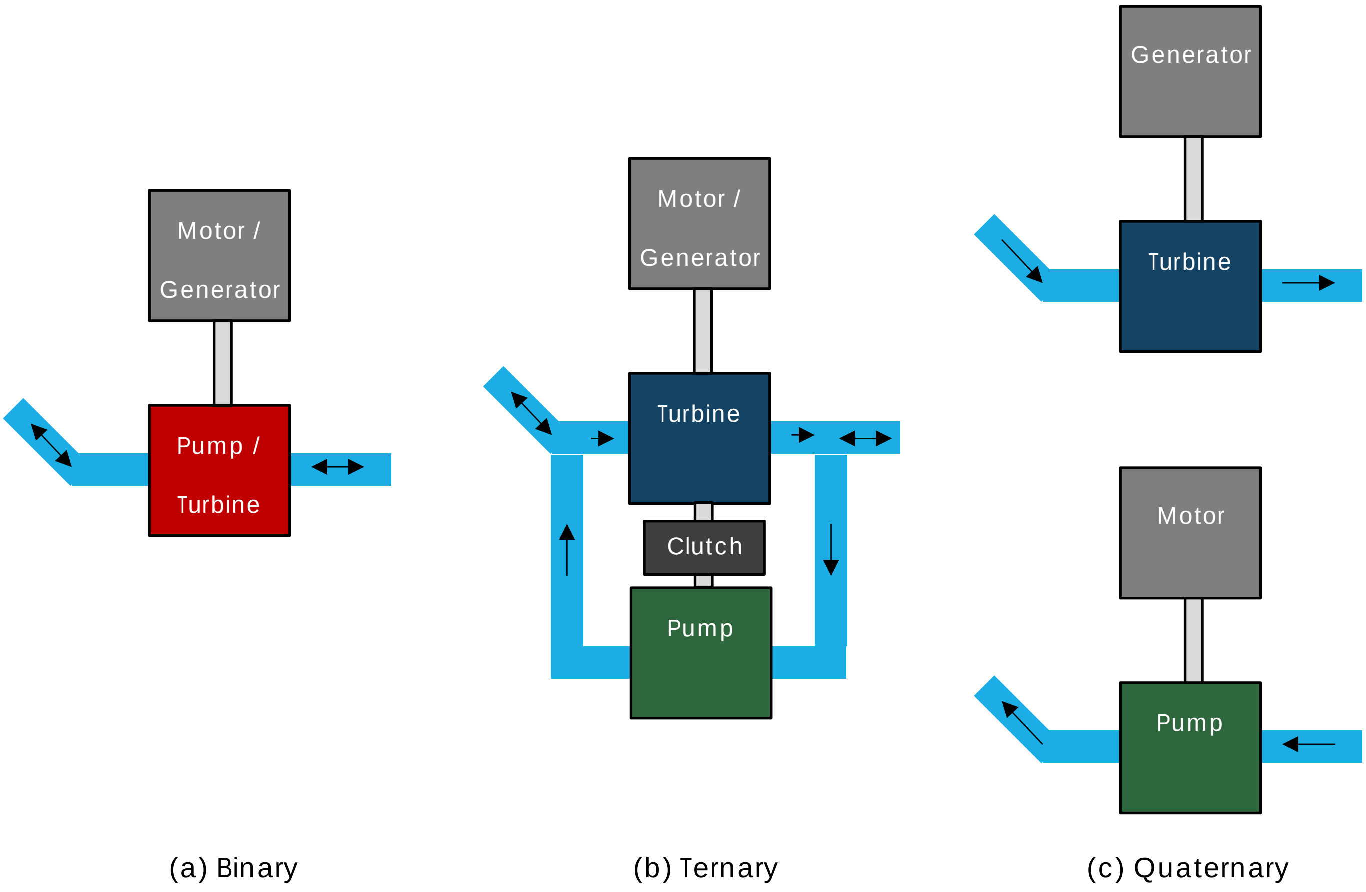


Figure 9: The three fundamental solutions to turbine and pumping mode PHES operation - Binary set, Ternary set and Quaternary set configuration.

3.2.5. Turbine

Pelton, Francis and Kaplan are the most commonly used hydraulic turbines. The force producing mechanism in Pelton is impulse and in Kaplan it is reaction. The Francis turbine uses a combination of impulse and reactive forces.

In the Pelton turbine pure impulse force from tangential water jets turns the shaft causing the impeller to rotate. Water needs to be stored at high altitudes, which result in high velocities making the Pelton turbine ideally suited when water energy is available at high heads and low flow rate. Standardised solutions are available up to 700m head,10MW in size with flow rates below approximately 5m^3/s [49].

The Kaplan turbine is virtually the opposite in design. A high axial water flow rate produces efficient production of a reaction force. When water is available at high flow rates and low head, a Kaplan turbine is the ideal choice. Standardised solutions are available up to 35m head and approximately 10MW [49].

The Francis turbine is a flexible choice and fits in the range between Pelton and Kaplan. Medium head and medium flow rate application. Francis turbines uses impulse and reaction force. Horizontal and vertical shaft systems are available with standardised design covering up to 250m and 18MW [49]. The Francis turbine is generally found to be the most popular hydraulic turbine in industry [54].

An overview of turbine design type and associated head and discharge flow is presented in Figure 10.

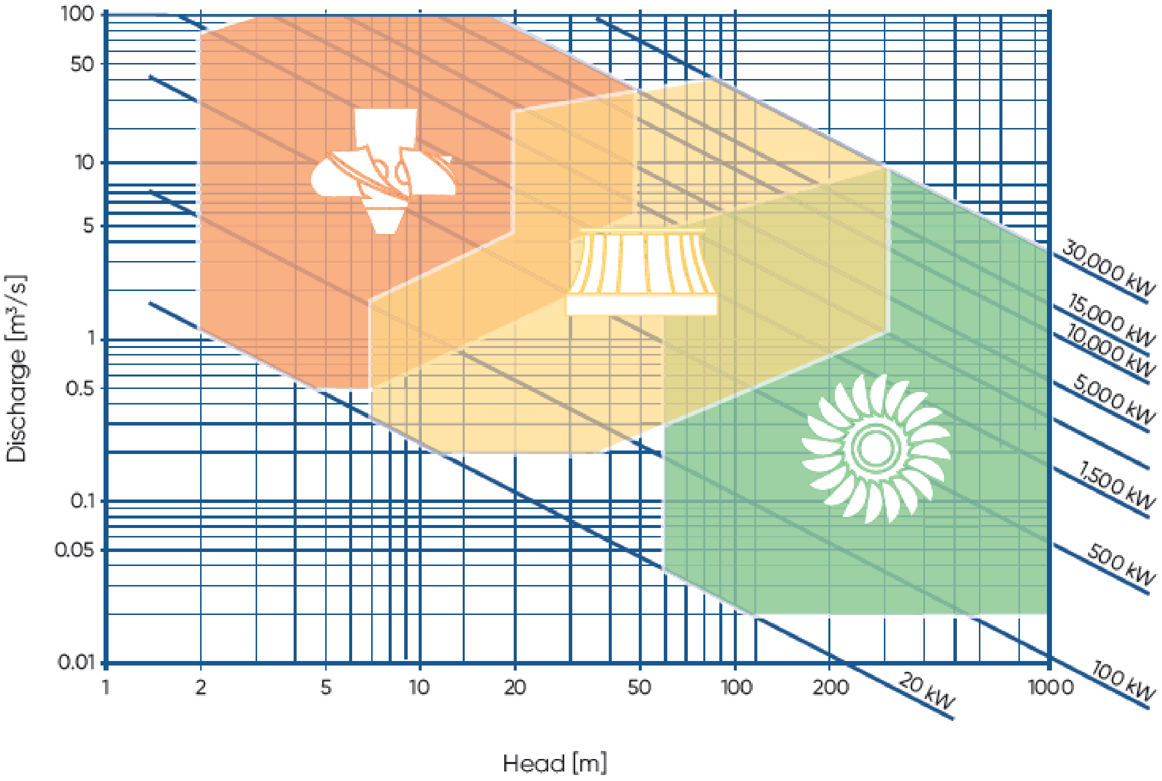


Figure 10: Small hydro power turbine design characteristics. From left to right, Kaplan (orange), Francis (yellow) and Pelton (green) turbine types [55].

For the purpose of this concept design, the Kaplan turbine is not a viable option due to this high head (> 100m) application and expected lower flow rates in order to minimise penstock (diameter) and reservoir costs.

The advantage of a Pelton turbine is its effectiveness at operating at lower turbine discharge with high efficiency at minimum turbine loading. The Pelton turbine thus can reduce hydraulic transients in the penstock which can reduce protection requirements, stresses and increase waterway asset life. With its ability to efficiently operate at lower loads, makes it ideal technology for spinning reserve capability. The centreline of the Pelton turbine's runner needs to be placed above the highest tail water level which reduces the effective head and may increase civil requirements for the target, deployable, design. The applicable design could be a vertical, 6 nozzle, 500 rpm unit. It is noted that the Pelton turbine is likely to be a robust, reliable, low maintenance potential option. When examining cost curves in [56], the relative cost is expected to be 24% higher for 100m head application for a Pelton Turbine in comparison to a Francis turbine.

In comparison, a Francis unit will realise a higher peak efficiency, and will also be a slightly more economical option with respect to capital outlay. The unit will also utilise the full effective head and achieve higher relative outputs (for a few metres additional head, say ~ 3% increase output for 100m head) comparing to a Pelton turbine, realising a slightly higher efficiency at rated load. The expected design typically will be a horizontal shaft with the turbine centreline above the maximum tail water level. The outlet of the draft tube would be submerged. The expected running speed of the Francis turbine would likely be 1000rpm which will realise a lower cost 6-pole AC generator compared to a lower speed (larger) unit.

For the design target of a 1MW – 5MW deployable solution, using the previous design assumptions and re-arranging power Equation 1, the prospective turbine volumetric flow rate ranges are:

$$Q_{1MW} = 1.13\, m^3/s$$

$$Q_{5MW} = 5.66\, m^3/s$$

3.2.6. Value of Storage

Studies by [35] and [36] have investigated the potential available revenue to be made in the NEM from large scale PHES developments by modelling historical price data from AEMO. Although the modelling inputs assume the electricity traders have perfect insight to market forecasting, the results give excellent insight into the optimal sizes of storage required for a peaking PHES development specific to the NEM.

The results from the knowledge sharing report of the Cultana Pumped Hydro Project in 2017 [35] are given in Figure 11. The graph shows the amount of revenue that could be ideally earned through energy arbitrage over the last 17 years. Each vertical column represents an upper reservoir with a utilisation capacity of 2, 4, 6, 8 or 10 hours respectively. This particular analysis utilises NEM data from the South Australian market region.

The figure communicates that an asset with a 2-hour storage capacity would yield approximately 60% of the value of an asset with 6 hours storage. Beyond 6 hours storage the incremental arbitrage value gain is minimal which suggests there is limited value in PHES peaking developments constructing storage reservoirs with capability beyond 6 hours discharge.

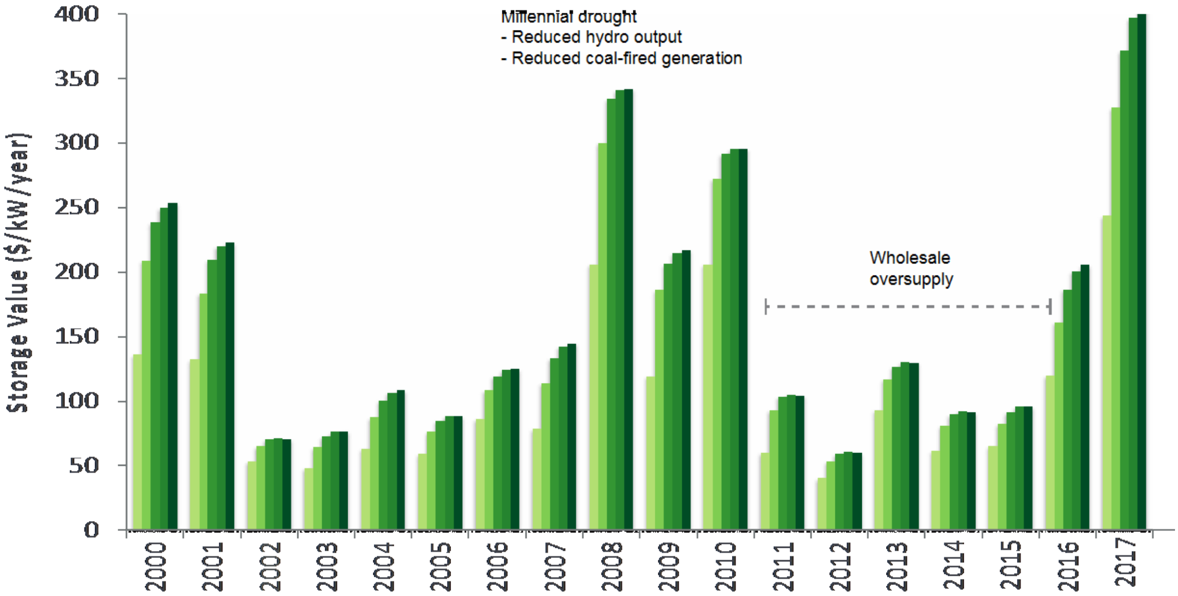


Figure 11: Historical value of storage in the NEM for the South Australian market for 2, 4, 6, 8 and 10 hours respectively [35].

These results were also supported by a study from the Melbourne Energy Institute (MEI) [36] in 2014. MEI found that 95% of the maximum arbitrage value was achieved with 6 hours storage and that there was minimal incremental marginal value to increase further. For sites with storages of 4 hours, approximately 80 – 90% of the potential earnings could be yielded. These results are given in Figure 12. The reason for these outcomes is that it is unusual for NEM prices to remain high for over 6 hours per day. Typical generating times in NSW for PHES are 6-9am and 5-8pm with pumping usually performed at night or during the day if the pool price is low or there is excess renewable generation.

From the market analysis, the design target for this concept plant is selected to be 6 hours, with margin to reduce the size to 4 hours, as required. Further consideration needs to be given to the incremental costs and any technological thresholds with respect to storage reservoir water volumes.

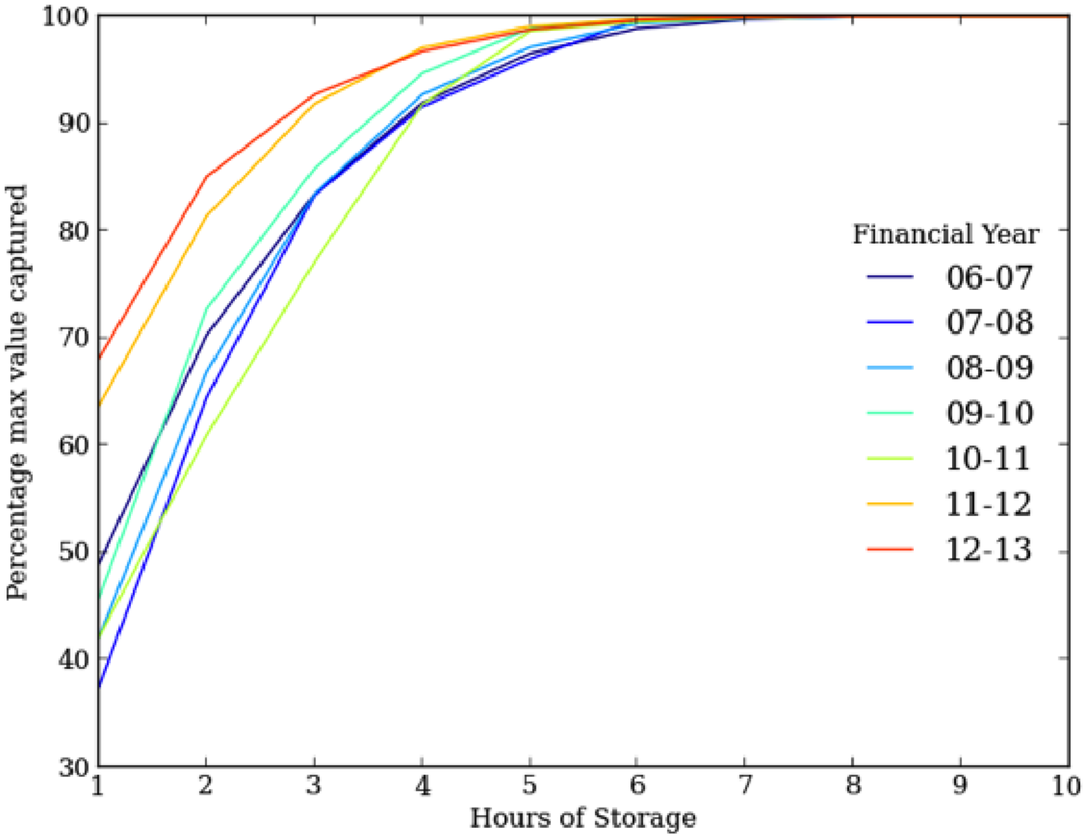


Figure 12: The arbitrate value of storage shown as a function of maximum potential yield [36].

3.2.7. Upper and Lower Reservoir

The size of a constructed reservoir is principally designed for the volume of water required to produce a proposed power output and expected energy yield over time. The selected site location must also accommodate the proposed reservoir design. The relationship between reservoir volume, head and energy is given by [50]:

$$PE = mgH = \rho VgH \quad \text{Equation 6}$$

Where:

PE = potential energy in Joules

m = mass of water in kg

g = acceleration due to gravity (9.81ms^{-2})

p = fluid density in kg/m^3 (water ~ 1000 kg/m^3)

V = volume of water in m^3

H = head in m

Using Equation 6 and given a minimum head of 100m as per [46] and an initial design target for a maximum annual energy export of 20GWh as per [45], a range of tank volumes can be found. Relevant results are show in . To maximise asset utility, it is assumed the total upper reservoir volume will be discharged once per day.

