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A Brief Appraisal of the Potential of Pumped Storage in New South Wales

by
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Abstract

With a national energy market turning to intermittent renewable sources, the challenge of reliably meeting variable demand intensifies. Despite its potential, large scale energy storage in the form of pumped hydroelectricity is limited to only two developments in NSW. This study aims to address the potential of pumped hydroelectric storage as a suitable form of energy storage in NSW. The purposes of pumped storage and various key concepts are outlined. Possible options for more widespread development including surface, coastal and underground storages are briefly drawn upon and discussed with illustrated example locations in NSW. It is recommended that further development be considered as suitable storage infrastructure, supporting a future energy market and renewable energy development.

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1. Introduction

Major hydroelectric power generation is conventionally achieved by driving a turbomachine (termed a turbine) by the flow of water. The most significant facilities for hydroelectric power generation are large dams delivering stored water to the turbine via an inlet pipe (termed a penstock). The rotational motion of the turbine is normally used to drive an electrical generator with the electrical energy delivered remotely via a network of power distribution lines. Hydro-electrical storage is a well-developed technology (Geoscience Australia and ABARE, 2010, Box 8.1).

For efficient hydroelectricity generation, it is important that the turbine be carefully designed to convert the imparted fluid power to impeller motion as efficiently as possible. Energy losses at the outlet from the turbine are minimised by discharging water through a specially tapered *draft tube*.

Hydro-electricity installations have a long life (over 50 years) with relatively high construction and infrastructure costs and low operating/maintenance costs. For OECD countries capital costs are estimated at US$2400 per kW with operating costs of only US$0.03 to US$0.04 per kWhr. (Geoscience Australia and ABARE, 2010).

In 2008, hydroelectricity accounted for roughly 16% of global electricity production, utilised across 160 countries with significant development in China and South America, ahead of more stable markets in OECD nations of North America and Europe (Geoscience Australia and ABARE, 2010). In the current Australian renewable energy market hydroelectric power leads the way. It accounts for roughly 60% of renewable energy generation, with a capacity of nearly 8400MW and over 100 operating hydropower stations. In 2009/10 hydroelectricity accounted for 5.5% of Australia's total electricity. In terms of large scale power generation, its development and use is well established compared with the relatively younger generation renewables of solar, bioenergy, wind and wave power (Clean Energy Council Australia, 2010).

However further growth and development of hydroelectric generation in Australia in recent decades has been viewed as restricted due to a number of challenges. These include:

- Prevailing dry climate with low rainfall and runoff, and high evaporation;
- Large variation of surface water flows intensified by climate change producing more severe periods of droughts and flooding;
- High and increasing competition for water resources and a resulting need for stricter maintenance of environmental flows; and
- Environmental factors including impacts on river health and valley inundation.

Another major challenge to the future of hydropower is a changing energy sector. Recent and expected near future changes include electricity market restructuring, increased alternative renewable energy generation, larger demand for increased user reliability, trend in more distributed generation and higher environmental standards (Hino et al, 2012).

In the 2010 Australian Energy Resource Assessment, the 2030 outlook for future growth in hydropower is "expected to be limited and outpaced by other renewables, especially wind energy" with an estimated annual growth rate of 0.2% mainly due to provision of small scaled hydropower plants associated with lower development costs, water usage and land usage. It is estimated that up to 60% of Australia's economically feasible hydroelectric power plants have already been developed (Geoscience Australia and ABARE, 2010).

However the provision of pumped storage hydroelectricity is given little consideration despite the need for storage technology outlined in the *2012 Draft NSW Renewable Energy Action Plan* (NSW Department of Trade and Investment, 2012). However pumped storage may be a possible means of further development of hydroelectric generation in the light of the above discussed present and future challenges, focussing on its application in NSW.

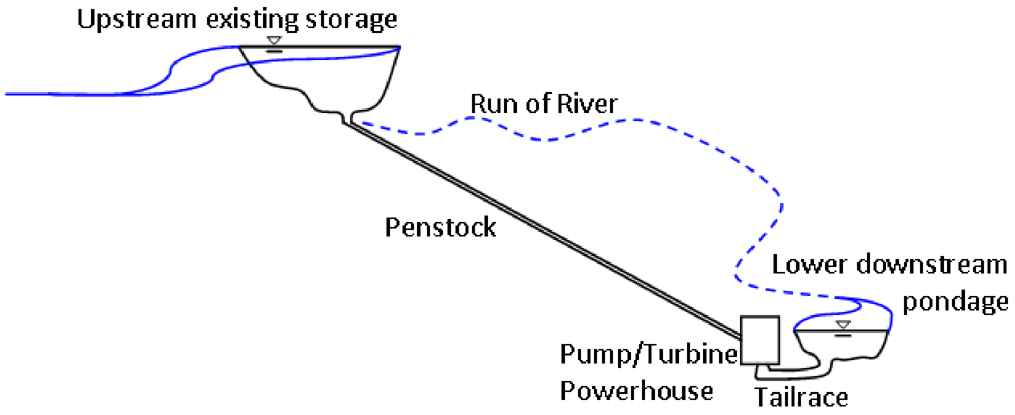

Figure 1: Conventional hydroelectric power station with upstream reservoir. Downstream reservoir provides the option of using the upstream reservoir as pumped storage.

Pumped storage is a complementary process to hydroelectricity generation. Pumped storage is the process of pumping water to an elevated water storage for subsequent hydroelectricity generation. When used in conjunction with conventional electrical energy supply systems, it provides the following:

- Improved load control by smoothing fluctuating loads associated with variable demand. Storage capacity acts to balance excess base supply against demand peaks, thereby reducing the total required capacity for energy generation;
- Cost incentive to generate power at off peak price, store it and distribute it at peak price;
- Improved reliability with rapid and responsive back up power generation. Pump-turbine systems can have an operational start-up and shut-down within a matter of seconds should break down occur;
- Frequency regulation, encouraging stabilized transmission and distribution control; and
- Commercial means of storage and subsequent release of energy generated by weather sensitive renewable technologies, such as wind or solar.

Pumped storage is not a new concept. A broad assessment of the literature shows that a series of detailed investigations have been undertaken over many years, particularly during the energy crisis of the 1970's (Armstrong et.al, 1975, Frost, 1974, Mosonyi, 1974). Pump storage development has been undertaken in many foreign energy markets. Across Europe this accounts for a storage of 5% of total generation capacity, 3% in the US and 10% in Japan (Hino et al, 2012). The largest growth is occurring in China where 50GW of pumped storage generating capacity is planned by 2020 (Ming et al, 2012).

While there is considerable potential for pumped storage in NSW, its application has been limited to two major installations:

1. **Tumut 3 Power Station**

   Tumut 3 Power Station is part of the Snowy Mountains Scheme and is located immediately below Talbingo Reservoir on the Tumut River (Snowy Hydro Ltd, 2003). System designers found that there was sufficient difference in elevation between the Blowering and Talbingo Reservoirs that a small intermediate storage (Jounama Pondage) could be constructed as a tailwater pool for the Tumut 3 Power Station.

   Consequently, Jounama Dam and its corresponding Pondage was used to upgrade Tumut 3 to incorporate a substantial pumped storage capability within the scheme. The power station has an installed peak generation capacity of 1500MW with six turbines each operating at a design flow of 190m^3/s. On average Tumut 3 generates 2.92PJ each year of stored energy (ANCOLD, 2010) distributed across the eastern mainland grid. The site offers 0.036PJ of stored energy output potential[1] in one generating cycle, assuming 87% efficiency.

2. **Kangaroo Valley / Bendeela Power Stations**

   As part of the Sydney water supply network (operated by Sydney Catchment Authority), pump stations were built within Kangaroo Valley to allow transfers of water supply from the Shoalhaven water supply scheme during times of severe drought.

   As these water transfers required pumping to a significant elevation above the Shoalhaven storage in order to flow into the headwaters of the Sydney catchments, artificial reservoirs were created on the mountain tops above Kangaroo Valley.

   This construction provided opportunity for a pumped storage capability with a peak generation capacity 240MW. In 2011/12 the scheme generated roughly 0.17PJ of stored energy (Eraring Energy, 2012). Similarly assuming 87% efficiency, it offers 0.054PJ stored energy output potential[2].

As a comparison, the power generation rates for Tumut 3 and Kangaroo Valley can be compared with Eraring Power Station (a conventional coal powered system) which has recently been upgraded to an installed capacity of roughly 2.8GW. Before upgrade outages over the past three years, in 2007/8 the station produced a little over 60PJ of energy, significantly greater than stored energy production (Eraring Energy, 2012).