PE (MJ)	E (GWh/yr)	Reservoir Volume (ML)
7,200	0.73	7.34
24,480	2.48	24.95
46,800	4.75	47.71
180,000	18.25	183.49

Table 6: Range of relevant tank volumes for the given energy export design.

Long project durations, component lead times and extensive on-site construction times lead to PHES projects having major development costs which are significant deterrents to prospective developers and equity investors. Total project times for large developments are found to be in the range of 7 - 9 years [57] from pre-feasibility to first synchronisation. Studies out of the United States suggest 12 years from ideation to first water on in commissioning [58]. Large projects often requiring large reservoir construction such as turkey nest dams or "dammed valleys" requiring custom engineered concrete dam walls and, in addition - long penstocks, cost in the range of hundreds of millions, to billions, in construction costs. This means, when a Final Investment Decision (FID) is made, the investor will likely not receive any return for over at least 7 years. This prospective investment may not be appealing for the private sector, as an example.

Usage of natural water reservoirs such as dams and rivers and/or state-owned water infrastructure often realises reservoir construction cost savings but comes with additional complexities involving water access licencing, environmental compliances and complex stakeholder engagements. This is predominantly because a significant amount of hydro potential is situated in environmentally sensitive locations, such as state conservation areas or national parks. In particular environmental and land stakeholders can introduce complexities which cause project delays and reputational risk.

The cumulative effects of the above-mentioned challenges create an investment option that is not so attractive in competition to other technologies such as solar PV, wind or open cycle gas turbines - which are often built in the desert or on low value, out of sight land. The current Australian political instability and lack of long-term commitment to energy policy combined with the world's most complex electricity market structure creates additional barriers for long build projects.

In contrast, the following constitutes a subset of some of the attractive features of a large-scale solar PV project:

- Minimal geotechnical works including excavation cost and risk;
- Known PV module and inverter costs;
- PV modules, supports and inverter modules manufactured off-site with pre-defined lead time;
- Well known time of installation per module;
- Typically installed on low value, private land;
- Use of Australian local labour for installation due to relatively low technical complexity;
- Plant can be flexibly sized to fit land area, budget or required power generation;

- Mature business case can be put forward to investors with minimal costs in feasibility and engineering studies.
- Recent NSW deployed utility scale project capital costs of \$2.93M/MW for Moree Solar Farm and \$2.84M/MW for the AGL Solar Project (Broken Hill and Nyngan) with project build times of 12 months and 15 months respectively achieved in 2017 [59] [60].

In consideration of the above-mentioned attractive features, the PHES facility should comprise of an upper and lower storage reservoir with the following requirements:

- Minimal geotechnical works
- Flexible, mature pre-designed storage reservoir with known capacities, costs and build times
- Minimal build complexity and on-site construction time
- Facilitate power generation at a target project capital cost of less than \$2.84M/MW
- An upper storage volume of less than 183GL (based on energy export < 20 GWh/yr).

The technical solution is to propose the use of a modular, free standing, above ground water storage reservoir design. Pre-engineered, mature designs already exist and are widely in use throughout Australia in the oil, gas, mining and agriculture sectors [61]. An example is illustrated in Figure 13.

Figure 13: Modular design, concrete wall, water storage tanks utilized in the Surat Basin, Queensland, for the coal seam gas industry. Build time 9 days [61] .

The following list highlights the key attractive features to support this novel concept for use in the power generation industry, specifically modular PHES:

- Reservoir sizes available in the range 1ML – 100ML with onsite build times ranging from 5 – 30 days respectively
- Short lead times for materials, typically 6 – 8 weeks
- Minimal geographic footprint with low impact on local flora and fauna
- Minimal geotechnical requirements and no excavation
- Mature technology with warranties in the order of 25 years
- Complete turnkey solution

Utilizing standard, pre-engineered tank data and $PE = mgH = \rho VgH$ Equation 6 the reservoir storage size can be optimized for a MPHES application. Details are summarized in Table 7 and communicated graphically in Figure 14. The final reservoir technical summary is presented in Table 8.

Reservoir Volume (ML)	Tank Requirement	Reservoir Diameter (m)	Reservoir Area (m^2)	Cost Est. ($M)	Power (MW)	$M/MW	kW/m^2
12	1 x 12 ML	70	3,848	0.5	0.49	1.02	0.127
25	1 x 25 ML	110	9,503	0.8	1.02	0.78	0.107
50	1 x 50 ML	140	15,394	1.2	2.04	0.59	0.133
100	4 x 50 ML *reticulated system	-	67,733	4.32	4.09	1.06	0.060

Table 7: Storage reservoir technical overview

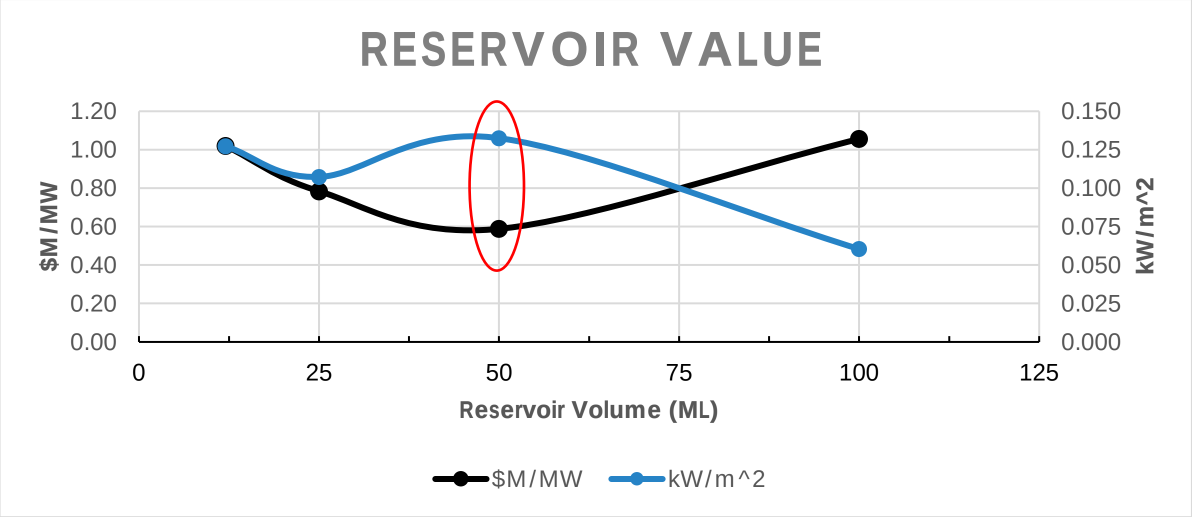


Figure 14: Optimal reservoir size characterized by high power density per unit area (blue) and lowest cost to serve (black).

V (ML)	p (kg/m3)	g (m/s2)	H (m)	PE (GJ)	E (MWh)	E (GWh/yr)	Nominal Discharge (hrs/day)	Overall efficiency	P (MW)	Q (m3/s)
12	1000	9.81	100	**11.77**	3.27	**1.19**	6	0.9	**0.49**	**0.56**
25	1000	9.81	100	**24.53**	6.81	**2.49**	6	0.9	**1.02**	**1.16**
50	1000	9.81	100	**49.05**	13.63	**4.97**	6	0.9	**2.04**	**2.31**
100	1000	9.81	100	**98.10**	27.25	**9.95**	6	0.9	**4.09**	**4.63**

Table 8: Upper and lower storage reservoir technical summary.

3.2.8. Penstock

A penstock is an enclosed pipe that delivers water to a hydro turbine [ref]. Design types include:

- Glass fibre reinforced, unsaturated polyester (GRP);
- Spirally welded steel;
- Polyethylene (PE) or Polyvinyl Chloride (PVC);
- Cast iron.

There is a variety of choices in selecting the appropriate material for penstocks. For large machines, high heads and pipe diameters greater than approximately 2 metres, steel pipelines are typically used [56]. These pipes are having significantly higher strengths, higher per unit length, transport and installation costs. Installation costs can vary significantly and are dependent on terrain, transportation and installation complexity. PVC or PE plastic pipes is an attractive solution for head application up to approximately 200m for a 300 – 500mm diameter pipe [44]. Major advantages with plastic pipes are they are typically cheaper, lighter and easier to install than steel.

Polyvinyl Chloride (PVC) pipes are normally installed underground and are not UV stabilised, requiring additional surface preparation. PVC are relatively brittle and not recommended for installation on rocky or harsh terrain. Suitability for PVC are typically up to 300mm diameter.

Polyethylene (PE) pipes can be laid on the surface, installed on water and can withstand rough handling on site (for example dragged by cable in long sections). Furthermore, PE pipes typically have a long-life span with few problems when properly installed. The principle disadvantage with PE pipes are their low strength and rigidity. Diameter ranges for PE in hydro application are 110 – 630mm typically.

Glass fibre Reinforced Polyester (GRP) are an acceptable material and are low weight, suitable for trenching, no additional surface treatment, low head loss, little maintenance requirements, chemically resistant, have long lifespans and low cost [44]. Drawbacks for this pipe include the higher relative requirements for anchoring and poor impact resistance. Diameters for GRP pipes range from 300 – 2000mm typically.

Given the target flow rate range of 1.13 to 5.66 m^3/s and assuming an acceptable frictional loss of 4% in the waterway, the optimal penstock diameter can be found via:

$$D = 2.69\left(\frac{n^2Q^2L}{H}\right)^{0.1875} \qquad \text{Equation 7}$$

Where:

D is the penstock diameter in metres

n is the materials roughness co-efficient (n=0.009)

Q is the flow rate

L is the length of the penstock in metres

H is the effective head in metres

Assuming a roughness co-efficient of 0.009 for plastic pipes, an arbitrary penstock length of 100-150m and a head of 100m, the pipe diameter upper and lower ranges for 1MW and 5MW turbine output respectively are:

$$D_{1MW} = 480 - 520\ mm$$

$$D_{5MW} = 880 - 950\ mm$$

It is noted for a 100m long penstock for example, doubling the length (ie. to 200m) increases the penstock diameter approximately 14%. A GRP penstock is selected due to the prospective sizing range being within the materials capability and expected marginally lower capital and life cycle costs.

Laying methods consist of either installing on the surface foundation or buried underground. Larger designs are also often installed in tunnels for access and routine inspections. Surface penstocks are preferred due to the reduced surface preparation and excavation risk. Surface penstocks are installed on spaced support cradles with concrete anchor blocks at bends. Installation methods are outlined in Table 9 and typical surface bracing design depicted in Figure 15.

Penstock Type	Surface	Buried
GRP	✓	✓
Steel	✓	
PE		✓
Cast iron	✓	✓

Table 9: Overview of penstock laying methods for different materials [44]

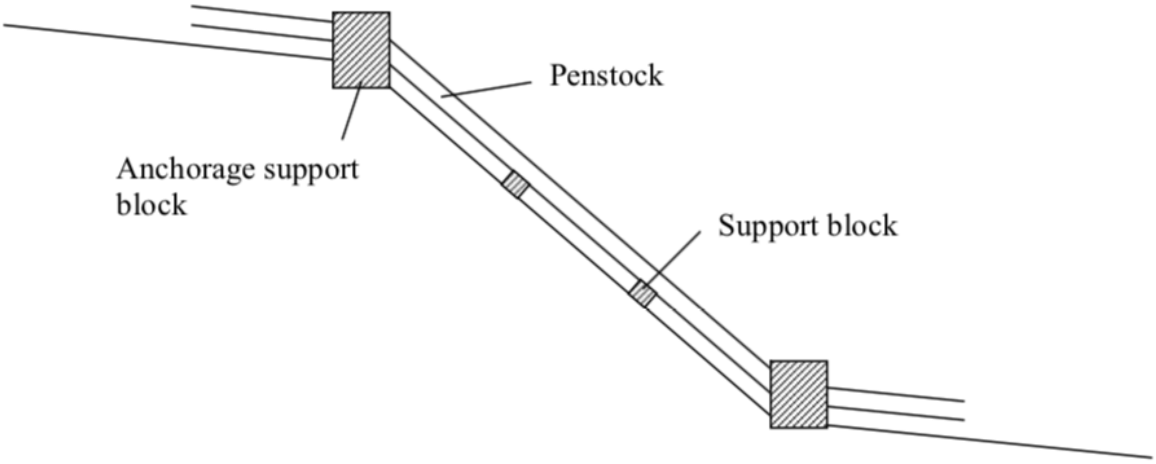


Figure 15: Typical surface penstock foundation and support design [56]

3.2.9. Rotating Machines

The electrical system for PHES consist predominantly of three designs categorised by the generator and applicable converter technology:

- Fixed speed Synchronous Machine
- Variable speed Synchronous Machine
- Variable speed Doubly Fed Induction Machine (DFIM)
- Fixed speed Asynchronous Machine

For quaternary application, this can include an Asynchronous machine (induction motor) for pumping mode.

The selection technology for generation is directly connected fixed synchronous machines due to the desire to reduce component counts, maintain operational simplification and reduce variety of failure modes. Frequency converters also add considerable cost to the plant. Due to the scalable design, modulation of generation (and load) is to be performed by dispatching individual machines as opposed to changing machine speed via governor or power electronics action.

For pumping, Direct Online (DOL) induction motors are selected also for their simplicity. As part of the operations strategy of the plant, the amount of starts and stops is to be monitored (and limited) in pumping mode to prevent accelerated thermal aging and stresses of the motor and transformer fleet during dispatch.

3.2.10. Connection Point

In NSW, DNSP Ausgrid have the large majority of their existing transformer population in the range of 19 – 33MVA with low voltage connections of either 6.6kV or 11kV [62]. The high voltage transformer voltages are either 33kV or 66kV [62]. The plant should be located ideally as close to existing infrastructure as possible. This has principle benefit of reducing upfront transmission costs and also minimising the length of any line or aerial infrastructure that would need to be managed by the owner or operator. The cost for the inclusion of excessive aerial transmission infrastructure would need to be borne by the project which can escalate costs rapidly. This should be avoided.

Installations below 10MW are relatively simple electrical installations with well-known costs, component selection, lead times and footprints. Selection of these items are largely Site specific, however for the purpose of this conceptual design it's intended to generate at 415V for unit sizes < 750kW and 3.3kV or 6.6kV for units up to 5MW. The step-up voltage is intended to be 33kV utilising a dry-type transformer to reduce fire system Building Code (BCA) and AS 2067 High Voltage Installation requirements alongside EPA bunding requirements. If the system is scaled outside the capacity of dry-type transformers (typically > 10MVA), a synthetic or natural ester-based oil filled transformer would be selected to improve the Sites fire safety and environmental risk profile.

3.2.11. Target Design Summary

Parameter	**Design Target**
Classification	Small-medium
Head	100m
Power	2 x 1MW = 2MW
Flowrate	2 x 1.16m^3/s = 2.32m^3/s
Pump/Turbine Configuration	Quaternary
Turbine Type	Francis
Energy Storage	6 hours
Operational Water Volume	50 ML
Waterway type	2 x GRP surface penstock
Penstock diameter	500mm [1]
Penstock length	100 – 150m [2]
Generating/Pumping Voltage	3.3kV

Table 10: MPHES technical design summary

---

[1] Approximate diameter +/- 200mm

[2] Approximate penstock actual length given vertical head of 100m.

3.3. Cost Base

For pre-feasibility studies, a typical cost estimate certainty is +/-30% [35]. Where available, local cost referencing is applied to maintain national context. Some of the cost estimates however in this chapter utilise cost curves developed in Norway by the Norwegian Water Resources and Energy Directorate (NVE). The *Cost Base for Small-Scale Hydro Power Plants (up to 10,000kW) 2012* [56], is a manual prepared as a tool for cost estimates of contractor civil work costs and component supply costs for mechanical and electro-technical plant.

Norway is a country that has 31GW of hydropower capacity which accounts for 95% of the country's total electricity supply [63]. Any equations utilised in this work are converted from 2012 Norwegian Krone (NOK) to 2019 Australian Dollars (AUD) using inflation and currency conversion scaling factors. Generally, the NVE cost curves are based on empirical figures.

3.3.1. Powerhouse

The cost for a powerhouse is highly location specific and can increase quite steeply with a large amount of rock excavation, blast volume or building the powerhouse underground. For this concept design, civil works should be minimised as far as practical with the ideal location requiring minor vegetation removal and ground preparation. The power station is to be a simple, above ground type with basic infrastructure. The total estimated price base is expected to be less than \$6,500/m^2 [56].

For the 1MW unit concept design with a rated flow of 1.13m3/s, a basic surface power

Surface power station with 100m head cost curve is given by:

$$H=100\ m:\ C_{ph} = 0{,}8038Q + 1.7 \qquad \text{Equation 8}$$

For an additional second unit 10% is added, and for ground compacting a further 10% is also added.

The estimated cost for the powerhouse is $596,000.

3.3.2. Waterway

Each material has different installation requirements, jointing methods, mechanical properties and relevant advantages and disadvantages. The costs of civil works are highly dependent on ground conditions. If the installation contains hills, is flat, contains rock or a lot of loose uncompacted material, costs can quickly escalate.

The target installation location for the PHES modular plant is expected to include favourable installation conditions as part of the Site selection process. With this assumption, the following cost curve can be considered conservative estimate for the surface preparation and foundational costs of the 500mm diameter GRP penstock:

$$\text{GRP pipes: } C_{grp} = 0.0007D^2 + 3.3197D + 2155 \qquad \text{Equation 9}$$

Supply of the penstock materials is given by:

$$\text{GRP PN6: } C_{sup} = 0.0007D^2 + 1.7882D - 623 \qquad \text{Equation 10}$$

An additional 30% is added to the pipe cost to accommodate installation costs.

Burying the pipe in a trench is expected to add an additional cost of approximately 25% with the main deterrent being the difficulty and risk in predicting the amount and type of material (eg. rock) sub surface. Constructing a 16m^2 tunnel to house the penstock in is expected to increase the cost by at least by approximately 500%. Building tunnels also significantly raises the skill and engineering requirements for the project to the point where the option is unfeasible.

3.3.3. Water Reservoirs

Water storage reservoirs are one of the largest economic and geographical challenges in the development of PHES systems. Typically, most of the obvious, natural locations for Hydro Power Potential are often already exploited. The economical construction of artificial water reservoirs is a key focus of this work. Table 11 outlines typical costs for relevant size water storage reservoirs.

Given the target design needs to be cost competitive with Solar which in NSW has been benchmarked in Chapter 3 at $2.8 – 2.9 M/MW, readily deployable PHES water storage costs need to be less than at least half this capital cost to allow for the remainder of the power generation infrastructure spend. For this reason, the suggested economically feasible option is the pre-engineered modular tank construction. As outlined in Section 57, the optimal tank size for energy storage was found to be 50ML at an estimated total cost of $1,200,000. This includes design, transport to site, favourable ground work preparation and installation.

Reservoir Volume (ML)	Reservoir Type	Reference	Cost Est. ($M)
25	Modular Tank (concrete panels)	[64]	0.8
50	Modular Tank (concrete panels)	[64]	1.2
20	Steel Tank	[65]	3.04
30	Steel Tank	[65]	4.0
20	Concrete Tank	[65]	3.91
50	Small rock fill dam	[56]	1.82
50	Flat Slab Deck Dam (Buttress)	[56]	4.73
50	Timber Crib Dam	[56]	3.48

Table 11: Cost estimates for different types of water storage reservoirs

3.3.4. Access Roads

Roads are required for construction purposes and also maintenance and inspection activities.

Empirical figures from hydro projects indicate a temporary style road construction on easy to moderate terrain conditions is approximately $190 per consecutive metre of road [56] for a Class 3 type forestry standard road in Norway. Maintenance on this type of road is typically 10% of the construction costs each year. The construction cost for Class 3 rural permanent road in Australia was found in a 2018 benchmarking report [66] by the Bureau of Infrastructure, Transport and Regional Economics to be between $0.4 - 1.1 M/km managed by local council.

A 200m length temporary style road access is estimated is estimated to be $38,000 based on empirical Norway projects. Utilising Australian data, it is expected to be at the lower end of the price range of $400,000 per kilometre given the land is to be privately owned with minimum stakeholders and is to be privately constructed. This yields for a 200m road a construction cost of approximately $80,000 built to the relevant Australian Standards.

A budgeted road cost of $80,000 for 200m of access road is included

3.3.5. Power Generation and Pumping

For quaternary application, separate turbine-generator and pump-motor sets are employed. The equipment is sourced directly from the factory and imported to Australia.

This is required to be directly cost competitive to solar panels. Currently major OEM branded engineering companies are often sourcing an *economy model* product option from China and rebranding to remain cost competitive and give customers the flexibility to access to a wider price range whilst still purchasing a brand they have built trust with over the years. This procurement process is absolutely essential to remain economically sustainable under the pressures faced in the power generation sector.

A 1MW horizontal synchronous generator with brushless excitation and electronic governor system is utilised with basic control and protection infrastructure. This is driven by the Francis turbine and coupled with a flywheel for enhanced inertial response between two pedestal bearings. A Francis turbine, flywheel and bearing configuration is depicted in Figure 16 general arrangement diagram that would be utilised in the concept MPHES. Figure 17 depicts the setup of the pump-motor and also shows the type of control panel and skid mount housing that is expected to be utilised.

The total cost of the 1MW concept Quaternary PHES set is approximately $321,000. Costs are outlines in Table 12.

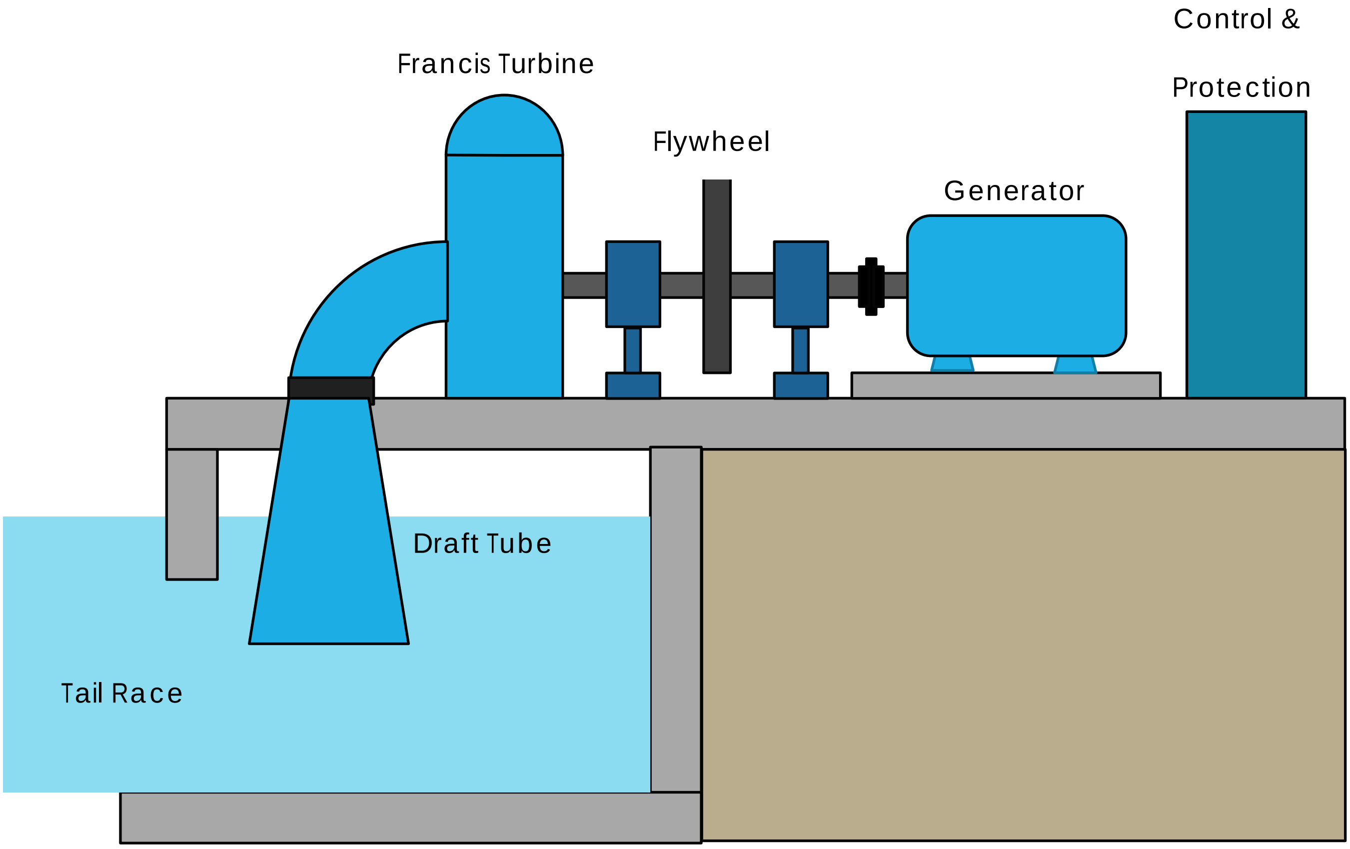


Figure 16: General arrangement of the MPHES major power generation plant

Figure 17: Diagram of typical 1MW skid mounted, turn key, pumping facility [67]

1000kW Turbine-Gen Set	**USD**	**AUD**	**Insurance (4%)**	**Import Duty & GST (20%)**	**Total**
Francis Turbine	40000	56400	2256	11280	$69,936
Generator	58500	82485	3299.4	16497	$102,281
Flywheel	5000	7050	282	1410	$8,742
Main Valve	5900	8319	332.76	1663.8	$10,316
Governor and Control	10800	15228	609.12	3045.6	$18,883
Excitation and protection	12000	16920	676.8	3384	$20,981
Transport	4600	6486	259.44	1297.2	$8,043
				Sub total	$239,181
1000kW Pump-Motor Set					
Pump	8680	12238.8	489.552	2447.76	$15,176
Induction Motor 1000kW	26555	37442.55	1497.702	7488.51	$46,429
Main Valve	5900	8319	332.76	1663.8	$10,316
Control and Protection	2500	3525	141	705	$4,371
Transport	3000	4230	169.2	846	$5,245
				Sub total	$81,537
			TOTAL 1MW PHES Quaternary Set		**$320,718**

Table 12: Cost estimate breakdown of major plant components of the 1MW concept Quaternary MPHES system

3.3.6. Electro-technical

The remaining items consist of interfacing components to connect all the main plant with each other and to the grid.

The cost of a Generator Step-Up Transformer (GSUT) that connects the plant to the power system is given by the cost curve [56]:

$$P = 1.4 – 10MW: \quad C_{gsut} = 0.0624*P^{1.1266} \qquad \text{Equation 11}$$

A cost of $69,000 is expected for a 2,200kW dry-type GSUT. The estimate is highly accurate as a dry-type, outdoor transformer size range 1.5MVA to 4MVA (up to approx. 33kV) from major OEM's delivered to Australia typically cost $60,000 - $90,000 AUD if purchased in 2018/19.

It is important for a modern power station to be completely autonomous, remotely operatable and require little operator manual intervention. For a control system to be able to remotely monitor and dispatch the plant, the cost is approximately $47,600 for a 1 – 2MVA sized station.

A switching station comprising of generator and motor HV switchgear, associated cabling and station transformer for a 500kW – 10MW sized station is represented by the cost curve [56]:

$$P = 0.5 - 10MW: \quad C_{ss} = 1.3224P^{0,9098} \qquad \text{Equation 12}$$

The estimated cost for the plant distribution system is $254,000 for a 2000kW sized station.

The cost for aerial transmission infrastructure to connect the plant to the local DNSP is estimated by a report commissioned by the Department of Primary Industries [68]. The average cost for three-phase, Aerial Bundled Cables (ABC) with steel poles was found to be $126,255 per kilometre installed on easy terrain.

3.3.7. Engineering, Procurement and Construction (EPC)

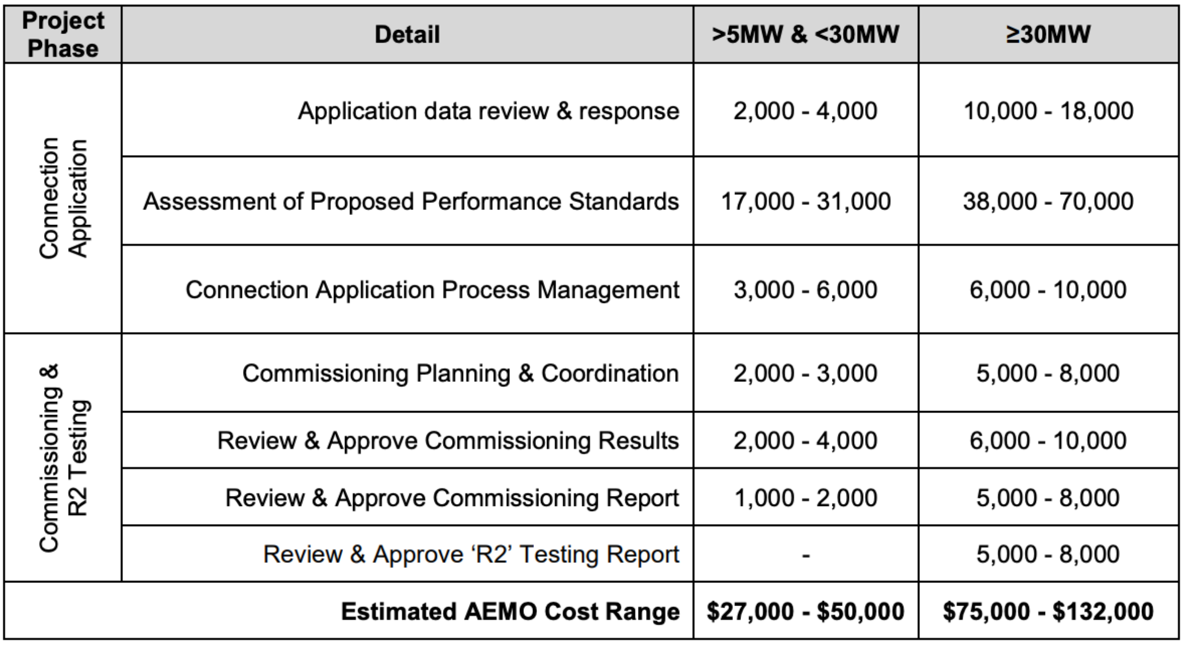
For hydropower projects, typical EPC costs are estimated at 7% [69] total capital costs. It is expected that this figure is a rather conservative estimate for a modular PHES project due to the minimal civil works being undertaken and that all the components are pre-engineered standard designs. Majority of costs are expected to be associated to project management and co-ordination. A 7% EPC cost is utilised and considered a conservative pre-feasibility estimate.

3.3.8. Network and Connection Charges

The connection for embedded generators in the range of 30kW – 5MW are required to follow the network connection process governed by Chapter 5A of the National Electricity Rules (NER). This class of connection is referred to as Non-Registered Embedded Generators. This size network connection does not require registration with AEMO and only registration and co-ordination with the relevant DNSP. The relevant cost for such a connection in NSW with Ausgrid is in total approximately $100,000 [70] and comprises of two parts. The first is a detailed enquiry fee approximately $20,000 and the second a connection application fee of approximately $80,000.

The connection for embedded generators greater than 5MW is required to follow the network connection process governed by Chapter 5 of the NER. This class of connection is referred to as Registered Embedded Generators. Chapter 5 is the process that typically applies to generators that will be registered with AEMO. The process in short has 4 parts, a preliminary enquiry, a detailed enquiry, and connection application and a connection offer. The relevant cost for such a connection in NSW with Ausgrid is in total approximately $100,000 [71] and comprises of three parts. The first is a preliminary enquiry fee of approximately $2,000, the second a detailed enquiry fee approximately $28,000 and finally a connection application fee of approximately $70,000. The Registered Embedded Generator connection also requires AEMO due diligence activities.

The costs for AEMO to undertake due diligence activities are given by nameplate capacity in . The cost range for a 5 – 30MW system are approximately $27,000 - $50,000 [72].



Project Phase	Detail	>5MW & <30MW	≥30MW
Connection Application	Application data review & response	2,000 - 4,000	10,000 - 18,000
	Assessment of Proposed Performance Standards	17,000 - 31,000	38,000 - 70,000
	Connection Application Process Management	3,000 - 6,000	6,000 - 10,000
Commissioning & R2 Testing	Commissioning Planning & Coordination	2,000 - 3,000	5,000 - 8,000
	Review & Approve Commissioning Results	2,000 - 4,000	6,000 - 10,000
	Review & Approve Commissioning Report	1,000 - 2,000	5,000 - 8,000
	Review & Approve 'R2' Testing Report	-	5,000 - 8,000
	Estimated AEMO Cost Range	**$27,000 - $50,000**	**$75,000 - $132,000**

Table 13: AEMO estimate for due diligence activities for different sized connection enquiries [72].

3.3.9. Operational Costs

Once the plant is commissioned, small hydropower plants require minimal maintenance. The very few components and minimal station auxiliary plant makes the technology highly reliable. Annual operation and maintenance costs range from 2.2% to 3% for small hydro plants with a global average of 2.5% [69]. A value of 2.2% the total investment cost is assumed for the MPHES plants annual maintenance costs due to the expected modularity and minor complexity. Planned major maintenance is expected every 15 years.

3.3.10. Access to Revenue

Energy arbitrage, Cap contracts and Ancillary Services are three of the most common ways for PHES plants supplying peak capacity to generate revenue.

Spot price energy arbitrage has undergone detailed modelling in the NEM by ARENA, MEI and McConnell et al. [35] [36] [73]. For the 6-hour reservoir size the energy arbitrage value that could be realised between the years 2004 – 2014 was found to range from $50 – 325 /kW/year [73] and for the years 2000 – 2017 was found to be $60 – 400 /kW/year [35]. Over the last three years the value of energy storage has increased significantly. ARENA have also investigated the revenue impact of PHES of varying plant sizes and found that the spot market arbitrage value decreased in revenue potential with an increase in project size. This is shown in Figure 18. The estimated potential income from energy arbitrage in the MPHES case with 6 hours storage, a value of $117/kW/year is assumed for the nominal 2MW deployment.