This report summarises a preliminary assessment of the potential for pumped storage in NSW.

Section 2 addresses various key principles including peak power generation, a simplified solution to the energy integral, literature review of losses and efficiency, a peak daily demand illustration, and its potential role in an energy system.

Section 3 canvasses possible options for pumped storage in NSW looking at four forms of storage including run-of-river, off-reservoir, coastal and underground. Possible examples are given in each to calculate potential storage capacity under the assumptions made in Section 2.

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[1] See section 2.2 and 2.3. Snowy Hydro Ltd (2003) gives Jounama Dam Active storage = 27800ML, Rated Turbine Head = 150.9m.

[2] See section 2.2 and 2.3. Moore (2012) gives Fitzroy Falls Active Storage = 9950 ML, Head ≈ 635m

Section 4 provides a brief review of the recently published *ROAM Consulting Report on Pumped Storage for AEMO 100% Renewables Project.* It was found that the report identifies additional locations in NSW that provide pumped storage potential. Although, its results alone should not be used as a measure of full pumped storage potential in NSW nor the broader National Energy Market.

Though well understood and extensively developed in foreign energy markets, pumped storage is largely under-utilised in NSW. There is a growing need to match intermittent energy generation with variable energy demand quickly and reliably. A further study in conjunction with the *NSW Draft Renewable Energy Action Plan* (NSW Department of Trade and Investment, 2012) should quantify how much storage is required under various planning horizons. Additional studies related to pumped storage application in NSW would include economic feasibility, detailed underground potential including mine conversion, seawater design challenges, and environmental considerations. Flood mitigation found in the *NSW Government State Infrastructure Strategy December 2012* (NSW Department of Premier And Cabinet, 2012) could possibly incorporate pumped storage. It is recommended that the potential for hydroelectric storage in NSW (and Australia more broadly) be assessed as a matter of priority.

2. Key Principles

Hydroelectricity generation potential depends on volume and elevation head of water supply – conventionally the best locations have reliable high river flows coupled with suitable dam storages providing great elevation head differences. In Australia, nearly all hydropower is associated with dams created in major river valleys.

2.1 Power Output and Power Input

A key aspect of hydroelectricity generation is the peak power that can be generated by a given installation. The available turbine power P_{out} (watts) can be readily computed using equation (1)

$$P_{out} = e_t \rho g Q \Delta H \tag{1}$$

Where:
e_t is the generation cycle efficiency
ρ is the density of water (approximately 1000 kgm^{-3})
g is gravitational acceleration (9.8 ms^{-2})
Q is the volume of water flowing through the turbine per second (m^{3}s^{-1}) and
ΔH is the difference in water surface level (or head measured in m) between points of inflow and outflow.

The amount of electrical power required as input P_{in} to pump a given Q up a change in elevation of ΔH is also given by an equation similar to equation (1)

$$P_{in} = \frac{\rho g Q \Delta H}{e_p} \tag{2}$$

except that e_p is now a pumping cycle efficiency.

2.2 Storing Energy

The second key aspect of pumped storage is the means in which energy is stored. Pumped storage stores energy by operating on a pumping and generating cycle, corresponding with total input E_{in} and output E_{out} energies (J) respectively. These energies are the respective sums of the instantaneous power input or output, multiplied by the time increment over which steady power is maintained. Equations (1) and (2) yield

$$E_{in} = \int P_{in} dt = \int \frac{\rho g Q \Delta H}{e_p} dt \tag{3}$$

$$E_{out} = \int P_{out} dt = \int e_t \rho g Q \Delta H \, dt \tag{4}$$

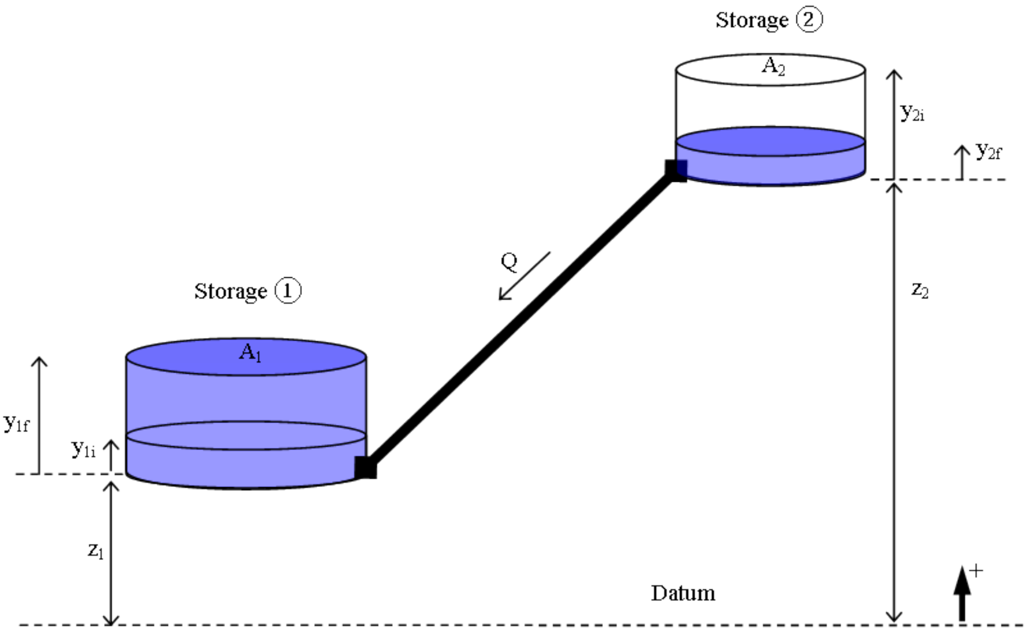

Figure 2: Simplified pumped storage system in generating mode

Consider a lower reservoir storage with a constant surface area A_1 connected to a upper reservoir storage with constant surface area A_2, both measured in m^2, as in the Figure above. To simplify calculations it is assumed that the flow Q (m^3/s) remains constant over the entire generating time period. Starting with continuity, noting $\forall$ (m^3) as the volume of fluid transferred over time t (s),

$$Q = \frac{d\forall_1}{dt} = -\frac{d\forall_2}{dt} \tag{5}$$

$$Q = A_1 \frac{dH_1}{dt} = -A_2 \frac{dH_2}{dt} \tag{6}$$

$$dH_1 = \frac{Q}{A_{1`}} dt \tag{7}$$

$$dH_2 = -\frac{Q}{A_2} dt \tag{8}$$

Both sides of equations (7) and (8) can be integrated, noting when $t = 0$, $H_2 = y_{2i} + z_2$ and $H_1 = y_{1i} + z_1$, where y_{1i} and y_{2i} are initial depths (m) and, z_1 and z_2 elevations above the datum shown in Figure 2. The difference in head between the storages as a function of time is obtained,

$$\begin{aligned} \Delta H(t) &= z_2 + y_{2i} - \frac{Q}{A_2}t - z_1 - y_{1i} - \frac{Q}{A_1}t \\ &= z_2 - z_1 + y_{2i} - y_{1i} - \frac{(A_2 + A_1)Q}{A_1 A_2}t \end{aligned} \tag{9}$$

Using this result in equation (4) yields an energy output as a function of time. Assuming that the generating efficiency and flow remain constant during the entire generation period, and integrating from t=0 to t = $\frac{\forall}{Q}$, where $\forall$ is the total volume of fluid transferred,

$$E_{out} = e_t \rho g Q \left[(z_2 - z_1 + y_{2i} - y_{1i})t - \frac{(A_2 + A_1)Q}{2A_1A_2} t^2 \right]_0^{\frac{\forall}{Q}}$$

$$E_{out} = e_t \rho g \forall \left[z_2 - z_1 + y_{2i} - y_{1i} - \frac{(A_2 + A_1)\forall}{2A_1A_2} \right] \qquad (9)$$

Simplifying the above expression and noting that $\frac{\forall}{A_1} = y_{1f} - y_{1i}$ and $\frac{\forall}{A_2} = y_{2i} - y_{2f}$, where y_{1f} and y_{2f} are the final depth after generating in the lower and upper storage respectively, we obtain a simplified solution to the energy integral,

$$E_{out} = e_t \rho g \forall \left[z_2 - z_1 + \frac{y_{2i} + y_{2f}}{2} - \frac{y_{1i} + y_{1f}}{2} \right] \qquad (10)$$

Equation 10 describes energy output in terms of a constant generating efficiency, for a specified volume of fluid and an averaged head separation undergoing a linear variation. Notice that the average head separation term, in square brackets, is composed of the elevation separation and the average depth range over the generating time in either storage. For a system where the elevation separation is significantly larger that the depth range of each storage, these terms becomes insignificant.