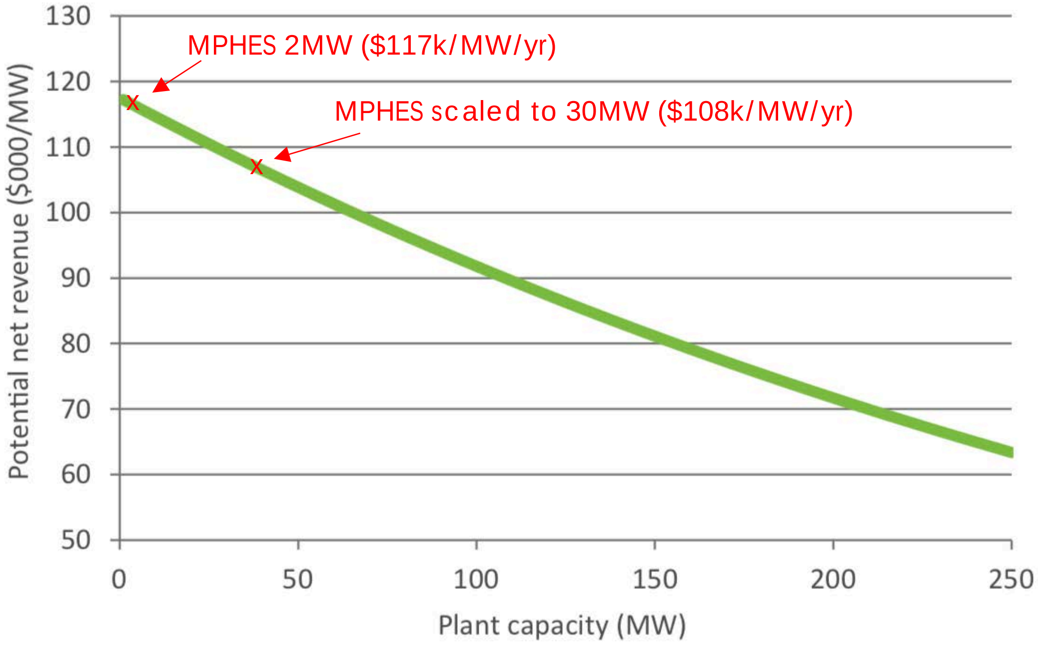
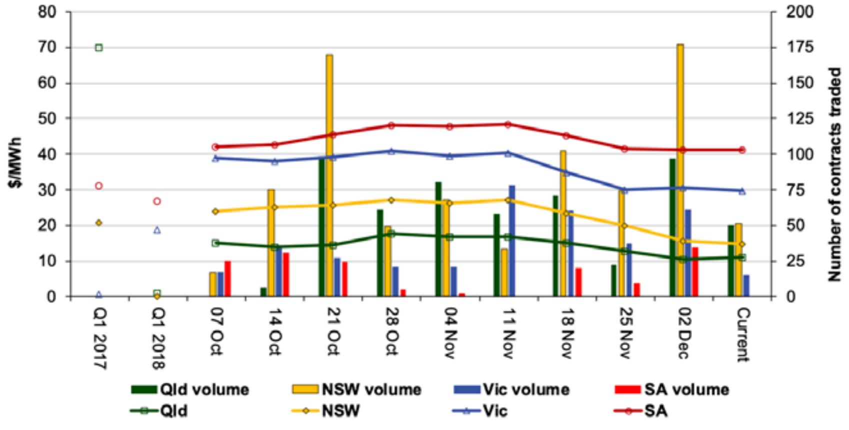


Figure 18: Arbitrage revenue estimate as a function of varying plant sizes

Cap contracts are also another way to generate income. Cap contracts are a derivative product that essentially protects customers (retailers or loads) from extreme electricity prices. A typical value of a cap contract traded in Australia is $300/MWh for the contracted energy volume [73]. It is noted the current Market Price Cap in the NEM is $14,500/MWh [74].

Generators that sell cap contracts typically obtain a consistent payment every trading interval regardless of whether they are required to dispatch. The value of cap pricing contracts in 2018 are detailed in Figure 19. It can be seen the range of cap contracts in NSW range from $15 – 25 /MWh with NSW having the highest volume of traded contracts. Taking an average value of $20/MWh, the potential revenue could yield a total of $20 * 8760 = $175,200/MW/year. For a 2MW plant this totals $350,400/year. It is noted that when the spot price exceeds $300/MWh the MPHES would be exposed to the market if the reservoir was empty (ie. It needed to operate in pump mode). To consider this impact, a cap contract value price range of $6 – 12/MWh as recommended by McConnell et al. [73] can be considered in addition of the arbitrage value to more accurately estimate the total annual revenue. A conservative cap value of $9/MWh is assumed for the evaluation of this revenue stream.



Source. ASXEnergy.com.au

Figure 19: Value of cap contract pricing across the NEM for 2018 [75]

Revenue from Ancillary Services is difficult to predict due to the wide range of variables and competitiveness involved in securing a contract for each service. As the income is not bankable, it is excluded from any economic benefit calculations. The intent of the MPHES it to be flexible and have inherent design capability to participate in all energy markets and future potential revenue streams as the market and generation mix evolves. That is, the design is inherently fit for the future.

It is important to consider the potential for FCAS services, however. For context, the Hornsdale Power Reserve 100MW, 129MWh lithium ion Tesla battery facility generates 17% of its revenue from energy arbitrage, 20% from FCAS regulation service and 63% from FCAS contingency service [76] [77]. Hornsdale generated over $15M in revenue in 273 days which is approximately $57,000 per day [77]. This is a significant change to the conventional power generation model and is a market participant to be closely watched, and learned from, into the future.

For System Restart (SRAS), there are currently two SRAS contracts in NSW. The total annual cost expected for 2018/19 for these two contracts network service in NSW is $10,726,660 [78]. This cost covers availability, testing and usage costs. This is a highly competitive market and the contracts not historically awarded to small plants, however, this could change in the future.

For Voltage Control (VCAS), NSW has two VCAS contracts. Total revenue for 2017/18 was $14,217,755 [78]. These contracts are to Transgrid for their substation static plant and Snowy Hydro for their synchronous condenser support at Murray and Tumut. This is also something not immediately accessible by new, small market entrants however as the NEM generation sources become more distributed this is an opportunity that could be accessible in the future by a scaled up MPHES.

It is noted in Australia there is currently no markets for fast frequency and inertia support.

4. Case Studies

4.1. Case Study 1: Concept 2MW MPHES Plant

The basis of the concept 2MW plant utilises the design and components as described in Chapter 3. The overall concept is depicted in Figure 20. To deploy this system, a location is selected for the Case Study that meets the design brief maximising the benefits whilst breaking down barriers outlined in Chapter 2.

The NSW government has announced three identified priority Renewable Energy Zones (REZ). These zones are in the state's New England, Central-West and South-West regions as shown in Figure 21. These identified zones are characterised by outstanding renewable energy resources, have reduced environmental and planning constraints and are in close proximity to existing transmission infrastructure and large load centres. The REZ are in alignment with the government's regional growth priorities, which have had extensive stakeholder consultation with local communities [79]. These characteristics are strong foundations for a sustainable, lowest cost opportunity for a MPHES development.

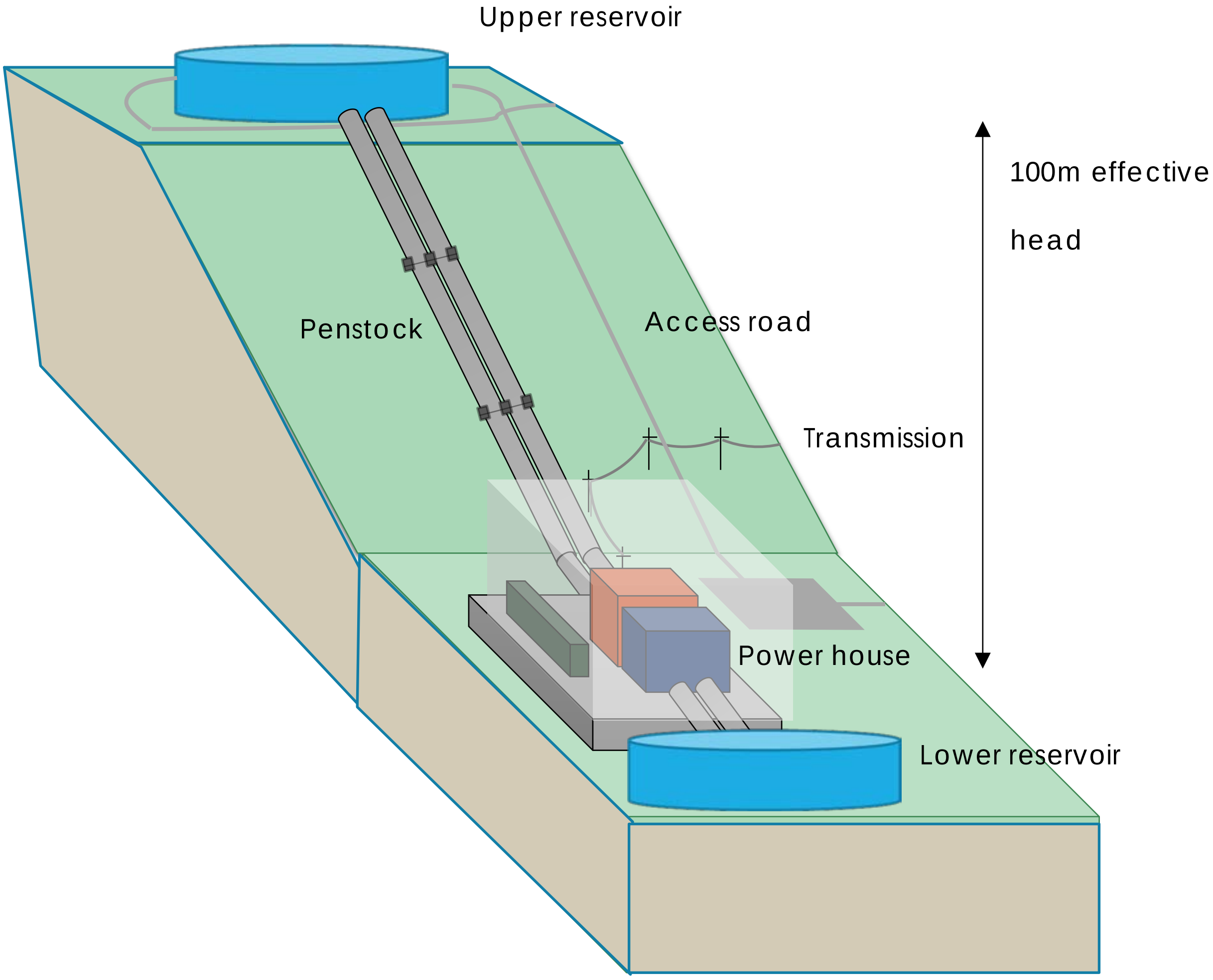


Figure 20: Concept design of the 2MW MPHES deployable plant

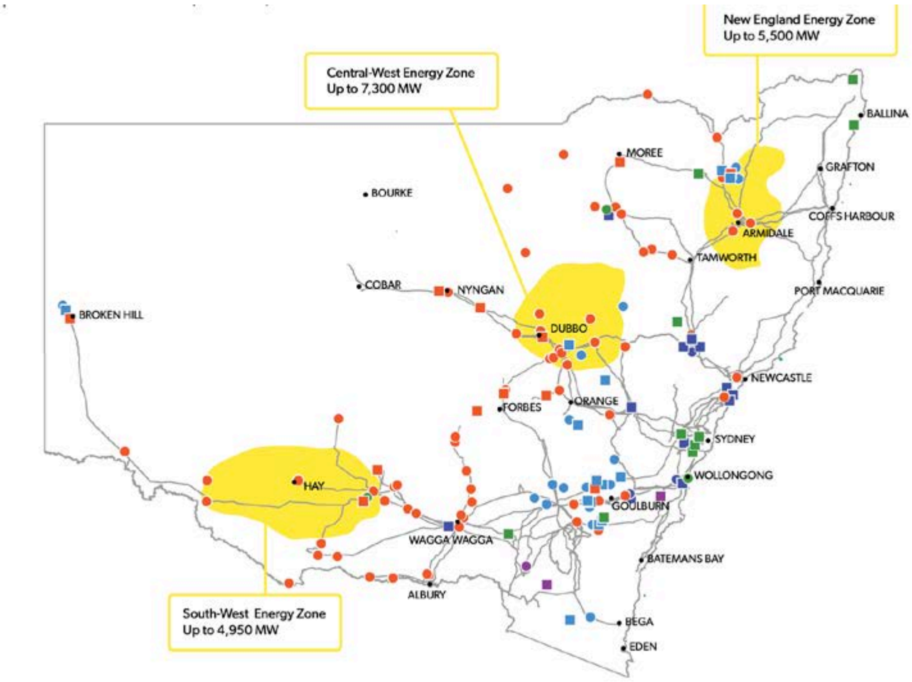


Figure 21: Identified priority Renewable Energy Zones (REZ) in NSW

The Central West Energy Zone is selected as it has multiple solar and wind farms in operation and an additional solar farm near Gulgong (87MW Beryl Solar Farm) due to come online in late 2019. This location provides an excellent opportunity for a complimentary MPHES facility. The most attractive feature of this zone is that it has Windamere Dam at its centre surrounded by transmission and distribution infrastructure with large capacity. Windamere dam has a water storage volume of 368GL which is more than half the volume of Sydney Harbour [80]. The Dam is owned by WaterNSW and is a significant state-owned water reservoir constructed over a ten-year period commencing 1974 with the main purpose being agricultural irrigation and potable water supply [80].

What makes this Site particularly attractive for a MPHES plant is the lake elevation of 546m and its surrounding terrain with elevations up to 900m. This translates to available hydro potential head in excess of 350m within the Lakes immediate surrounds. As the concept plant is initially designed with 100m hydraulic head, a close by location to the lake is selected with flatter terrain and minimal tree growth. The selected area is also close to access roads, transmission and on private land. The Dam’s huge water volume of 368GL will be used to fill the storage reservoir. The storage reservoir of the MPHES is less than 0.01% of the dam volume making environmental impact of the scheme for initial filling practically insignificant.

Its noted the feasibility of being able to acquire and actually build on this specific piece of land is beyond the scope of this Case Study. Figures 89, 89, 90 and 90 detail the proposed land allocation and site specific detail graphically.

A financial and technical summary is given in Table 14:.

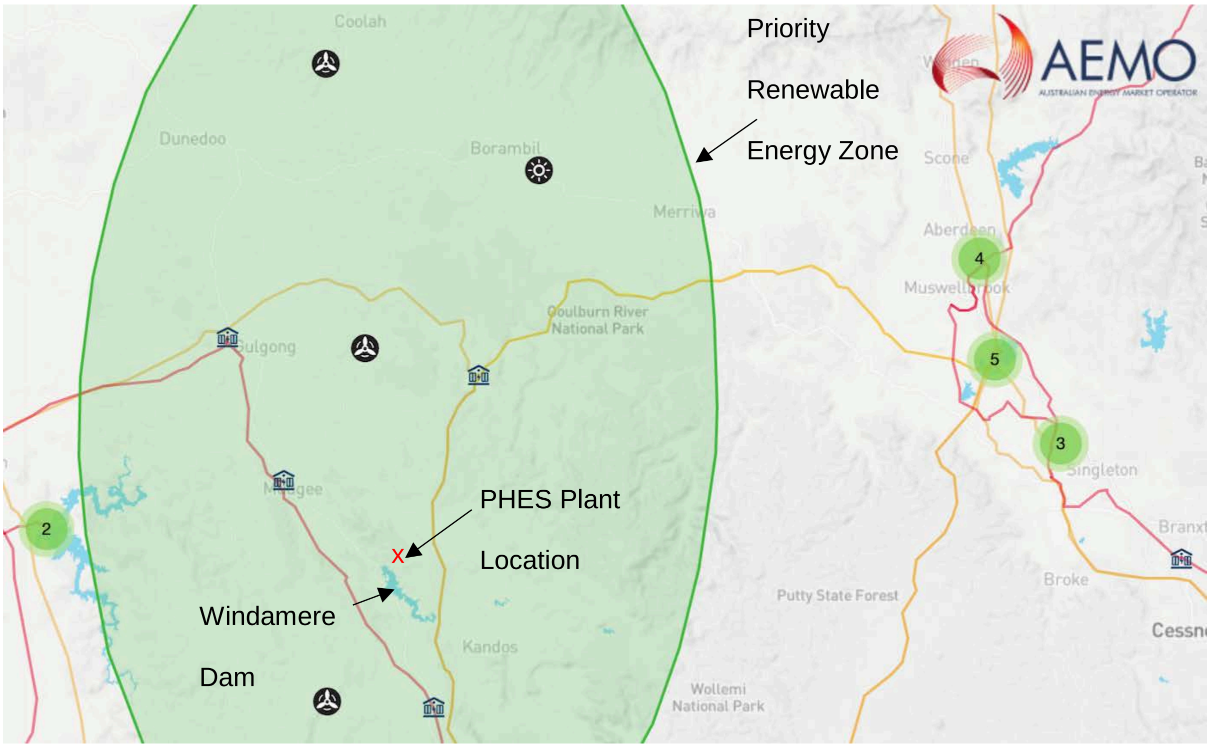


Figure 22: REZ surrounding Windamere Dam. Screenshot taken from AEMO interactive maps

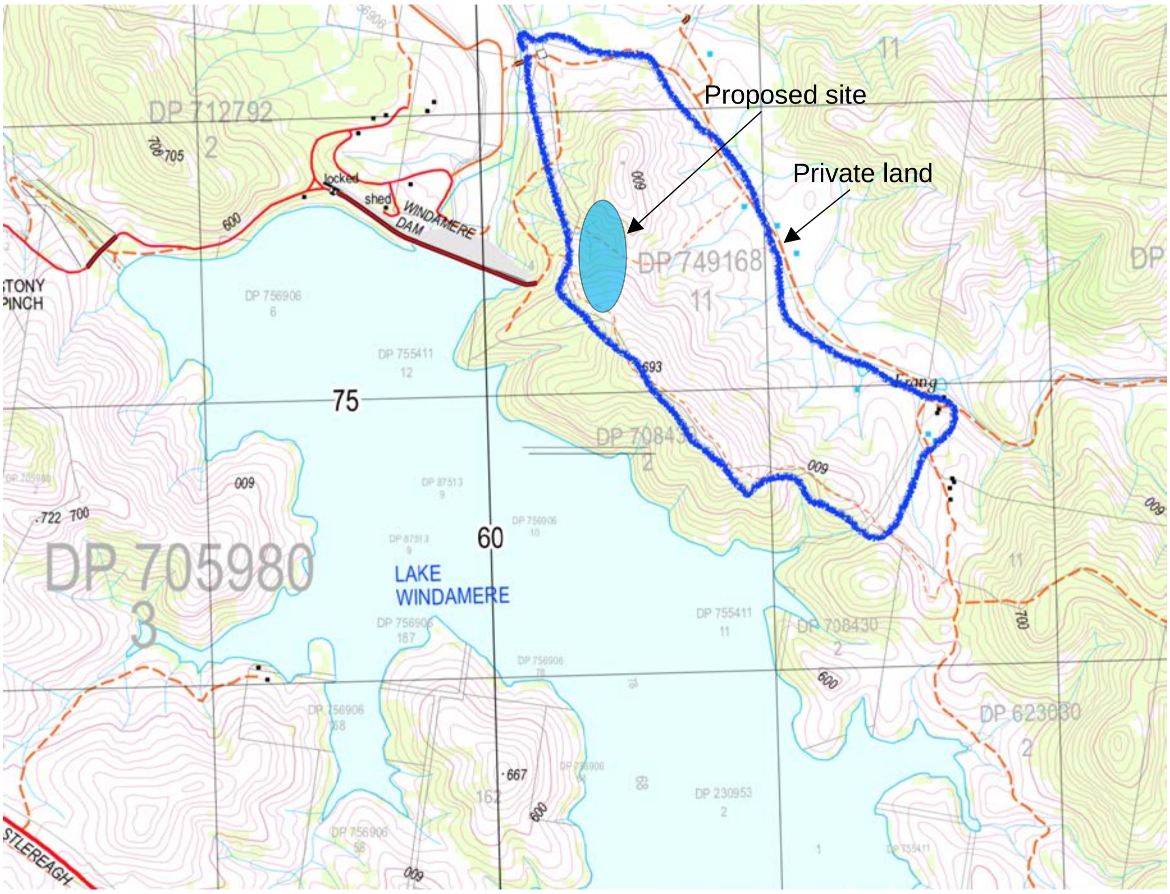


Figure 23: Lot designation outline. Screenshot taken from SIX Maps [81]