2.3 Losses and Efficiency

Conventional storages use high flow turbines with separate pumping units. Francis turbines are most common for heads of 15-300 m (although in Europe applications occur for heads over 600 m) and for large, well designed and operated machines, hydraulic efficiencies of 90-95% can be achieved (Mosonyi,1972). Heads over 800 m require Pelton wheel generation with efficiencies that can range from 85-90% (Massey, 1998). Kaplan turbines are used for lower heads suitable to tidal applications. Centrifugal pumping units are used according to the head range with a high efficiency range of 88-93% (Mosonyi,1972).

More common in recent designs is the use of reversible pump-turbine systems with both pumping and generating efficiency at around 90% (Chen, 1993) and comparable savings in power station capital costs of 10-18%. In a single stage system these have been used for heads up to 600 m (Serbia) and up to 1200 m (Italy) in a multistage system.

Variable speed technology is used in modern design to increase efficiency allowing multiple optimum pumping rates for varying head applications (Pannatier et al, 2008).

Chen (1993) and Martin (2011) give one way conduit losses in the range of 1.5 - 4%. Amongst these are those due to friction influenced by the gradient of the piping and local losses in bends, valves, inlets, outlets and draft tubes. Unfavourable flow conditions due to poor design increases the likelihood of cavitation, vibration and reduced turbine/pump efficiency. Unlike conventional hydroelectric generation, flow occurs in both downstream and upstream directions and minimal loss conduit design requires this consideration. Physical models are used to obtain optimal geometric configuration (Lehne, 2012).

Other energy losses include generator motor and transformer inefficiencies and those associated with operation such as start-up, shutdown and flow reversal.

To convert energy output to energy input, cyclic efficiency is used. Most modern sources typically quote overall cyclic efficiencies for large scale systems of 70 - 80% (Levine, 2011, Chen, 1993, Hino et al., 2012, Parformak, 2012, Luick et al., 2011). Martin (2011) estimated this range as 27% - 52% for smaller-scale pumped storage systems. For simplicity in this report, cyclic efficiency is assumed constant at 75% with corresponding pumping (e_p) and generating (e_t) efficiency both assumed to be a constant value of 87%.

2.3.1 Volumetric Losses and Water Usage

Unlike conventional hydro-electric generation, pumped storage returns water used for generation to the original storage. Ideally the water required would be the minimum volume of either storage, with the ability of returning it to the system at any time. However this may not be the case.

Volumetric losses occur due to leakage with sealing failure and evaporation. Evaporation losses are particular important for freshwater storages in Australia, especially those with large surface areas and high retention times. Losses in the upper storage will cause a loss of stored energy. If the upper storage is open to a receiving flow, such as a dam on a river, these losses may be replaced or yield additional hydroelectric generation.

A closed upper off-reservoir storage scheme could be built in conjunction with a lower existing storage (as shown in Figure 3). If the lower storage is the larger of the two and its surface area remains relatively constant when water is pumped for storage, the upper reservoir storage adds additional surface area to the body of water. This can either increase evaporation, or during periods of high rainfall, can potentially act as additional direct rainfall catchment area, supplementing existing water supply.

To minimise this energy loss and corresponding water usage, preferentially surface storages should be concentrated in eastern NSW where evaporation is generally lower and rainfall higher than the rest of the State. For the region east of the Great Dividing Range average annual surface evaporation ranges from 1200-1600mm per annum and rainfall from 800-1800mm per annum (BOM, 2005). This location is also in proximity to major population centres and existing dams, which potentially can reduce transmission and capital costs. A water balance can be performed using location specific data for various seasons to calculate the net loss or gain, and corresponding stored energy loss or gain.

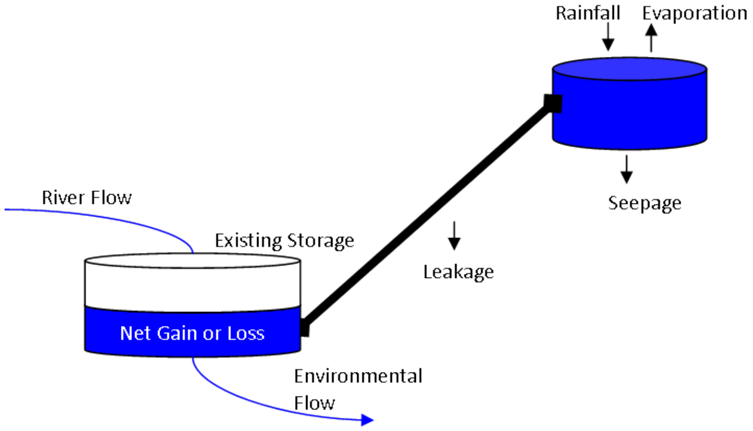

Figure 3: Additional fluxes created to an existing reservoir storage with a closed upper storage

2.4 Design Considerations

Hydroelectric systems do not operate efficiently once the mean water velocities U start to exceed approximately 6ms^{-1}. Because the required cross section of the penstocks A is the ratio of Q and U, to achieve high instantaneous power levels from these systems, designers must balance possible differences in water level against the sizes of the penstocks.

Therefore, locations where large volumes of water can be stored at height with large gradients above a lower reservoir are prized for their potential for pumped storage. Frost (1974) suggests a number of desirable design parameters that are presented in Table 3.

Table 1: Parameters related to pumped storage design (Frost, 1974)

Design Parameter	Desired Value	Reason
Head Separation, ΔH	150m minimum Greater than 250m preferable	- Lower storage volume required - Smaller conduit cross section - Smaller powerhouse
Horizontal Distance/Vertical Distance (H/V) Ratio	Less than 10, Preferably less than 4	- Minimise friction losses - Minimise conduit costs - Less than 4 avoids required inclusion of a surge tank
Maximum Head: Minimum Head in each storage	1.2:1	- Smaller powerhouse - Maximise cyclic efficiency

2.5 Managing Variable Electricity Demand

A primary objective of pumped storage systems can be to better manage daily power demand. NSW electricity demand data from the Australian Energy Market Operator (AEMO) has been used to illustrate how pumped storage can effectively produce more uniform daily electricity generation. In 2011, half hourly electricity demand peaked during the summer at 14600MW in comparison to a winter peak of 12900MW (AEMO,2011). The daily load curves for the respective peak days, 1st February and 19th July, are shown in Figure 4.

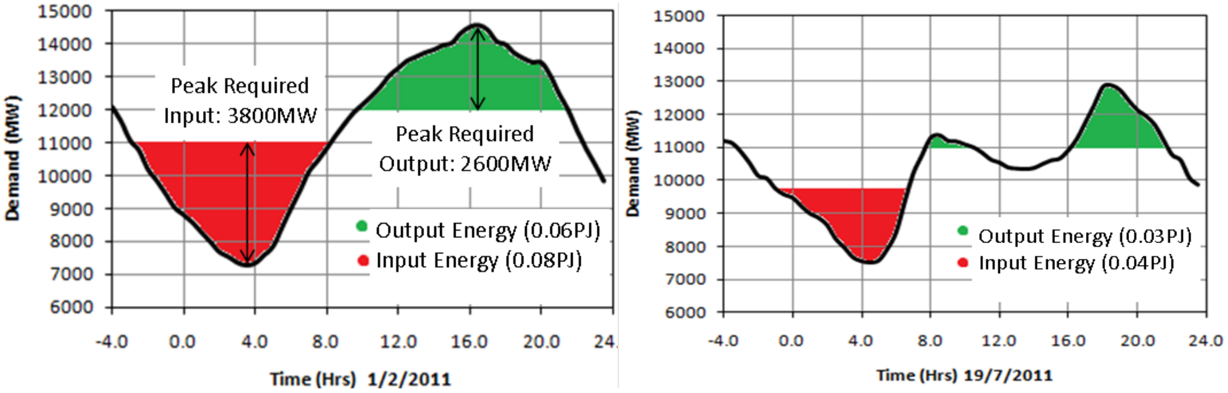

Figure 4: Daily load curves for peak days in 2011- 1st Feb (left) & 19th July (right) for NSW (based on AEMO data)

Current trends in demand curves show a high singular summer peak related to increased air conditioning use on hot days. In the winter, power tends to peak in the early morning and evening, with a depression in between.

Suppose pumped storage operated on the 1st February 2011 to allow peak generation to not exceed 12000MW. Optimal operation would store sufficient off-peak energy (E_{in} = 0.08PJ, equation (3), in this example shaded in red) from the night before to meet a forecasted spike of excess demand (E_{out} = 0.06PJ, equation (4), shaded green) for the day following.

Note that correspondingly, a peak power input of 3800MW would be required during pumping. This is a value comparably greater than the peak power output of 2600MW, highlighting a particular consideration in selecting design peak power capacity.

The effect of pumped storage would have been a much more uniform load curve, with demand ranging by 1000MW, in comparison to 7400MW without storage, over the 23 hour period. The effect reduces the need for peak power and encourages more stable intermediate power operation.

On this particular peak summer day the average half hour electricity spot price during the 12h generating period (9.30am-9.30pm) was approximately $2420/MWh compared with $41/MWh during an 11h (9pm-7am) pumping period the night before (AEMO,2011). The corresponding electricity sale revenue that could be leveraged from pumped storage could have been substantial, at approximately $39 million.

The above calculations can be repeated for the peak winter day to limit generating capacity to 11000MW. Demand range reduces from 5400MW to roughly 1200MW.

An integrated pumped storage system may also be designed and scheduled to manage weekly or seasonal load. Another current priority is to store and distribute intermittent renewable energy from solar and wind.

2.6 Managing Intermittent Renewable Generation

Pursuing a Renewable Energy Target of 20% by the year 2020, Australia's energy market has begun a significant transformation. The market will soon host and manage multiple forms of renewable generation. However, such a market requires a greater degree of system flexibility and generation management than is currently available in order to match the intermittent and variable power generated by renewable sources with concurrent system demand.

The *2012 Electricity Statement of Opportunities* reveals roughly 5000MW of wind power generation proposed capacity and 600MW of large scale solar power in NSW (AEMO, 2012). Added to this is a forecasted 1870MW of installed rooftop solar for the state in 2020, mentioned in the *2012 Draft NSW Renewable Energy Action Plan* (NSW Department of Trade and Investment, 2012). All of which will generate variable amounts of power according to location and technology installation. Figure 5 shows wind generation variability on a representative day at four of NSW currently operating windfarms.

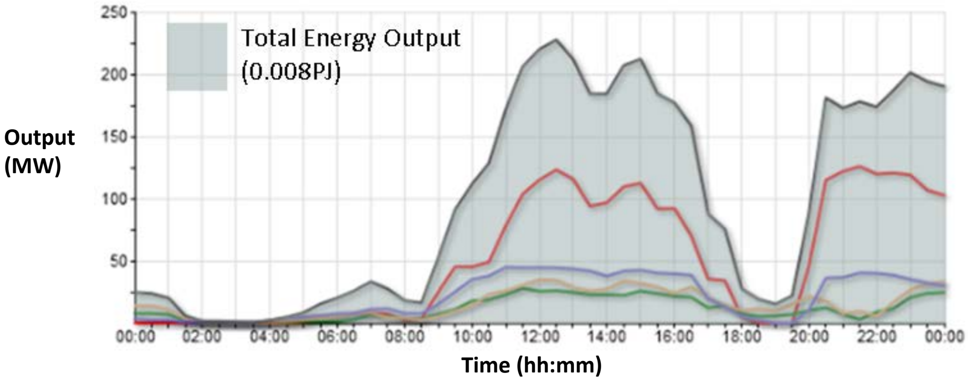

Figure 5: NSW windfarm output on 21/11/12 - Capital, Cullerin Range, Gunning, Woodlawn, Total (adapted from Miskelly, 2012)

Porter et al. (2012) presents studies in the US that assessed the impact of wind generation variability on a coal and natural gas system. On days where periods of significant variation between wind generation and demand existed, coal and natural gas plants where cycled to absorb this variability. The curtailing and subsequent ramping involved in cycling led to increased heat rates, reduced operating efficiency and increased SO$_2$, NO$_X$ and CO$_2$ emissions. Should the frequency of short-term variation increase over a certain threshold, the long term benefits of wind generation on the system become questionable.

Solar power systems are simlarly subject to variability. Solar power generation tends to peak with demand during the daytime. However considerable variations can occur from day to day due to cloudiness. Cloudcover may be present from a matter of seconds to days, refracting and absorbing incoming solar radiation, varying that available at the surface for solar power generation. The NSW State Government is currently working with AGL Energy and First Solar Australia in delivering a 106MW large scale solar farm in Nyngan (NSW Department of Trade and Investment, 2012). Figure 6 shows variation in daily global solar exposure during 2012 for the BOM Nyngan Airport weather station. Along with the more predictable seasonal variability, daily exposure variation is evident. The proposed solar panel for the 200 hectare (Carroll, 2010) Nyngan farm can yield an approximate efficiency up to 15% (Suntech Power Holdings, 2012). Roughly 0.009PJ would store the maximum variation of daily energy output at the site from the 2012 data.

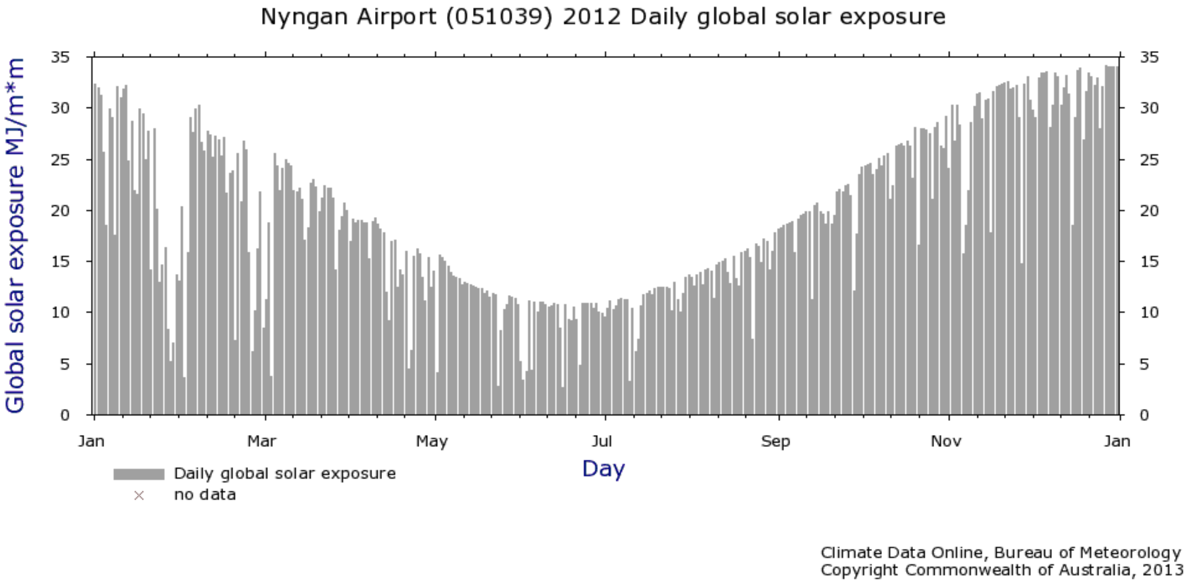

Figure 6: Variation in daily global solar exposure 2012 (BOM, 2013)

Currently the majority of peak power demand is handled by open cycle gas turbine (OCGT) generation with a total of roughly 1300MW installed peak generation capacity in NSW (NSW Department of Trade and Investment, 2012). It is also interesting to note the additional 4330MW of proposed OCGT capacity in 2012 (AEMO, 2012). It seems likely that much of NSW's variable power generation will be handled OCGT generation.

OCGT generation relies on natural gas as a fuel source for energy production, converting it to electricity with an efficiency in the range of 35-42%. During the process 480-575 kg/MWh of greenhouse gases and 50g/MWh of nitrogen oxides are emitted. Fuel costs of US$0.45-0.7/kWh lead to higher operational costs over an operational lifetime of 30 years. (Seebregts, 2010)

In comparison, pumped storage has the flexibility of choosing input energy fuel source to power pumping. This could be renewable off-peak energy associated with no fuel costs and emissions. This energy input is converted to output energy with an efficiency double that of the OCGT range (Section 2.3). Though pumped storage capital costs are expected to be higher, operational costs are expected be lower over a lifetime similar to conventional hydropower of 50 years (Geoscience Australia and ABARE, 2010). While a cost comparison study would be useful, it can be seen that pumped storage has potential as an attractive alternative to OCGT generation.

Rather than cycling conventional systems, Figure 7 shows how pumped storage could be integrated into an energy system to absorb volatilte renewable generation and meet realtime demand quickly and reliably. The role of pumped storage should be considered as a matter of priority.