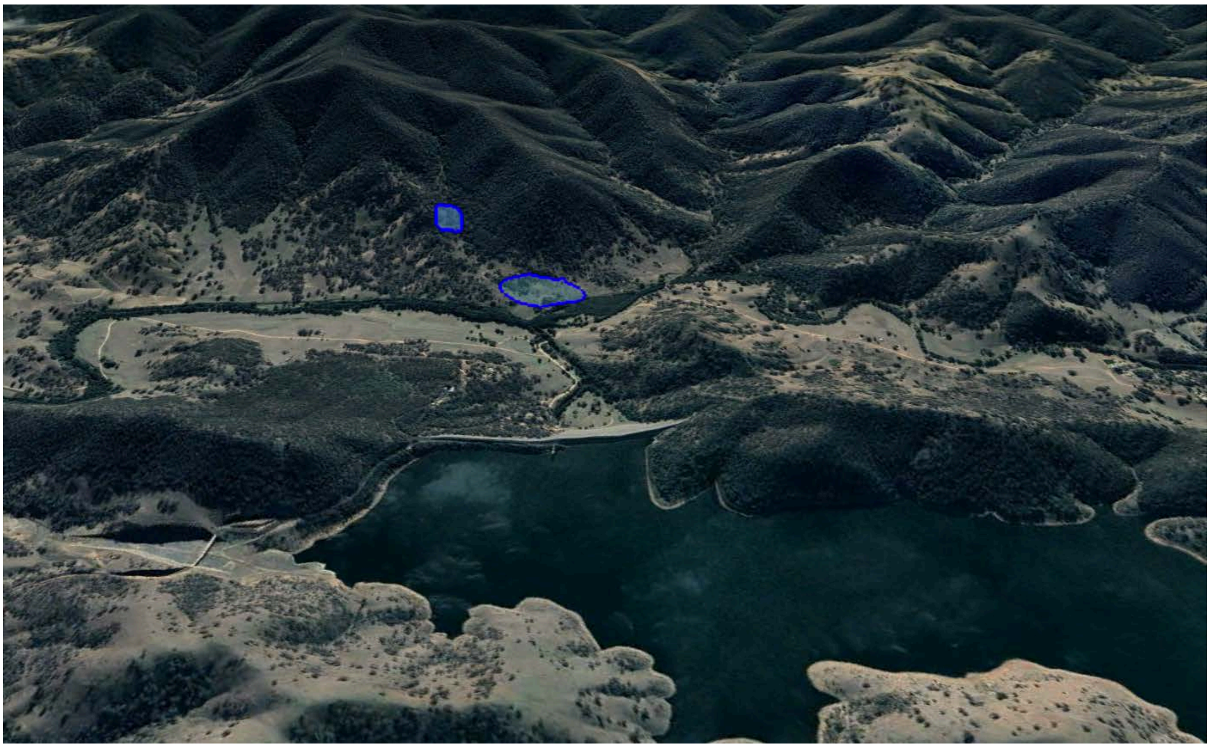


Figure 24: Google earth site location

Figure 25: Google earth site location with MPHES overlay. Upper reservoir 613m and lower reservoir 513m giving 100m elevation difference.

Plant Item	Cost ($ AUD)	Comment
Surface PowerStation	596,000	Above ground, modular shed type steel frame, color bond roof, concrete base, plumbing and misc. power and lighting, security and emergency systems
Waterway	94,065	2 x 100-150m surface penstock, 480-520mm dia GRP
Upper and Lower Reservoirs	2,400,000	2 x 50ML modular concrete wall tanks
Roads	80,000	200m Class 3 road to AS standard
Electro-mechanical power equipment	642,000	2 x 1000kW turbine/generators, 2 x 1000kW pump/motors. Governor and excitation for generator, main valves, motor DOL. Machines to operate at 3.3kV terminal voltage. Equipment pre-built, skid mounted
Main Transformer	69,000	2.2MVA dry-type GSUT, step up 3.3kV generator voltage to either 11 or 33kV.
Control System	48,000	Basic PLC control and HMI's, remote operation capability
Distribution and Switchgear	254,000	Switchboard, ACB's, Station transformer, control relays and protection. Station transformer to supply a 415V aux station supply from GSUT LV winding.
Overhead lines	126,255	1km, steel poles, ABC aerial line
DNSP Connection	100,000	DNSP Connection fee < 5MW
AEMO Due Diligence	0	Not applicable, non-registered embedded via NER 5A
EPC	308,652	Assumed 7%
TOTAL	**$4,717,972**	Total capital costs (2MW facility)
Total Capital per MW (+/- 30%)	**$2,358,986**	Benchmark cost ($/MW)

Table 14: Financial and technical summary for the 2MW MPHES Case Study at Windamere

4.2. Case Study 2: Concept Floating MPHES Plant

A further Case Study is briefly visited. The change as compared to the land-based deployment is the requirement to construct only one reservoir – the upper reservoir. The following summarizes the key differences:

- Removal lower reservoir cost
- Reduce land footprint of site
- Utilisation of otherwise unused space
- Access to higher heads close to water reservoirs otherwise unusable
- Addition of floating dock for powerhouse
- Addition of flexible coupling and expansion joints for penstock
- Same principal as established floating solar technologies (albeit heavier duty floating modules necessary)
- Further potential cost savings and efficiencies

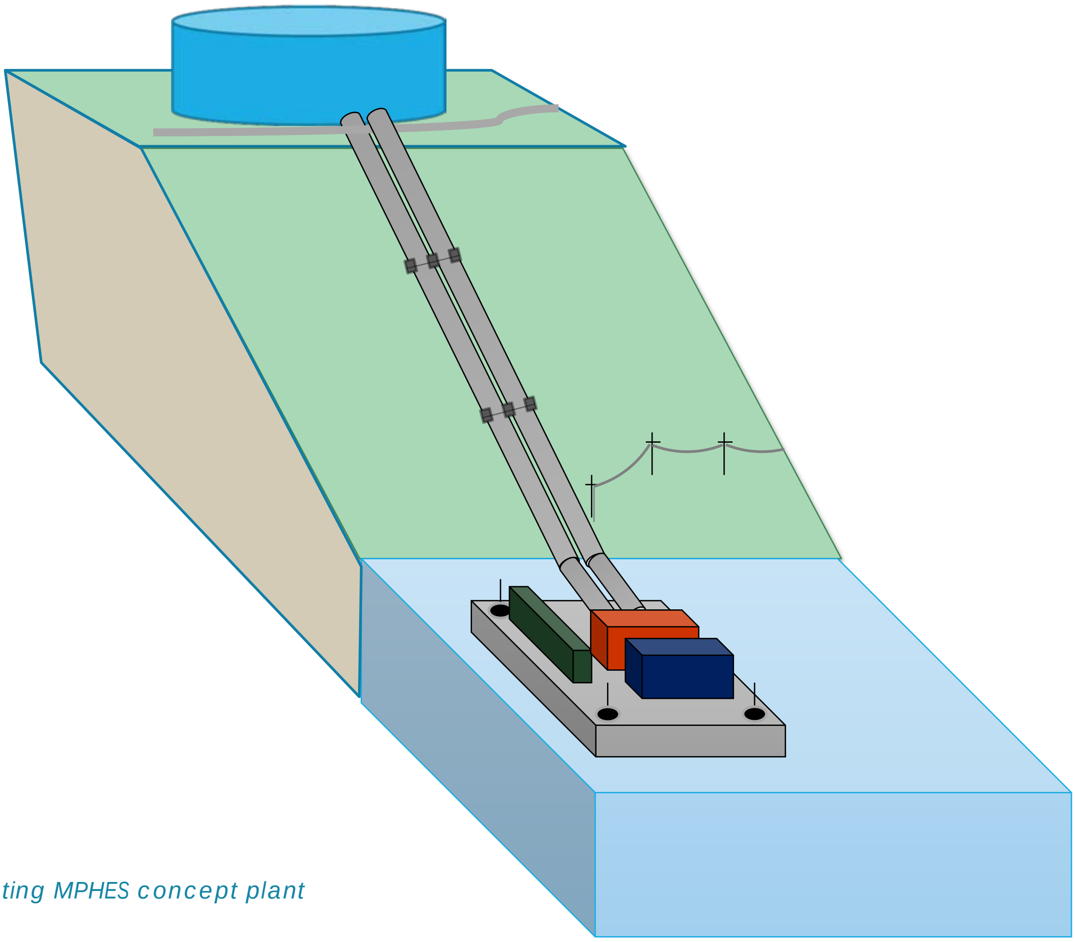


Figure 26: Floating MPHES concept plant

Further technical detail or feasibility commentary is beyond the scope of this Case Study. A conceptual approach is offered in Figure 27 and Figure 28. Figure 29 shows a Google earth overlay with a scaled up (5 x 2MW) 10MW deployment at Windamere Dam.

Figure 27: Floating dock example of practical application [82]

Figure 28: Floating dock individual float modules [82]

Figure 29: Google earth site location with Floating MPHES overlay with a scaled (5 x 2MW) 10MW deployment. Upper reservoir 651m and lower reservoir 546m giving 105m elevation difference.

Plant Item	Cost ($ AUD)	Comment
Floating PowerStation	400,000	Basic steel frame and roof. Extra cost to additional painting for surface protection and increases of IP level of equipment. Equipment design for outdoor ratings
Waterway	94,065	2 x 100-150m surface penstock, 480-520mm dia GRP
Upper Reservoir	1,200,000	1 x 50ML modular concrete wall tanks
Floating dock	100,000	200m^2 floating dock, 100,000kg capacity, 480kg load per floating block, 200 blocks, $278 per block, includes transport, install and decking
Roads	80,000	200m Class 3 road to AS standard
Electro-mechanical power equipment	642,000	2 x 1000kW turbine/generators, 2 x 1000kW pump/motors. Governor and excitation for generator, main valves, motor DOL. Machines to operate at 3.3kV terminal voltage.
Main Transformer	69,000	2.2MVA dry-type GSUT, step up 3.3kV generator voltage to either 11 or 33kV.
Control System	48,000	Basic PLC control and HMI's, remote operation capability
Distribution and Switchgear	254,000	Switchboard, ACB's, Station transformer, control relays and protection. Station transformer to supply a 415V aux station supply from GSUT LV winding.
Overhead lines	126,255	1km, steel poles, ABC aerial line
DNSP Connection	100,000	DNSP Connection fee < 5MW
AEMO Due Diligence	0	Not applicable, non-registered embedded via NER 5A
EPC	217,932	Assumed 7%
TOTAL	**$3,331,252**	Total capital costs (2MW facility)
Total Capital per MW (+/- 20%)	**$1,665,626**	Benchmark cost ($/MW)

Table 15: Financial and technical summary for a 2MW Floating MPHES Case Study at Windamere

5. Results

The technical design base in Chapter 3.2 and cost base in Chapter 3.3 was applied to two Case Studies. Further detail of these Case Studies is given in Appendix I. The cost curves are presented in Figure 30.

For P = 1 – 30MW, from Figure 30 the capital cost per MW expressed in million AUD for the conceptual MPHES and Floating MPHES is given by:

$$C_{MPHES} = 2.79\ P^{-0.104}$$

$$C_{FMPHES} = 1.73\ P^{-0.053}$$

The scalable costs for the MPHES are found to be generally lower than the NSW benchmark of recent solar PV grid connections.

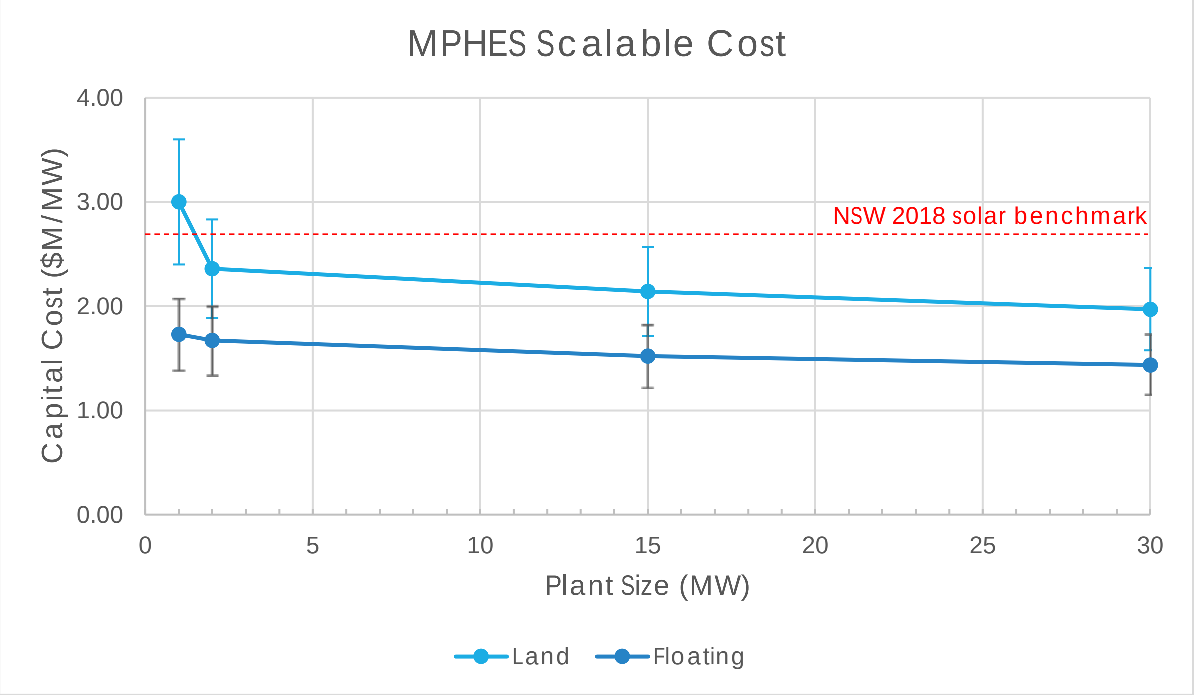


Figure 30: Cost curves for scalable land based (ie. two constructed reservoirs) MPHES system and floating (ie. one constructed upper reservoir) MPHES system.

To evaluate the economic feasibility of the concept MPHES the Net Present Value (NPV) and pre-tax Internal Rate of Return (IRR) has been determined based on the technical cost and anticipated revenue streams alongside the relevant assumptions. The calculation is performed in RETScreen. The results are detailed in Appendix I and summarised in Table 16.

Reflecting on the project risk profile, the given positive NPV and IRR above 10%, it could be considered economically viable and above the benchmark for a typical private sector project hurdle rate.

Financial Viability	**MPHES**	**FMPHES**
Simple Payback	16.4 years	10.5 years
NPV	$875,000	$2,600,000
IRR	10.2 %	18.8 %
B-C ratio	1.6	3.6

Table 16: Economic analysis summary showing payback period, NPV, IRR and benefit-cost ratio for the two case study MPHES system

6. Conclusions and Recommendations

The following is a summation of the conclusions found in this research:

1. The concept of a MPHES is technically viable utilising conventional and well-established technologies. This may offer an opportunity to reduce project development times from pre-feasibility to first water on from the order of years to months.
2. Scalable MPHES has the advantage of being deployable and makes use of lower value, unused land, otherwise not suitable for large scale PHES development
3. MPHES is not considered to replace large scale PHES, but offer a potential alternative to wider spread, distributed energy storage to support non-synchronous power generation technologies achieve future NER compliance and enhance power system stability and security.
4. Analysis of Case Studies indicates the deployable MPHES approach is financially viable and can offer scalable and dispatchable power at lowest cost to serve. It is also flexible to support emerging and future revenue streams making it fit for the future.
5. MPHES has been found to be able to synergise the characteristic advantages of solar and wind with the technical benefits of synchronous machine technology
6. Pre-engineered reservoirs and skid-mounted type standardised components can fast track project development times and lower risk. This is expected to be favoured by equity investors and improve access to project financing mechanisms.
7. MPHES can significantly reduce entry barriers that limit pumped hydro deployment, increasing competition in the NEM and accelerating innovation.
8. MPHES promotes sustainability in the NEM by firming other renewable power generation by its inherent dispatchability. Dispatchability, modularisation and

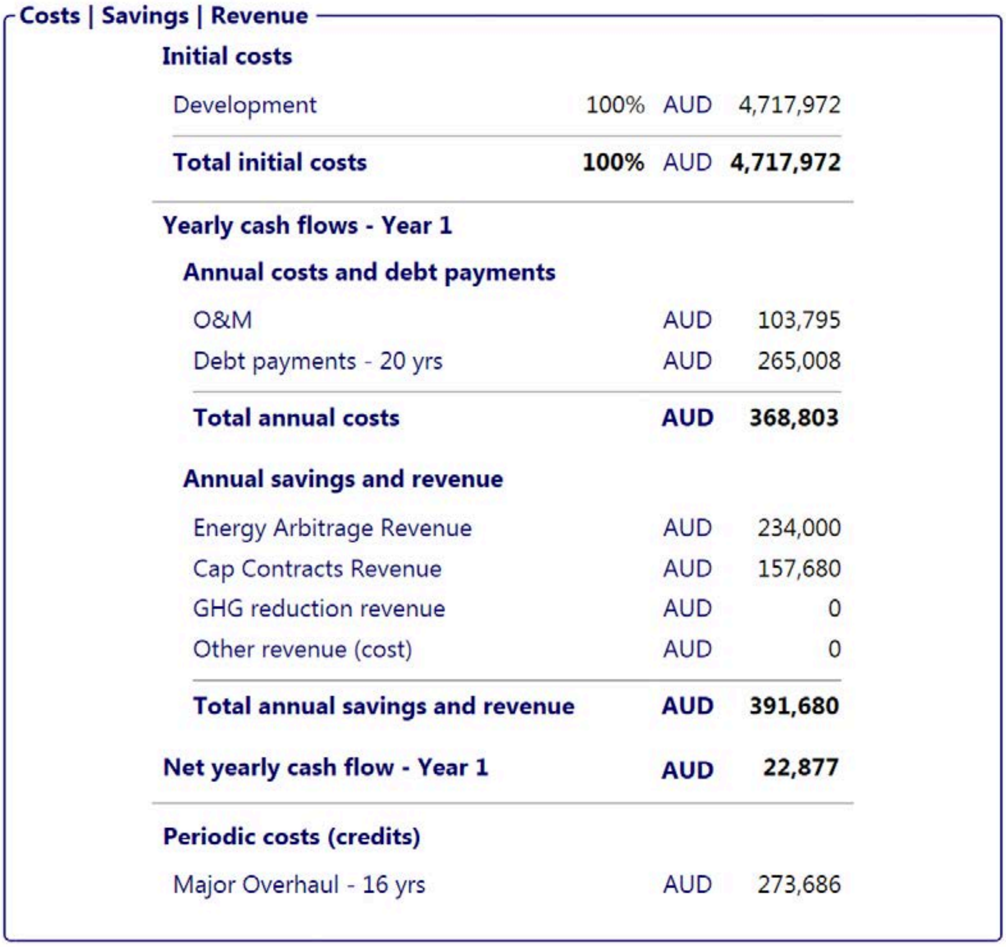
simplicity are key properties as renewable play an expanding role in Australia's future generation mix.

Recommendations for further work and potential solutions are:

1. The NSW government are actively pursuing energy storage grid integration both large scale and distributed, conventional and new technologies. WaterNSW are also seeking expressions of interest for energy storage technologies with opportunity to create value from existing state-owned dam assets. REZ's have been identified to encourage development. It is currently and excellent time to propose a MPHES concept plant in NSW.
2. Further economic analysis in the viability of MPHES targeting only ancillary services markets in lieu of energy arbitrage revenue. Utilising revenue frameworks from both domestic and foreign energy markets to investigate what potential future revenue could be yield from only ancillary services including FFR, SCR and inertia provision.
3. A key consideration for MPHES deployment is proximity to transmission infrastructure. It is recommended to select site locations in close proximity to existing aerial lines or substations, without network constraints.
4. Further technical analysis is required to evaluate the practicality of a floating powerhouse, including the transition interface from a land based to water-based penstock.
5. Explore the opportunity of potential revenue from open energy exchange platforms such as The Decentralised Energy Exchange (or dEx) and Power Ledger.

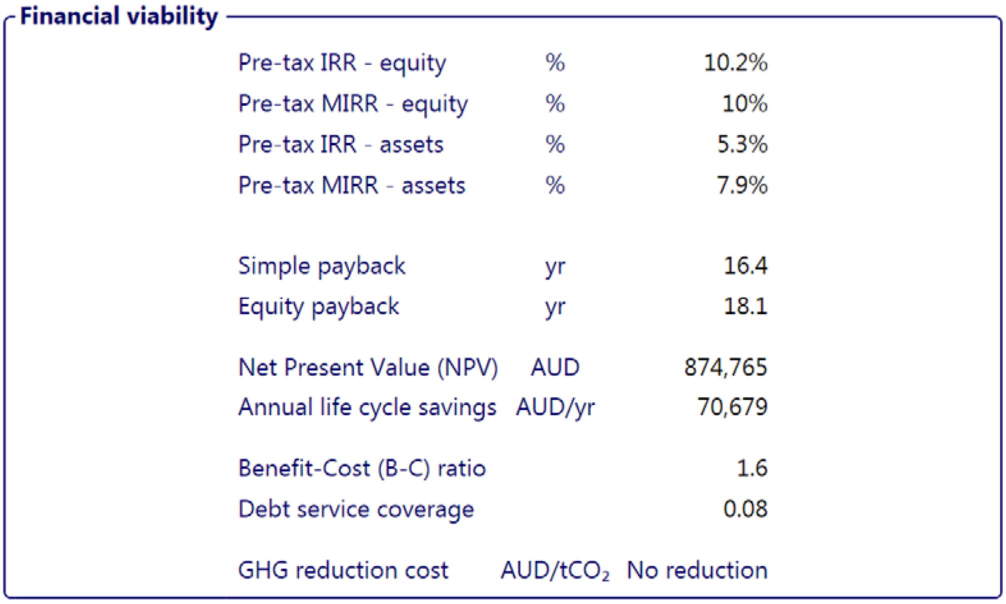
APPENDIX I - Financial Viability

Land based MPHES – RETScreen analysis



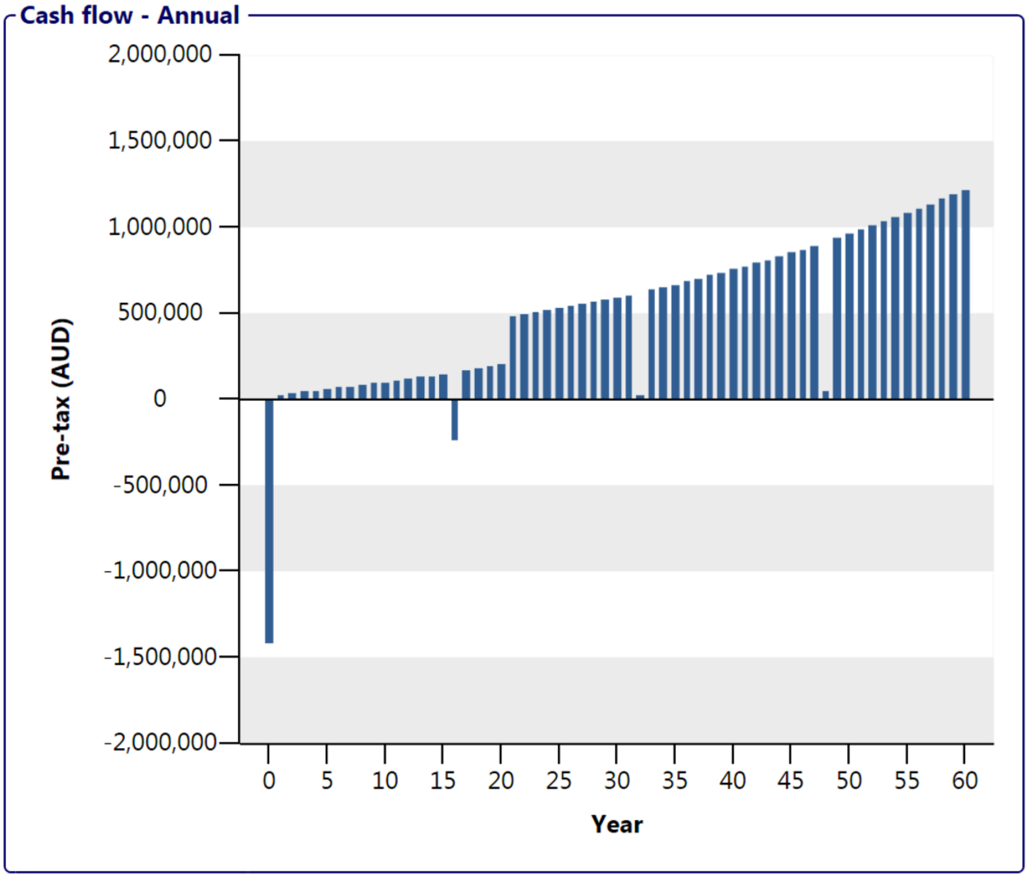
Costs | Savings | Revenue

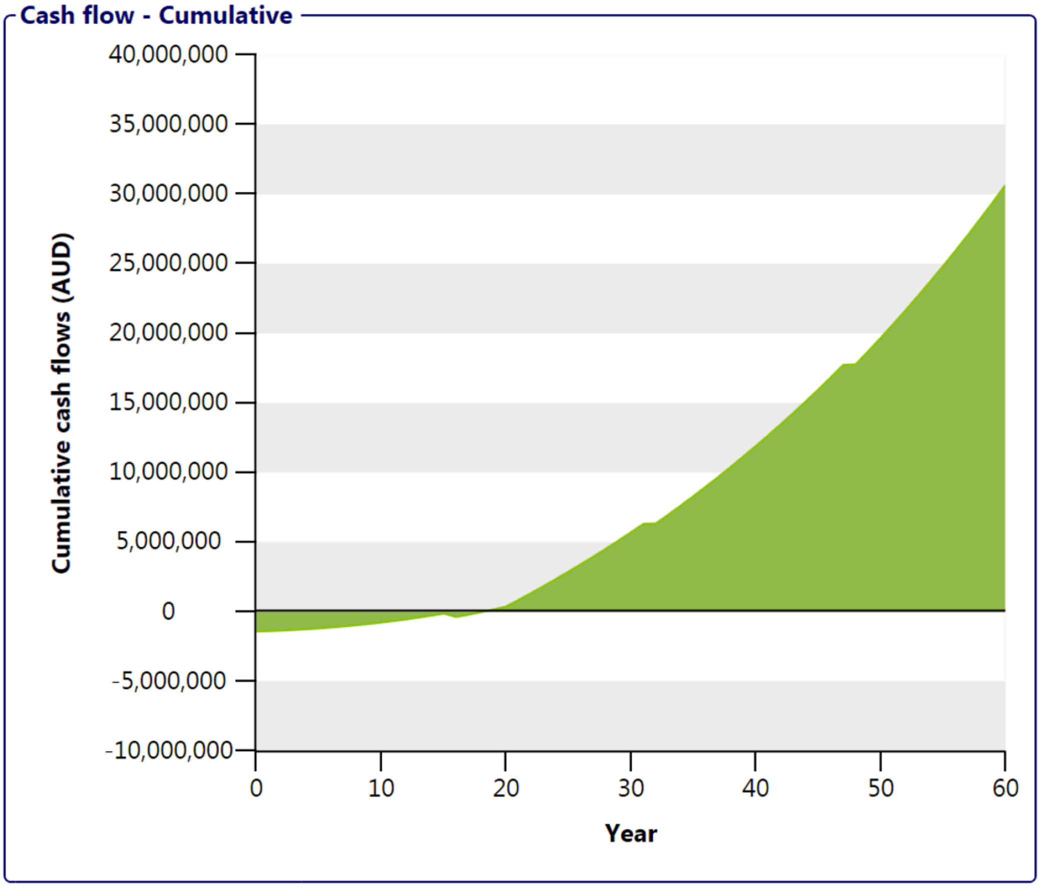
Initial costs			
Development	100%	AUD	4,717,972
Total initial costs	**100%**	AUD	**4,717,972**
Yearly cash flows - Year 1			
Annual costs and debt payments			
O&M		AUD	103,795
Debt payments - 20 yrs		AUD	265,008
Total annual costs		**AUD**	**368,803**
Annual savings and revenue			
Energy Arbitrage Revenue		AUD	234,000
Cap Contracts Revenue		AUD	157,680
GHG reduction revenue		AUD	0
Other revenue (cost)		AUD	0
Total annual savings and revenue		**AUD**	**391,680**
Net yearly cash flow - Year 1		**AUD**	**22,877**
Periodic costs (credits)			
Major Overhaul - 16 yrs		AUD	273,686



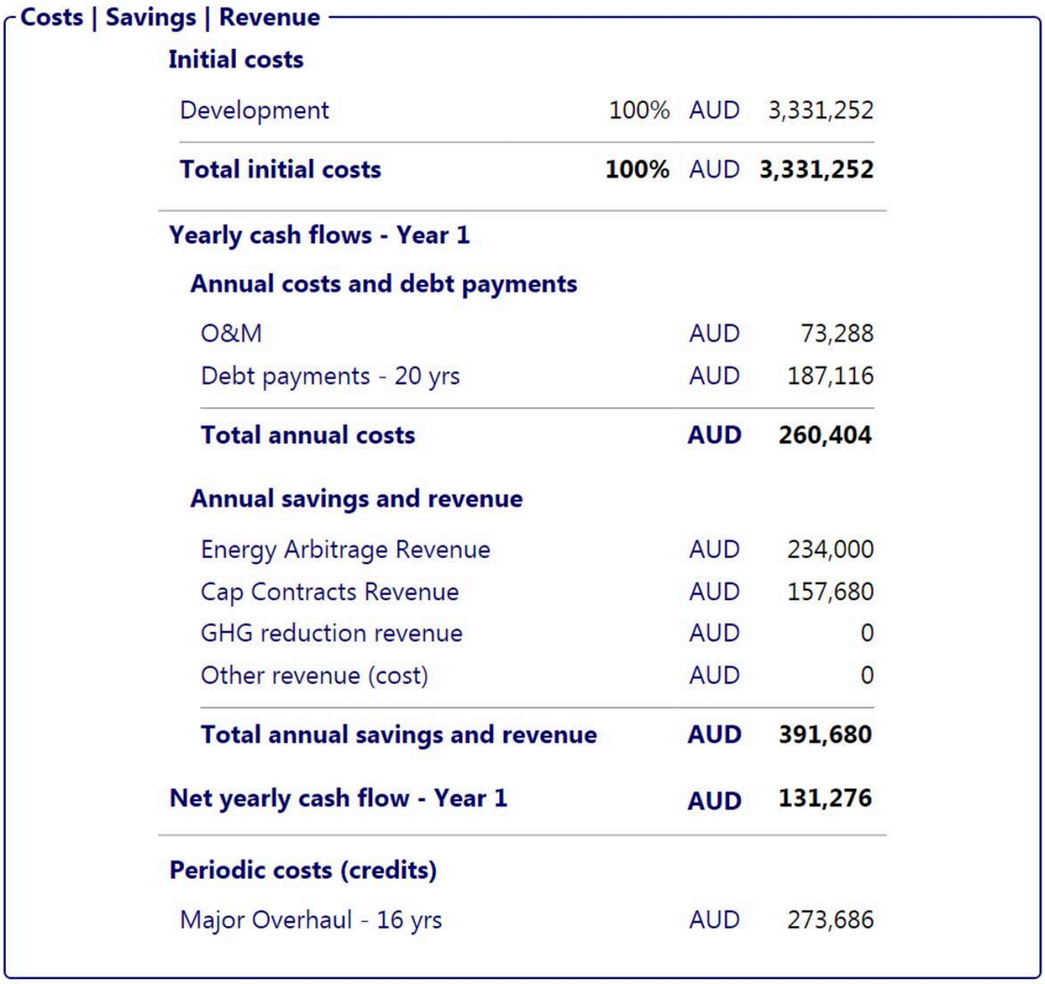
Financial viability

Pre-tax IRR - equity	%	10.2%
Pre-tax MIRR - equity	%	10%
Pre-tax IRR - assets	%	5.3%
Pre-tax MIRR - assets	%	7.9%
Simple payback	yr	16.4
Equity payback	yr	18.1
Net Present Value (NPV)	AUD	874,765
Annual life cycle savings	AUD/yr	70,679
Benefit-Cost (B-C) ratio		1.6
Debt service coverage		0.08
GHG reduction cost	AUD/tCO$_2$	No reduction


Cash flow - Annual
Pre-tax (AUD)
2,000,000
1,500,000
1,000,000
500,000
0
-500,000
-1,000,000
-1,500,000
-2,000,000
0
5
10
15
20
25
30
35
40
45
50
55
60
Year


Cash flow - Cumulative
Cumulative cash flows (AUD)
40,000,000
35,000,000
30,000,000
25,000,000
20,000,000
15,000,000
10,000,000
5,000,000
0
-5,000,000
-10,000,000
0
10
20
30
40
50
60
Year

Floating MPHES – RETScreen analysis



Costs | Savings | Revenue

Initial costs

Development	100%	AUD	3,331,252
Total initial costs	**100%**	AUD	**3,331,252**

Yearly cash flows - Year 1

Annual costs and debt payments

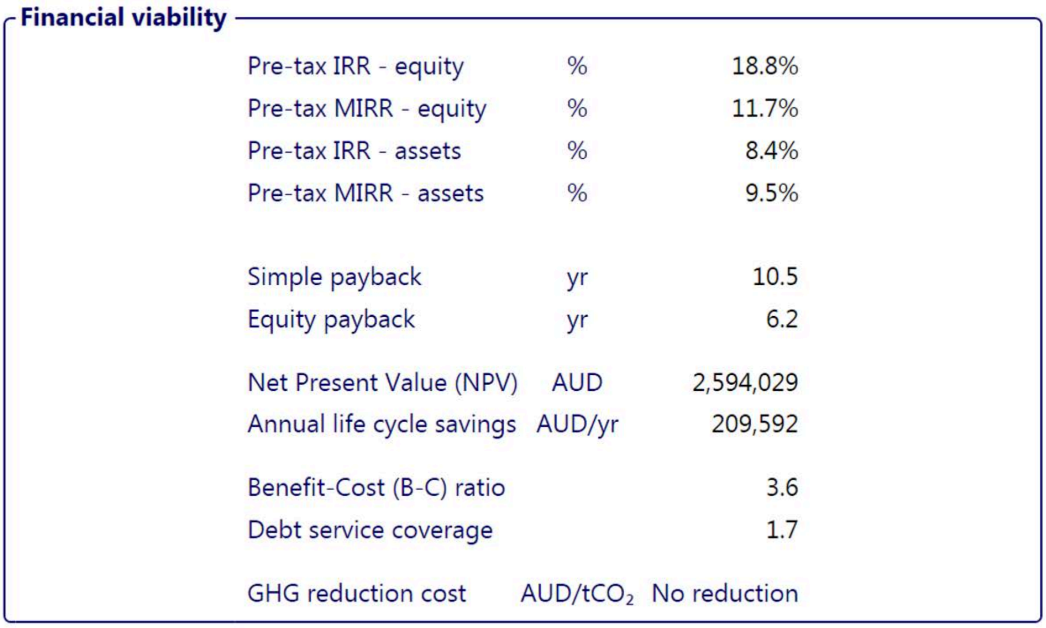
O&M	AUD	73,288
Debt payments - 20 yrs	AUD	187,116
Total annual costs	**AUD**	**260,404**