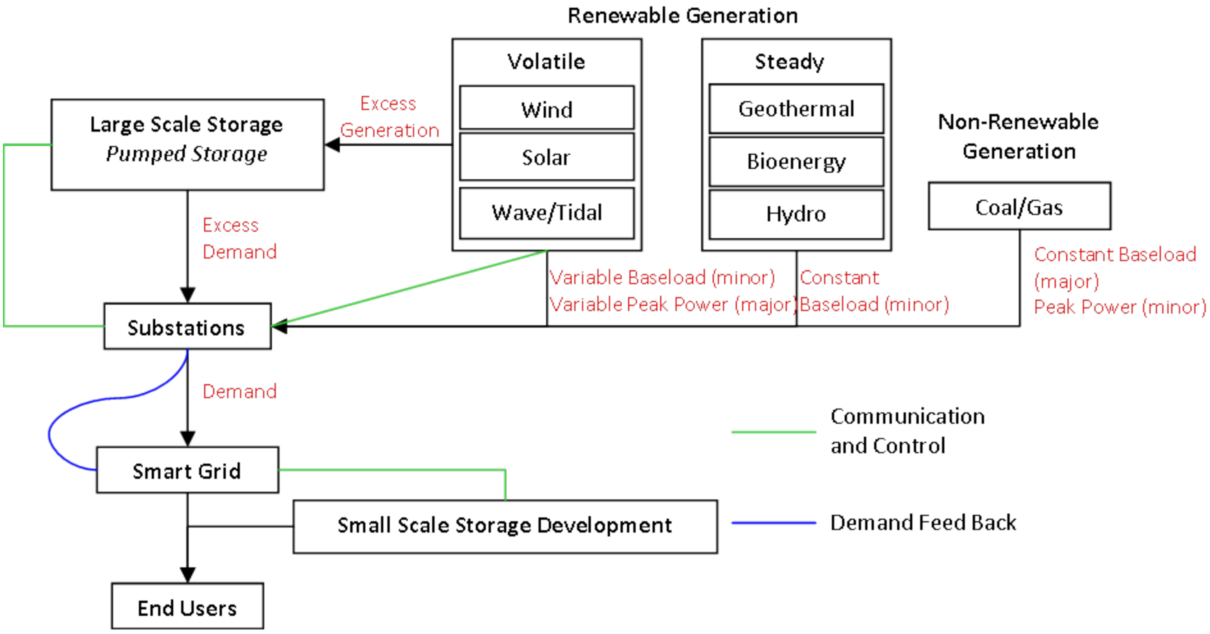

Figure 7: Pumped storage within an interdependent energy system

3. Possible Options for More Widespread Use of Pumped Storage in NSW

The following section discusses possible pumped storage options for NSW. Referring to Sections 2.2 and 2.3, calculations involving generated stored energy will assume a constant 87% generation efficiency and the entire volume of the smaller storage is emptied (or filled).

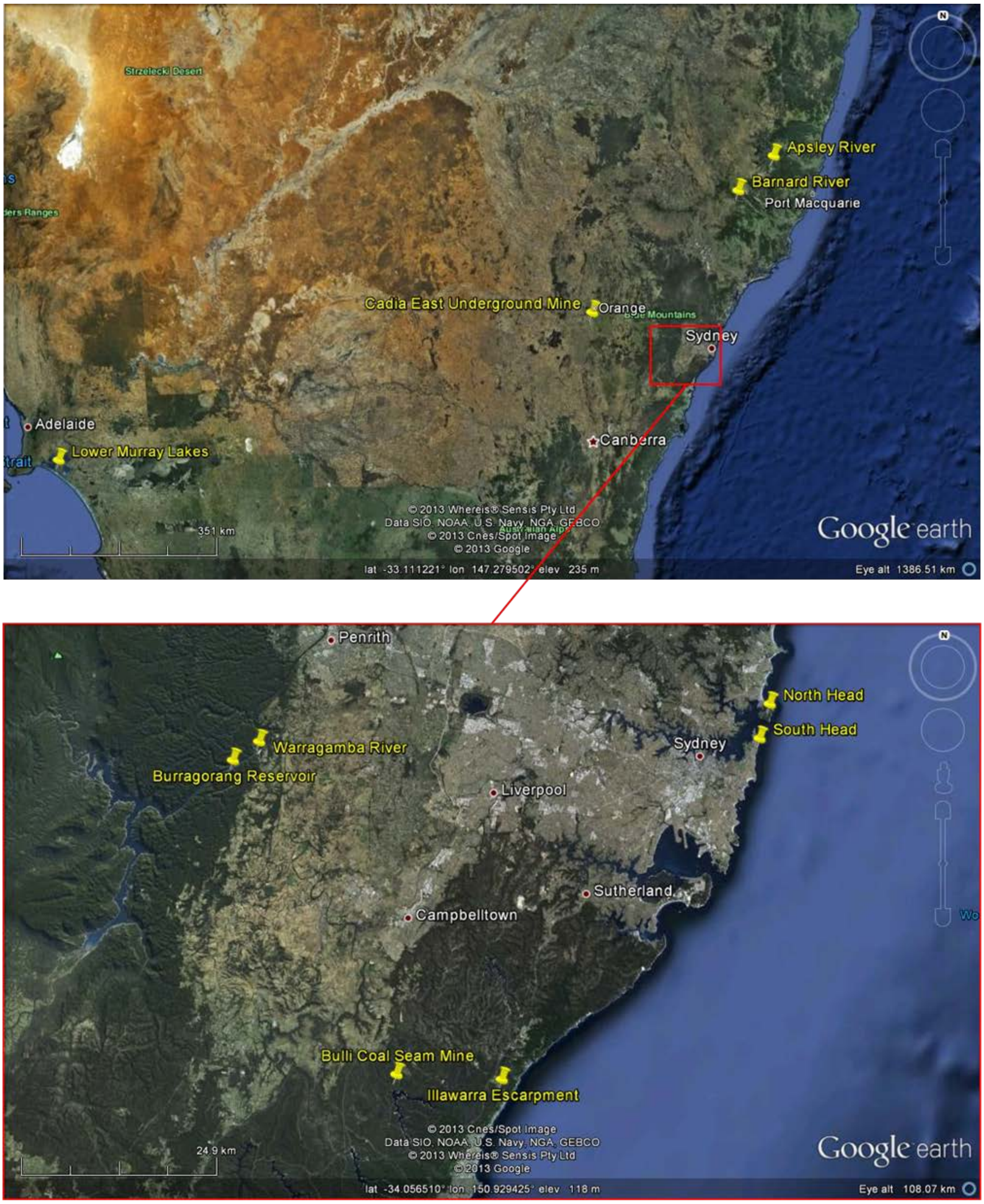

Figure 8: Potential storage locations in NSW and Sydney region

3.1 Downstream Run-of-the-River Storages

One of the options for pumped storage is to construct storages downstream of existing dams (Figure 1) with the associated penstock and pump/turbine infrastructure similar to that of the Tumut 3 design.

Environmentally, this is an attractive option as often the reaches downstream of major dams are highly disturbed environmentally. Existing environmental management techniques could be enhanced by the variable flux associated with pumped storage.

Further, Australian reservoirs can be adversely impacted by strong stratification inducing anoxic or nutrient-enriched conditions within the reservoir. The circulation induced by pumped storage could potentially be managed to ameliorate poor water quality conditions without changing energy efficiency significantly.

There are two primary challenges associated with the implementation of such schemes:

- Difficulties associated with the penstock inlet from the upstream reservoir. Retrofitting new outlets from existing dam structures is not impossible but is complex. Conveying water over the dam crest is possible but cavitation is a consideration if the height of water lift from the upstream reservoir dam surface to the dam crest is substantial (equal to or greater than 6 m).

- Constructing a downstream storage that will yield a significant energy storage reservoir. Pumped storage relies on having water reservoir downstream with adequate volume that can be lifted back into the upstream reservoir.

The Sydney Warragamba system can presently transfer significant volumes of water between the Tallowa system and Lake Burragorang. In this system the peak water level height occurs at Wingecarribee Reservoir with a water surface roughly 500 m above the Warragamba water surface. However the straight line transfer distance is approximately 75 km with consequent significant friction losses and capital costs.

A possible option would be to dam the Warragamba River downstream of the existing dam prior to its confluence with the Nepean River. This roughly 3 km strip of river shown in Figure 9 is characterised by steep gully terrain. A dam could utilise existing terrain or excavation of the existing channel could provide a deeper artificial channel with larger storage volume and maximum head difference. If a supposition was made that this lower storage had a volume of 3000ML, based on an average stream width of 60m, dam height of 20 m above the existing water surface and over a length of 2.5 km downstream of the Warragamba Dam, then this could provide an average drop in head of 50 m from the upper dam water surface. Stored energy output is calculated at only 0.001PJ due to the low head location. However such a system could potentially utilise existing hydroelectric infrastructure currently owned and operated by Eraring Energy (currently limited to operating in non-drought conditions).

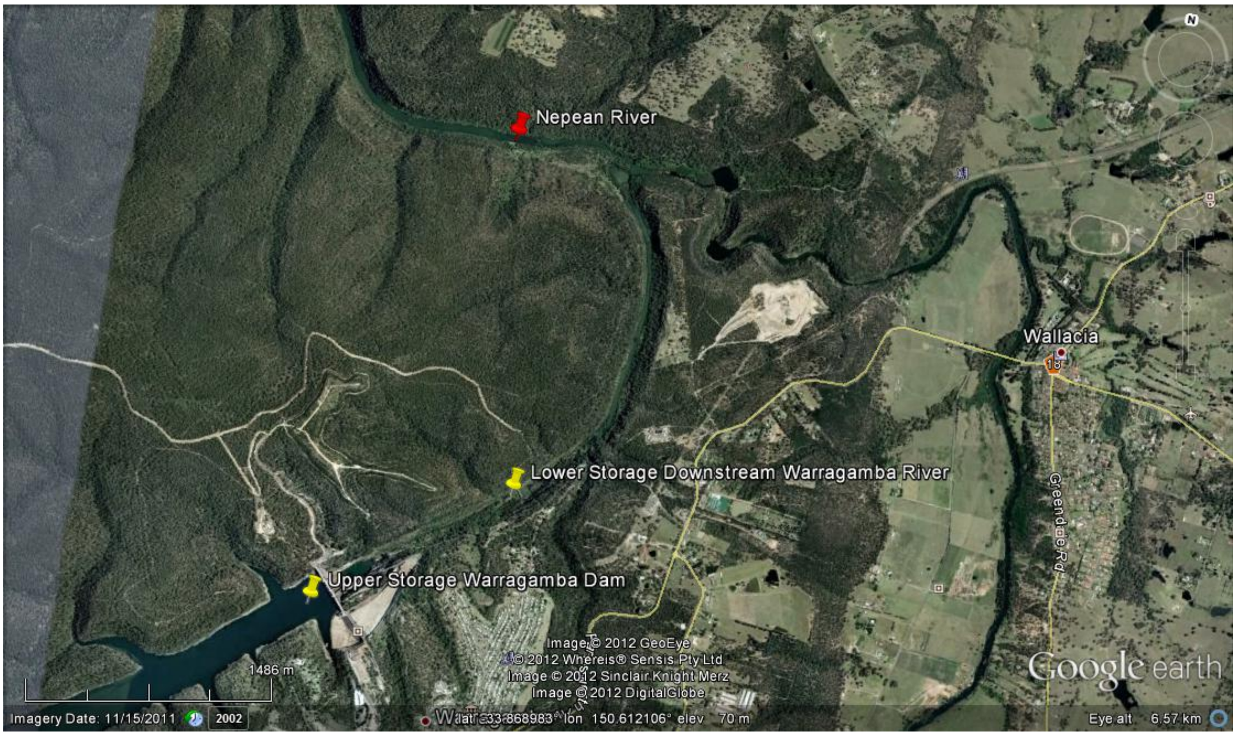

Figure 9: Warragamba River (Google Earth)

Smaller scale examples could include pumped storage installation between existing downstream storages such as the Cascade Dams and, Medlow and Greaves Dam near Katoomba, and Cordeaux Reservoirs near Wollongong.

The major limitation observed in the run-of-river storage is that head differences tend to be low in flat terrain over larger horizontal distances. Thus energy storage capacity is also low unless a sufficiently large volume is transferred. In a river system this requires high flow and steep terrain to maintain head difference. In the light of high capital expenditure, low energy storage may not be feasible

3.2 Upstream Off-Reservoir Storages

Upstream off-reservoir storages involve damming an existing reservoir tributary or construction of embankment ponds in nearby higher terrain to provide head difference and pumped storage potential as in Figure 10.

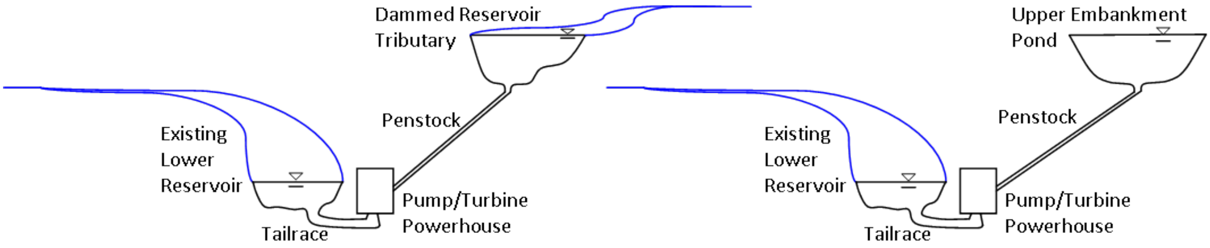

Figure 10: Upstream off-reservoir storage- dammed tributary (left) and embankment pond (right)

Dammed tributaries can a provide large storage volume. Construction of a side dam within the existing Burragorang storage, Figure 11, would be able to store 168000ML maximum water surface height 70 m above the Burragorang surface level. This would have a storage potential of 0.050PJ.

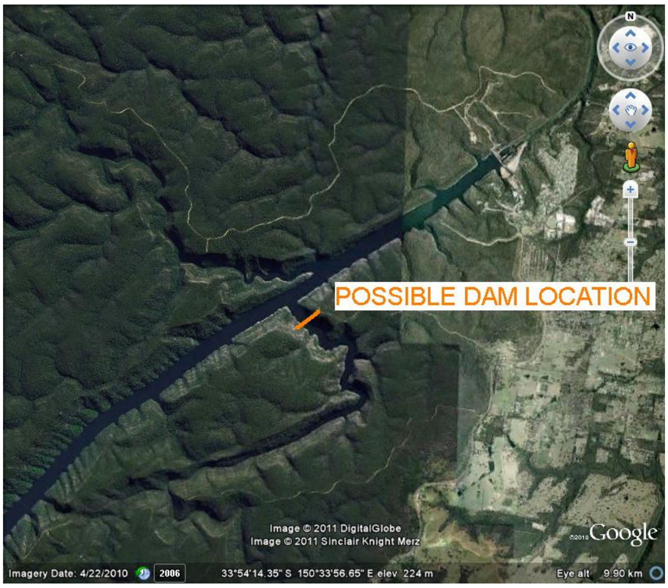

Figure 11: Burragorang side dam upstream of Warragamba Dam (Google Earth)

NSW electricity authorities assessed pumped storage opportunities in both the 1970's and 1980's. A number of high potential sites along the Great Dividing Range were identified – some taken to preliminary engineering design by SMEC and listed as possible future hydroelectric developments. A scheme on the Apsley River, an upper tributary to the Macleay River, was identified as being able to generate 1000 MW for up to 7 days. It would utilise an 800 m elevation head drop through a 2 km conduit, connecting the lower dam on the Apsley River to an intermediate dam on Budd's Mare Creek, and an upper storage in Moona Plains. This is equivalent to 0.605 PJ of stored energy potential. At the time these assessments were undertaken mapping was poor in comparison to present day digital information.

Approximately 100 km south east, another off-reservoir storage scheme was considered as part of the Barnard River Water Supply Project, in 1981 by the Electricity Commission of NSW. Initial stages of the proposal were approved and completed in 1983, diverting water from the Barnard River to the Hunter River system to supplement Liddell and Bayswater Power Station cooling water requirements.

The later pumped storage stage was never commissioned. This would have included a 90 m dam on the Barnard River (Figure 12) just downstream of the Orham Creek Dam. An upper storage was suggested roughly 4 km westward at Bralga Tops, corresponding to a 300 m head separation and an installed capacity of 1000MW with a 4 hour generation potential, providing 0.014PJ of stored energy.

Figure 12: Pumped storage as part of the Barnard River Water Supply Project (Goggle Earth)

Upstream off-reservoir storages show promising energy storage potential providing significantly larger head differences like that of Apsley River site or in the case of the Burragorang example, larger volumes.