Annual savings and revenue

Energy Arbitrage Revenue	AUD	234,000
Cap Contracts Revenue	AUD	157,680
GHG reduction revenue	AUD	0
Other revenue (cost)	AUD	0
Total annual savings and revenue	**AUD**	**391,680**
Net yearly cash flow - Year 1	**AUD**	**131,276**

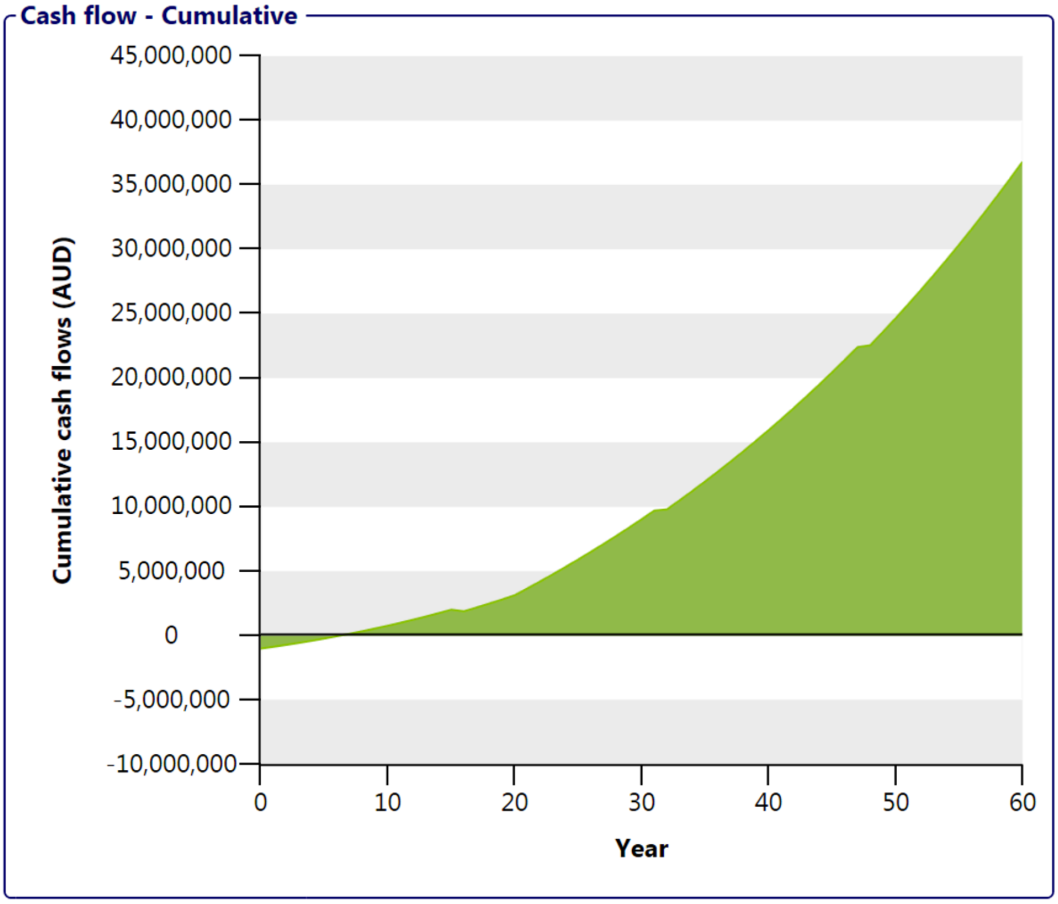
Periodic costs (credits)

Major Overhaul - 16 yrs	AUD	273,686

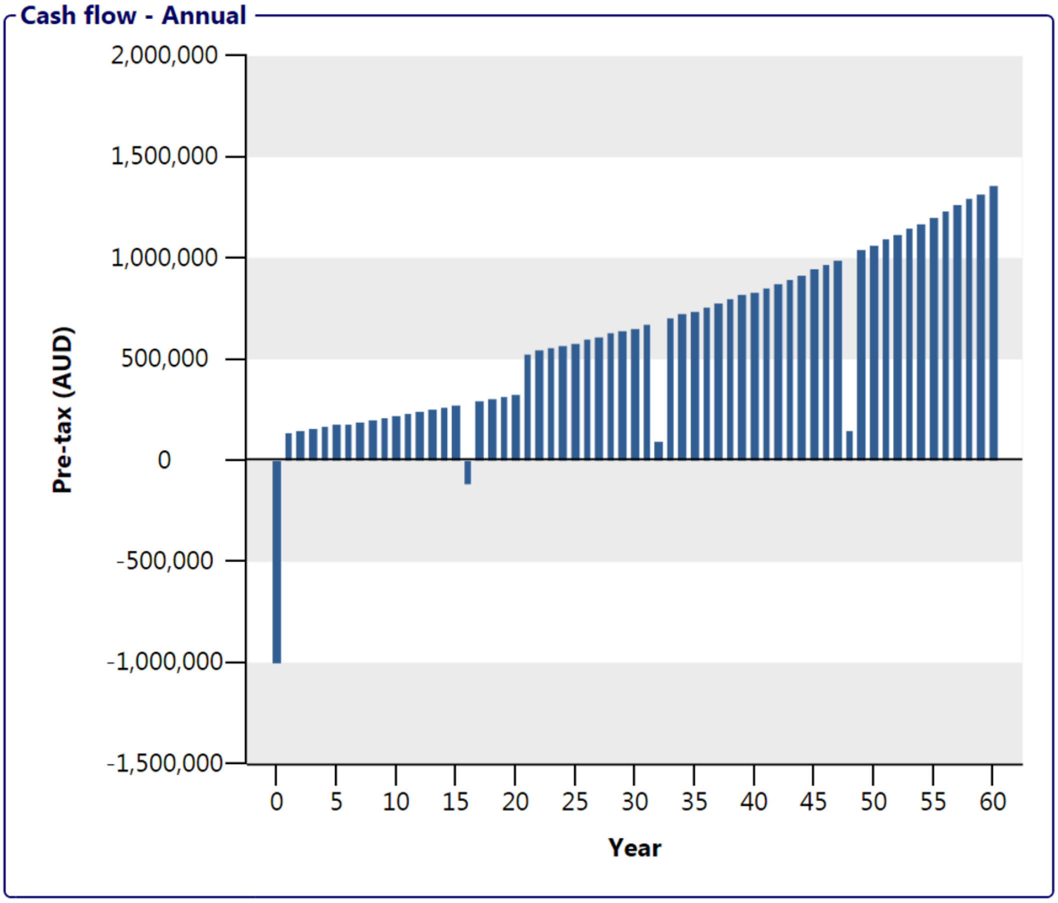


Financial viability

Pre-tax IRR - equity	%	18.8%
Pre-tax MIRR - equity	%	11.7%
Pre-tax IRR - assets	%	8.4%
Pre-tax MIRR - assets	%	9.5%
Simple payback	yr	10.5
Equity payback	yr	6.2
Net Present Value (NPV)	AUD	2,594,029
Annual life cycle savings	AUD/yr	209,592
Benefit-Cost (B-C) ratio		3.6
Debt service coverage		1.7
GHG reduction cost	AUD/tCO_2	No reduction



Cash flow - Cumulative



Cash flow - Annual

Cost Benefit Summary

Cost-benefit 2MW MPHES	Amount
Land based concept plant capital cost	$4,717,972
Floating concept plant capital cost	$3,331,252
Energy Arbitrage p.a. benefit	$234,000
Cap contract revenue p.a. benefit	$157,680

Table 17:

Land based MPHES cost curve

$y = 2.7903 * P^{-0.104}$, $R^2 = 0.8526$, \$M/MW for $1 < P < 30$MW.

Floating MPHES cost curve

$y = 1.7332 * P^{-0.053}$, $R^2 = 0.9906$, \$M/MW for $1 < P < 30$MW.

Future energy arbitrage revenue forecast

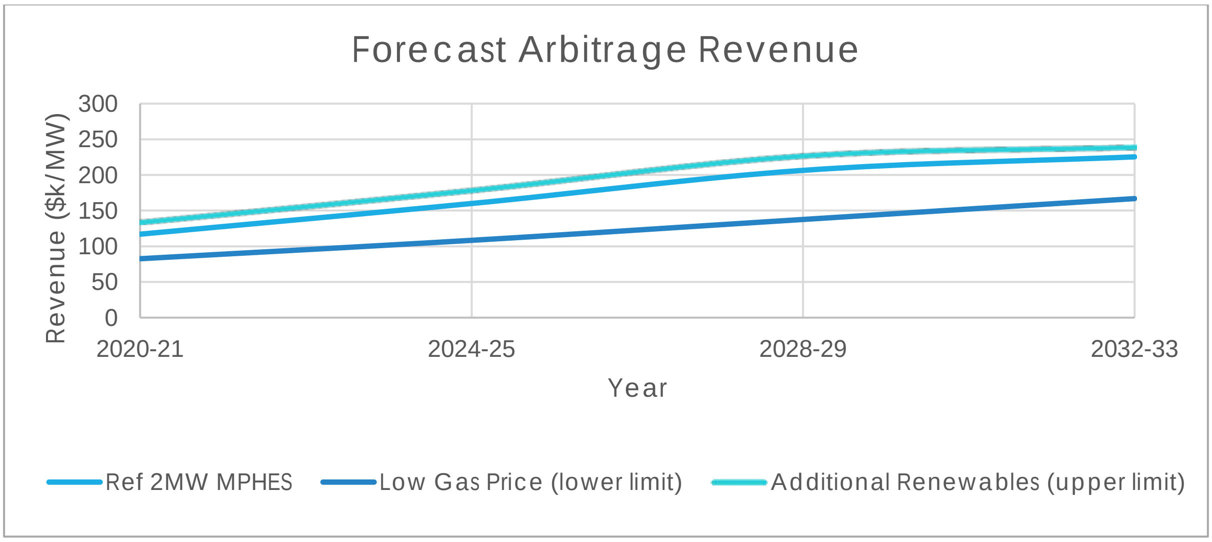


Figure 31: Future value of energy arbitrage of 2MW PHES compared with different forecast scenarios. Adapted from [10]

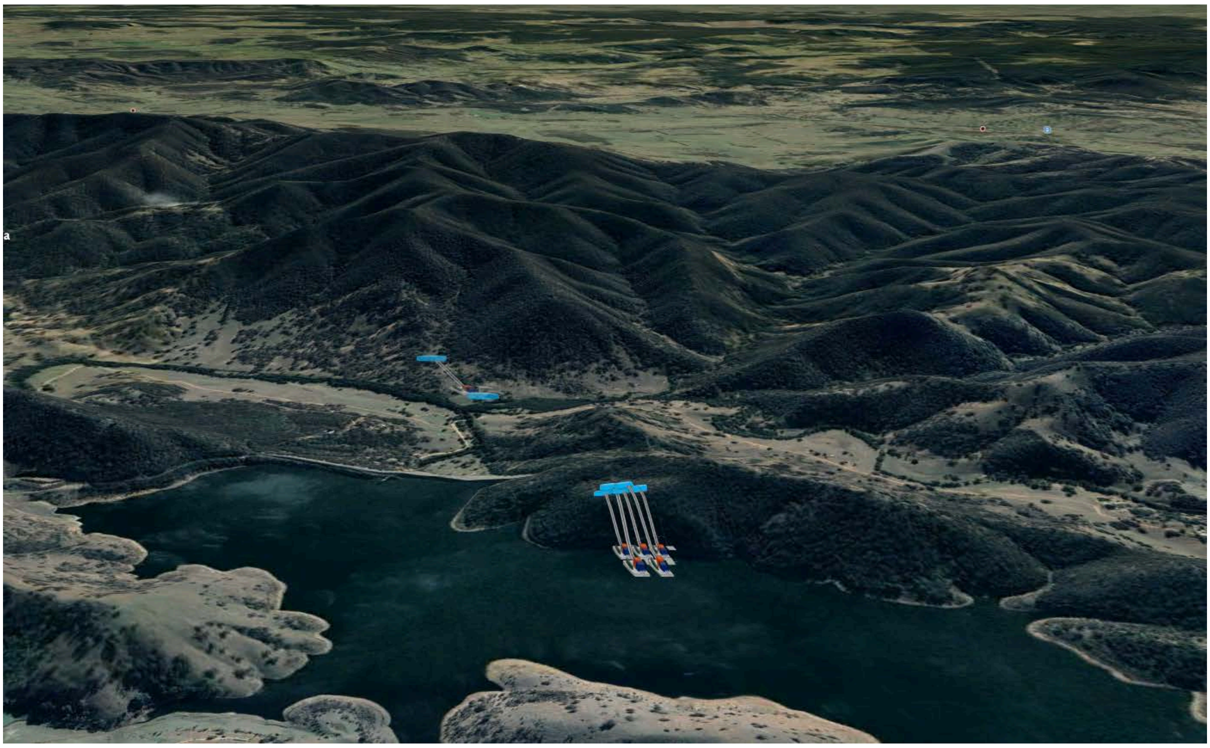


Figure 32: Google maps overlay showing land based 2MW concept plant and 10MW scaled PHES at Windamere Dam.

References

[1] US Department of Energy: Water Power Technologies Office Peer Review Hydropower Program, "Oak Ridge National Laboratory," 2016. [Online]. Available: https://www.energy.gov/sites/prod/files/2017/04/f34/modular-pumped-storage-hydropower-feasibility.pdf. [Accessed 20 August 2019].

[2] Shell Energy North America: Hydro battery update, Oakridge National Laboratory, *US Department of Energy,* 2018.

[3] NSW Government, "NSW Pumped Hydro Roadmap," State of NSW through its Department of Planning and Environment, 2018.

[4] REN21, "RENEWABLES 2018 GLOBAL STATUS REPORT: A comprehensive annual overview of the state of renewable energ," REN21: Renewable Energy Policy Network for the 21st Century, 2018.

[5] Internation Hydropower Association (IHA), "2018 Hydropower Status Report: Sector trends and insights," IHA, 2018.

[6] Institute for Energy Economics and Financial Analysis (IEEFA), "China plans massive pumped hydro investment to ease renewable energy curtailments," [Online]. Available: http://ieefa.org/china-plans-massive-pumped-hydro-investment-to-ease-renewable-energy-curtailments/. [Accessed 22 April 2019].

[7] Australian Energy Regulator (AER), "Generation capacity and peak demand," AER, [Online]. Available: https://www.aer.gov.au/wholesale-markets/wholesale-statistics/generation-capacity-and-peak-demand. [Accessed 12 March 2019].

[8] European Energy Research Alliance , "TECHNOLOGICAL DEVELOPMENTS FOR PUMPED- HYDRO ENERGY STORAGE," EERA, 2014.

[9] Hydro Tasmania, "Battery of the Nation – Tasmanian pumped hydro in Australia’s future electricity market. Concept Study Knowledge sharing report," 2018.

[10] CSIRO, "GenCost 2018: Updated projections of electricity generation technology costs," CSIRO, 2018.

[11] P. G. (. Jenny Hayward, "Electricity generation technology cost projections 2017-2050," CSIRO, 2017.

[12] T. G. GE, "This Unique Combo Of Wind And Hydro Power Could Revolutionize Renewable Energy," GE, 16 October 2016. [Online]. Available: https://www.ge.com/reports/unique-combo-wind-hydro-power-revolutionize-renewable-energy/. [Accessed 14 April 2019].

[13] ARENA, "One step closer for giant Kidston solar and pumped hydro," 17 November 2017. [Online]. Available: https://arena.gov.au/news/one-step-closer-giant-kidston-solar-pumped-hydro/. [Accessed 27 December 2018].

[14] Genex Power, "250MW Kidston Pumped Storage Hydro Project (K2H)," 2015. [Online]. Available: https://www.genexpower.com.au/project-details.html. [Accessed 27 December 2018].

[15] AEMO, "The National Electricity Market Fact Sheet," [Online]. Available: https://www.aemo.com.au/-/media/Files/Electricity/NEM/National-Electricity-Market-Fact-Sheet.pdf. [Accessed 27 December 2018].

[16] AEMO, "National Electricity Market," [Online]. Available: https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM. [Accessed 27 December 2018].

[17] K. M. C. M. T. E. M. O. Alan Finkel, "Independent Review into the Future Security of the National Electricity Market: Blueprint for the Future (Finkel Review)," Commonwealth of Australia, 2017.

[18] Australian Energy Storage Alliance (AESA) , "Opportunities for Utility Scale Battery Storage in NSW: A report by the Australian Energy Storage Alliance in partnership with AECOM and supported by the NSW Energy and Resources Knowledge Hub through the NSW Department of Industry".

[19] AGL, "Liddell Innovation Project: Frequently asked Questions," 2015. [Online]. Available: https://www.agl.com.au/-/media/aglmedia/documents/about-agl/sustainability/rehabilitation-and-transition/frequently-asked-questions.pdf?la=en&hash=354C409999D7733C3A67B411D8F5CA14. [Accessed 27 December 2018].