3.3 Coastal Storages

Given the frequent occurrence of extended droughts, surface water variability and high water resource demand, the use of saline pumped storages (Figure 13) have attractive potential in NSW. Other advantages include proximity to population centres and an infinite water availability. (*Section 8.4 Outlook to 2030 for Australia's Hydro Energy Resources and Market* Geoscience Australia and ABARE, 2010).

However seawater hydroelectricity poses significant challenges including sand filtration, high cavitation, corrosion control, salt deposition, marine organism growth, high energy intake environment and risk of contamination of land with leakage. These were the cited reason for its abandonment in South Australia during the 1960s (Frost, 1974). Through the 1980s and 1990s Japan designed and developed the first and only operating (since 1999) seawater pumped storage in the Okinawa Islands. Larger scale development has been planned at Glinsk Mountain, Ireland to store intermittent renewable power of planned wind and wave power. Details of the respective projects are summarised in Table 2. Noted features of the Irish design include: (Organic Power, 2011).

- Breakwater inlet design with reinforced concrete intake structure;
- Austenitic stainless steel pump-turbine;
- Variable speed generating system;
- Underground powerhouse and conduit design;
- Asphaltic reservoir floor sealing and rubber sheet dam lining; and
- Seawater seepage monitoring and detection system with drainage control.

Table 2: Seawater pumped storages

Design Features	Okinawa Islands, Japan	Glinsk Mountain, Ireland (planning)
Installed Capacity (MW)	30	960
Generating Time (h)	6	6
Effective Storage Volume (ML)	590	8900
Effective Head (m)	136	296
Stored Energy Output Capacity (PJ)*	0.0007	0.023

*Assuming 87% generating efficiency
(Hino et al, 2012. Organic Power, 2011.)

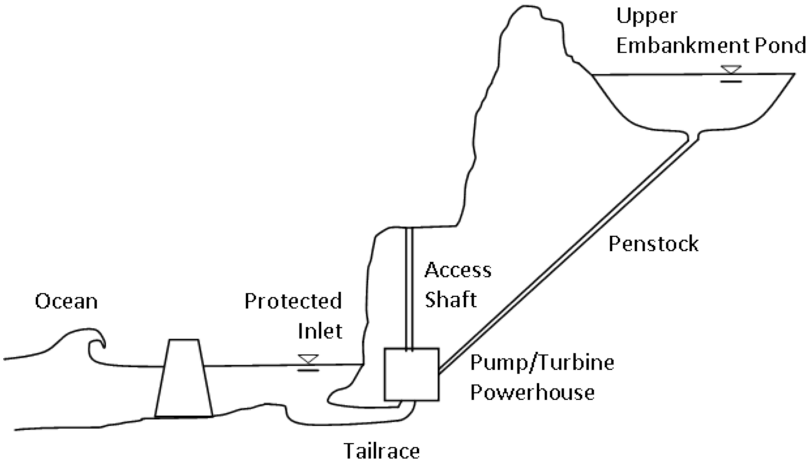

Figure 13: Coastal pumped storage features - underground powerhouse design

In NSW, coastline cliff tops and large headlands offer potential sites. The stretch of coastline just north of Wollongong shown in Figure 14, from Austinmer to Stanwell Park, is bound by the steep adjacent Illawarra Escarpment with flat elevations up to 400 m near Maddens Plains; this is approximately 2 km horizontally from the coastline. 0.010PJ of stored energy generation could be provided potentially by a 3000ML pondage in the upper escarpment.

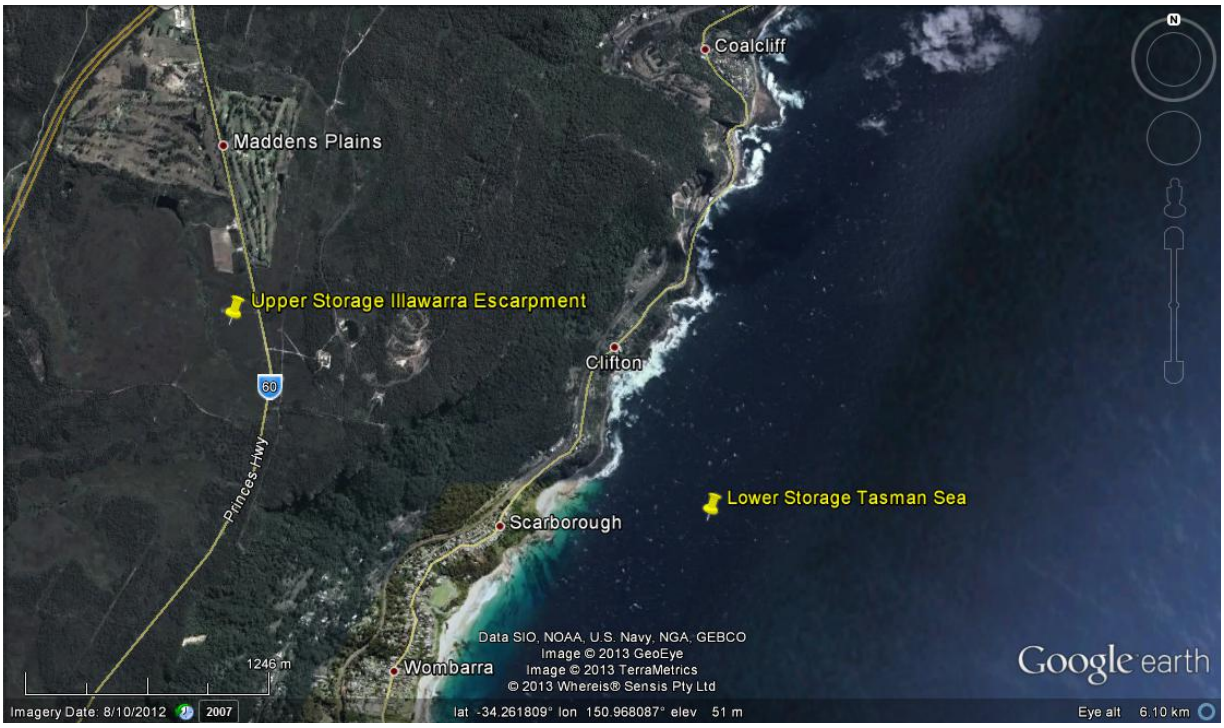

Figure 14: Coastal storage in the Illawarra escarpment(Google Earth)

Other smaller scale metropolitan projects are possible due to the steep NSW coastal escarpment. Cliff top parks and reserves shown in Figure 15 from North Bondi to Watsons Bay could be converted to a chain of small pumped storage systems and utilise heads at roughly 80 m. The playing fields at Christison Park at Vaucluse are a potential upper storage with an approximate surface area of 25000m^2 and with an average depth of 3 m would provide roughly 0.00005PJ of stored energy. Similarly a 500ML storage on North Head could provide 0.0004PJ storage. However the economic feasibility of such small scaled projects may be questionable due to high capital costs. Lower pump-turbine efficiency would also be expected, although the 87% generation value is used here for comparison.