[20] H. Saddler, "Australia’s electricity market is not agile and innovative enough to keep up," The Conversation, 17 February 2017. [Online]. Available: https://theconversation.com/australias-electricity-market-is-not-agile-and-innovative-enough-to-keep-up-72870. [Accessed 27 December 2018].

[21] WaterNSW, "Who we are," 2018. [Online]. Available: https://www.waternsw.com.au/about/who-we-are. [Accessed 27 December 2018].

[22] NSW Government, "Hydro Energy in NSW," [Online]. Available: https://energy.nsw.gov.au/renewables/renewable-generation/hydro-energy. [Accessed 28 December 2018].

[23] G. Jetson, "Pumped hydro storage – an Australian overview," 2017 March 2017. [Online]. Available: https://georgejetson.org/pumped-hydro-storage-australia/. [Accessed 28 December 2018].

[24] P. B. WSP, "Utility scale bulk energy storage Current use in the NEM, and its importance in a future low carbon electricity system," 2016.

[25] NSW Government Chief Scientist & Engineer, Mary O'Kane, "Final report from the Energy Security Taskforce," 19 December 2017.

[26] AEMO, "Integrated System Plan For the National Electricity Market," July 2018.

[27] NSW Government, "Hydro Energy in NSW," [Online]. Available: https://energy.nsw.gov.au/renewables/renewable-generation/hydro-energy. [Accessed 2 January 2019].

[28] F. Brady, "Dictionary on Electricity Contribution on Australia (CIGRE)," CIGRE, 1996.

[29] Snowy Scheme Museum, "Snowy Scheme Museum Celebrating the Snowy Mountains Hydro-Electric Scheme," [Online]. Available: https://www.snowyschememuseum.com.au/. [Accessed 2 January 2019].

[30] Snowy Hydro, "Looking forward - Snowy 2.0," [Online]. Available: https://www.snowyhydro.com.au/our-scheme/snowy20/. [Accessed 2 January 2019].

[31] Marsden Jacob Associates, "NEM outlook and Snowy 2.0," Report prepared for Snowy Hydro Limited, 2018.

[32] ARENA, "Media Release: Shoalhaven pumped hydro could double in size," [Online]. Available: https://arena.gov.au/assets/2018/10/ARENA-Media-Release_Origin-

Shoalhaven-pumped-hydro-expansion-feasibility-study.pdf. [Accessed 2 January 2019].

[33] ARENA, "Kidston pumped storage project: Feasibility study into the construction of a pumped storage hydroelectric power plant at the disused Kidston Gold Mine in North Queensland.," [Online]. Available: https://arena.gov.au/projects/kidston-pumped-storage-project/. [Accessed 2 January 2019].

[34] Renew Economy, "600MW pumped hydro project proposed for northern NSW," 11 October 2017. [Online]. Available: https://reneweconomy.com.au/600mw-pumped-hydro-project-proposed-for-northern-nsw-11244/. [Accessed 3 January 2019].

[35] ARENA, ARUP, Energy Australia, The University of Melbourne, "Cultana Pumped Hydro Project: Knowledge Sharing Report," Australian Government - Australian Renewable Energy Agency, 2017.

[36] Melbourne Energy Institute (MEI), "Opportunities for Pumped Hydro Energy Storage in Australia Arup-MEI Research," 27 February 2014.

[37] ROAM Consulting, "ROAM report on Pumped Storage modelling for AEMO 100% Renewables project," 2012.

[38] Black & Veatch, "COST AND PERFORMANCE DATA FOR POWER GENERATION TECHNOLOGIES Prepared for the National Renewable Energy Laboratory," NREL, February 2012.

[39] CSIRO, "AEMO 100% Renewable Energy Study: Energy Storage," CSIRO, Newcastle, 2012.

[40] NSW Government, "Handbook for large-scale hydro energy projects," State of NSW through its Department of Planning and Environment , 2018.

[41] NSW Government, "NSW Planning Portal: What is an "Environmental Planning Instrument (EPI)"?," [Online]. Available: https://www.planningportal.nsw.gov.au/node/2057. [Accessed 2 January 2019].

[42] New South Wales Government, "NSW Legislation: Environmental Planning and Assessment Regulation 2000," 28 February 2019. [Online]. Available: https://www.legislation.nsw.gov.au/#/view/regulation/2000/557. [Accessed 25 April 2019].

[43] WaterNSW, "Water Access Licences," [Online]. Available: https://www.waternsw.com.au/customer-service/water-licensing/about-licences/water-access-licences. [Accessed 25 April 2019].

[44] C. Penche, Layman's handbook on how to develop a small hydro site. Second Edition., European Small Hydropower Association (ESHA), 1998.

[45] The Clean Energy Council, "Grid," [Online]. Available: https://www.cleanenergycouncil.org.au/resources/technologies/grid. [Accessed 25 April 2019].

[46] AEMO, "Participant Categories in the NEM," [Online]. Available: http://www.aemo.com.au/-/media/Files/Electricity/NEM/Participant_Information/Participant-Categories-in-the-NEM.pdf. [Accessed 25 April 2019].

[47] AEMC, "National Electricity Rules Version 120," 11 April 2019. [Online]. Available: https://www.aemc.gov.au/regulation/energy-rules/national-electricity-rules/current. [Accessed 25 April 2019].

[48] Ausgrid, "Embedded generation information pack: non-micro embedded generators," [Online]. Available: https://www.ausgrid.com.au/Connections/Apply-for-a-connection/Embedded-generation/Connecting-non-micro-Embedded-Generation. [Accessed 25 April 2019].

[49] Voith, "Small hydro," [Online]. Available: http://voith.com/corp-en/industry-solutions/hydropower/small-hydro.html. [Accessed 9 March 2019].

[50] G. B. Gharehpetian, Distributed Generation Systems: Design, Operation and Grid Integration. 1st Edition., Butterworth-Heinemann; 1 edition (June 7, 2017), 2017.

[51] C. G. Bahtiyar Dursun, "The role of hydroelectric power and contribution of small hydropower plants for sustainable development in Turkey," *Renewable Energy,* vol. 36, pp. 1227-1235, 2011.

[52] M. K. I. U. J. J. R. E. E. d. C. B. Fabio Jose Garcia, "Design Requirements of Generators Applied to Low-Head Hydro Power Plants," *IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 30, NO. 4, DECEMBER 2015.*

[53] Oregon State University, "ESE471 Lecture Slides - Energy Storage Systems: Pumped Hydro," [Online]. Available: section 3: pumped-hydro energy storage - Oregon State University
web.engr.oregonstate.edu/~webbky/ESE471.../Section%203%20Pumped%20Hydro.p.... [Accessed January 2019].

[54] Voith, "Pumped storage machines Reversible pump turbines, Ternary sets and Motor-generators," Voith Hydro Holding GmbH, Germany, 2011.

[55] Andritz Group, "SMALL AND MINI HYDROPOWER SOLUTIONS," 2018. [Online]. Available: https://www.andritz.com/resource/blob/33446/d2118386d6a8dbbec556c6e159391c64/hy-small-and-mini-hydropower-solutions-en-data.pdf. [Accessed 16 May 2019].

[56] Norwegian Water Resources and Energy Directorate (NVE), "COST BASE FOR SMALL-SCALE HYDROPOWER PLANTS (<10,000kW)," Oslo, Norway, 2012.

[57] ARENA, "Renewable Power Generation Costs in 2014: Chapter 7 Hydropower," 2014. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_RE_Power_Costs/IRENA_RE_Power_Costs_2014_report_chapter7.pdf. [Accessed 9 February 2019].

[58] J. Gilmore, "ARENA WIRE: Winning the uphill battle. How pumped hydro could solve the storage problem," 20 August 2017. [Online]. Available: https://arena.gov.au/blog/pumped-hydro/. [Accessed Feburary 2019].

[59] ARENA, "Moree Solar Farm," [Online]. Available: https://arena.gov.au/projects/moree-solar-farm/. [Accessed 12 February 2019].

[60] ARENA, "AGL Solar Project - Broken Hill and Nyngan Solar Farms," [Online]. Available: https://arena.gov.au/projects/agl-solar-project/. [Accessed 12 February 2019].

[61] Concept, "Successful concept tank relocation," 31 May 2017. [Online]. Available: https://www.conceptservices.com.au/2017/05/successful-concept-tank-relocation/. [Accessed 15 February 2019].

[62] Ausgrid, "Area Plans Overview: Attachment 5.23," Ausgrid, 2014.

[63] International Hydropower Association (IHA), "Norway Statistics," [Online]. Available: https://www.hydropower.org/country-profiles/norway. [Accessed 22 February 2019].

[64] Concept Environmental Services, "Concept Tanks," 2019. [Online]. Available: https://www.conceptservices.com.au/. [Accessed 2018 November 22].

[65] NSW Government: Department of Primary Industries, Office of Water, "NSW Reference Rates Manual Valuation of water supply, sewerage and stormwater assets," [Online]. Available: https://www.water.nsw.gov.au/__data/assets/pdf_file/0004/549598/nsw-reference-rates-manual-valuation-of-water-supply-sewerage-and-stormwater-assets.pdf. [Accessed 26 March 2019].

[66] Australian Government: Department of Infrastructure, Regional Development and Cities, "Road construction cost and infrastructure procurement benchmarking: 2017 update," 2017.

[67] Zonga Pump Industry Co., "Centrifugal Water Pumps," [Online]. Available: http://www.zongdapump.com/product/60826896862-807400685/Centrifugal_1800_m3_h_Double_Suction_Water_Pump_for_Irrigation.html. [Accessed 25 April 2019].

[68] Victora State Government: Environment, Land, Water and Planning Department (DELWP), "PB Report: Indicative Costs for Replacing SWER Lines," [Online]. Available: https://www.energy.vic.gov.au/safety-and-emergencies/powerline-bushfire-safety-program/reports-and-consultation-papers/pb-report-indicative-costs-for-replacing-swer-lines. [Accessed 23 April 2019].

[69] IRENA, "RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES Volme 1: Power Sector Issue 3/5 Hydropower," June 2012.

[70] Ausgrid, "Non-Registered Embedded Generators Guideline Part of NER Chapter 5A Information Pack," Ausgrid, 2015.

[71] Ausgrid, "Registered Embedded Generators Guideline Part of NER Chapter 5 Information Pack," Ausgrid, 2015.

[72] AEMO, "SCHEDULE OF FEES AND CHARGES FOR GENERATOR CONNECTIONS," AEMO, 2018.

[73] T. F. M. S. Dylan McConnell, "Estimating the value of electricity storage in an energy-only wholesale market," *Applied Energy,* vol. 159, pp. 422-432, 2015.

[74] AEMO, "Market Notices: CHG0049458 : Planned System Change - 2018/19," AEMO, 18 June 2018. [Online]. Available: http://aemo.com.au/Market-Notices?searchString=63243. [Accessed 25 April 2019].

[75] Australian Energy Regulator (AER), "Electricity Report: 9 - 15 December 2018," AER, 2018.

[76] Hornsdale Power Reserve, [Online]. Available: https://hornsdalepowerreserve.com.au/. [Accessed 24 April 2019].

[77] South Australian Council of Social Service (SACOSS), "Utility Scale Storage in the Move to Zero Carbon: A review of the first 9 months of HPR Operation," October 2018. [Online]. Available: https://www.aemc.gov.au/sites/default/files/2018-10/SACOSS.pdf. [Accessed 16 April 2019].

[78] AEMO, "Non-market ancillary services cost and quantity report 2017-18: An Annual Report required by the National Electricity Rules for the National Electricity Market," 2018.

[79] NSW Government, "Renewable Energy Action Plan," September 2013. [Online]. Available: https://energy.nsw.gov.au/renewables/renewable-energyoffers/renewable-energy-action-plan. [Accessed 22 April 2019].

[80] WaterNSW, "Windamere Dam," [Online]. Available: https://www.waternsw.com.au/supply/visit/windamere-dam. [Accessed 22 April 2019].

[81] NSW Government, "Department of Finance and Services Spatial Information eXchange," Department of Finance and Services, [Online]. Available: http://maps.six.nsw.gov.au/etopo/geopdf/25k/8832-1S%20LUE.pdf. [Accessed 12 March 2019].

[82] Ningbo Botai Plastic Technology Co., Ltd., "Floating pontoon bridge dock," [Online]. Available: https://www.alibaba.com/product-detail/Floating-Pontoon-Bridge-Dock_60480500077.html?spm=a2700.7724838.2017115.54.72981829pRDXAX&s=p. [Accessed 22 April 2019].

[83] a, "title," aemo, 1999.

[84] ACCC, "Restoring electricity affordability and Australia’s competitive advantage," June 2018. [Online]. Available: https://www.accc.gov.au/regulated-infrastructure/energy/electricity-supply-prices-inquiry/final-report. [Accessed 1 March 2019].

[85] AEMO, " 2018 Electricity Statement of Opportunities: A report for the National Electricity Market," 2018.

[86] AEMO, "2019 Planning and Forecasting Consultation Paper: Scenarios, Inputs, Assumptions, Methodology, Timeline, and Consultation Process," 2019.

[87] AEMO, "Participant categories in the National Electricity Market," [Online]. Available: https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Participant-information. [Accessed 2019 May 2019].

[88] B. L. a. A. B. Matthew Stocks, "Development of a Cost Model for Pumped Hydro Energy Storage," in *Asia Pacific Solar Research Conference*, Sydney, 2018.

[89] M. S. B. L. K. A. a. A. N. Andrew Blakers, "An atlas of pumped hydro energy storage: The Complete Atlas," Australian National University, 2017.

[90] Absaroka Energy LLC, "Banner Mountain Pumped Storage Hydro Project Briefing Document," Bozeman, MT, 2018.

[91] ANU, "Closures of coal-fired power stations in Australia: Local unemployment effects," Australian National University: Centre for Climate Economics & Policy, 2018.

[92] Parsons Brinckerhoff, "Indicative costs for replacing SWER lines," Department of Primary Industries, Melbourne, 2009.

[93] CSIRO, "Australian electricity market analysis report to 2020 and 2030," CSIRO, 2014.

[94] NHA – Pumped Storage Development Council, "Challenges and Opportunities For New Pumped Storage Development," A White Paper Developed by NHA’s Pumped Storage Development Council, 2017.

[95] A. L. Sætre, "Master Thesis: Variable Speed Pumped Storage Hydropower for Balancing Variable Power Production in Continental Europe," Norwegian University of Science and Technology, 2013.

[96] Absaroka Energy LLC, "GORDON BUTTE CLOSED LOOP PUMPED STORAGE HYDRO FACILITY BRIEFING DOCUMENT," 2019.

[97] N. B. P. O. R. U.-M. a. S. D. Boualem Hadjerioua, "Can Modular Pumped Storage Hydro (PSH) be Economically Feasible in the United States?," Environmental Sciences Division, Oak Ridge National Laboratory, Knight Piésold and Co., 2015.

[98] Hydro Tasmania, "Battery of the Nation Analysis of the future National Electricity Market Exploring a vision where Tasmania plays a significantly expanded role in the NEM," 2018.

[99] IRENA, " ELECTRICITY STORAGE AND RENEWABLES: COSTS AND MARKETS TO 2030," 2017.

[100] Melbroune Energy Institute (MEI), "Pumped Hydro Energy Storage," in *Australlian Energy Storage Conference and Exhibition*, 2014.

[101] B. Hadjerioua, "Modular Pumped Storage Hydropower Feasibility and Economic Analysis," in *U.S. Department of Energy: Energy Efficiency and Renewable Energy. Water Power Technologies Office Peer Review Hydropower Program*, Oak Ridge National Library, 2017.

[102] Norden: Nordic Energy Research, "Wind power based pumped storage Pre-Feasibility Study," Suðuroy, Faroe Islands, 2013.

[103] NSW Government, "NSW Emerging Energy Program Overview," State of NSW through the Department of Planning and Environment, 2018.

[104] L. d. Vilder, " Offshore pumped hydropower storage Technical feasibility study on a large energy storage facility on the Dogger Bank. Master Thesis," 2017.

[105] D. K. Okot, "Review of small hydropower technology," *Renewable and Sustainable Energy Reviews 26 (2013) 515–520,* 2013.

[106] Advisian, Worley Parsons Group, " 2017 Price Reset Water Security," Sydney Desalination Plant Pty Ltd, Sydney, 2016.

[107] A. Cunsolo, "Revenue Stacking in the NEM The Commercialisation Of Energy Storage: Revenue Streams, Present And Future," in *Australian Energy Storage Conference and Exhibition*, Adelaide, 2018.

[108] P. A. B. a. M. B. L. Dr Matthew Stocks, "Pumped Hydro Energy Storage to support a 50-100% renewable electricity grid," Australian National University (ANU), 2017.

[109] Summit Blue Consulting, "SMALL HYDROPOWER TECHNOLOGY AND MARKET ASSESSMENT," Energy Trust of Oregon, 2019.

[110] R. G. G. K. Antoine Rogeau, "A generic GIS-based method for small Pumped Hydro Energy Storage (PHES) potential evaluation at large scale," *Applied Energy, Elsevier, 2017, 197, pp.241 - 253,* no. 197, pp. 241-253, 2017.

[111] Energy Security Board, "The Health of the National Electricity Market: 2017 Annual Report," Energy Security Board, 2017.

[112] A. Tomasel, "The energy storage potential of a hybrid renewable generation grid connected to a pumped hydro-generation plant for effective connection into the energy market, off peak switchable developing load demand market and act as ancillary regional voltage suppor," University of Southern Queensland, 2014.

[113] ARENA, "Winning the uphill battle. How pumped hydro could solve the storage problem," [Online]. Available: https://arena.gov.au/blog/pumped-hydro/. [Accessed 14 April 2019].

[114] ARENA, "ARENA WIRE - Pumped Hydro Energy Storage," [Online]. Available: https://arena.gov.au/news/technology/pumped-hydro-energy-storage/.