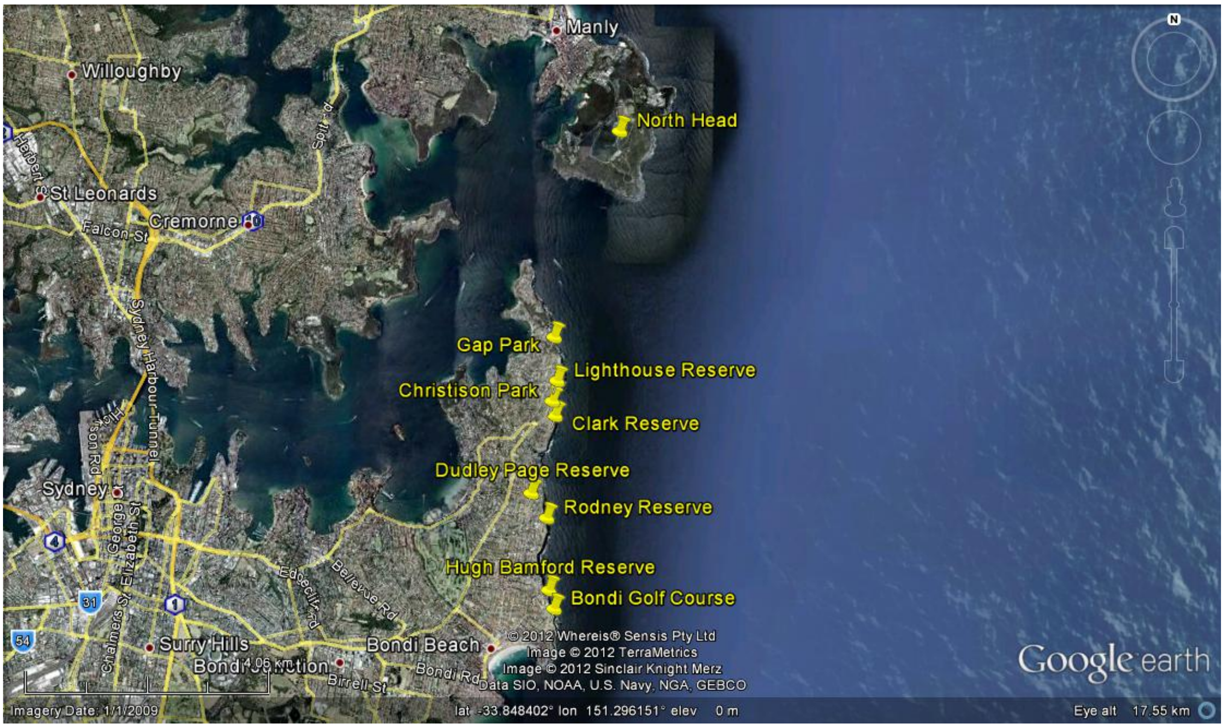

Figure 15: Elevated coastal parks and reserves from Bondi to Manly (Google Earth)

Alternative large volume storages are available using tidal inlets. The surface area of the Lower Murray lakes is approximately 750 km^2. The ecological issues associated with maintaining such a large freshwater storage became clear over the last few years as evaporation and low river inflows significantly degraded the lakes system. If freshwater supply can be protected by a more compact barrage system adjacent to the Murray inlet at the bulk of the lakes system, salt water barrages could be used to develop a salt water reservoir and energy storage system at the coast. With an average 6 m water depth, at a 3 m elevation above mean sea level, stored energy output of 0.059PJ could be created. This however, assumes that the flow is constant during generation. For applications with large volume and low elevation separation, this assumption may not be valid and requires further investigation. However stored energy efficiency could be enhanced by operating in generating mode during low tide and pumping during high tide. The tidal range for the Murray inlet is roughly 1.3 m (BOM, 2010).

3.4 Underground Storage

Underground storage was first conceptually proposed in the late 1960s at a World Power Conference in Moscow, with the topic considered a concept of pumped storage innovation amongst research in the following decade (Armstrong et al, 1975). Finland was the first to have taken the concept to the early stages of development in Parainen in 1972 (Holm, 1972), however there is little evidence in records or literature that development went ahead. Allen (1977) presents a paper briefly addressing economics, technologies, geology, size feasibility and layout. Ramer (1981) from the US had patented the concept of solution mining an underground salt dome and converting it to a large underground cavern for pumped storage operation. After what seems to be a large gap in literature, Uddin (2003) readdressed the concept of limestone mine conversion referencing a particular site in Ohio. Martin (2011) summarises the underground pump storage concept and presents the concept of smaller scale aquifer pumping plants. That year at the *Fragile Earth International Conference* in Munich and in 2012 at the *European Geosciences Union General Assembly*, Luick et al., (2012) reports current research initiatives at the University of Duisburg-Essen and the Ruhr-University Bochum investigating pumped storage applications including utilising abandoned coal mines and open cut mines.

While underground powerhouse and conduit design have been used in coastal (e.g. Okinawa, Japan) and surface storage (e.g. Dinorwig, UK), underground lower reservoirs have never been developed. Martin (2011) attributes this to the large scale nature of the project, both funding and resources, amidst complex geotechnical challenges such as those presented in Uddin (2003).

Despite the challenges, literature suggests underground design as being far less constrained by surface topography, offering greater heads in flatter terrain and optimal vertical conduit layout. Greater head range requires less storage volume and vertical conduit design provides lower capital costs, fast starting times, operational benefits and reduced frictional loss (Armstrong, 1975). By utilising upper existing storages or seawater intakes, underground storages have reduced footprint and impact on surface environments such as National Parks in high altitude terrain and surface water flow.

Suitable rock for an underground storage should be resistant to erosion by water and leakage, with sufficient structural strength to avoid collapse, such as limestone or granite (Allen, 1977). Excavated rock spoil would be of economic value. Identifying suitable locations requires regional geological assessment and thorough geotechnical investigation of suitable sites that is beyond the scope of this report, however this research is encouraged.

Utilising existing mine locations is particularly attractive for a number of reasons including adaptive reuse rather than inadequate attempts of rehabilitation and abandonment of highly altered environments, and also lower capital expenditure in utilising existing underground excavation, civil works and facilities (Luick et al, 2012). Figure 16 outlines single and multistage units in conjunction with head limitations associated with machine design.

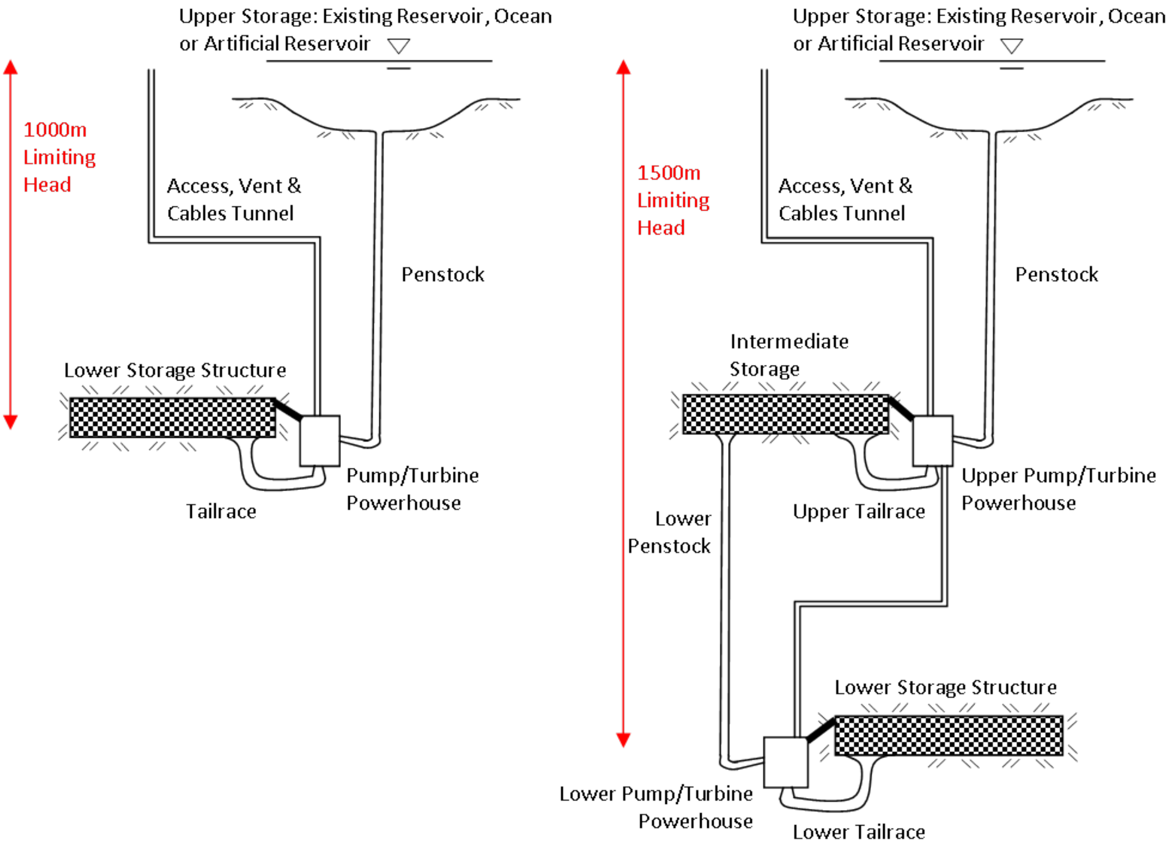

Figure 16: Single stage (left) and two-stage underground system (right), (developed from Allen, 1977 and Armstrong et al., 1975)

3.4.1 Mining to Pumped Storage Conversions: Australian Potential

The only evidence of this found in Australian pumped storage literature is in the writings of Frost (1974). It is mentioned that the old Balmain Colliery was once proposed as a lower storage 1000 m below Sydney Harbour as an upper storage.

Conventional power generation within eastern Australia relies on the mining of coal, often in large seams beneath the surface. Further, overseas demand for the high quality black coal available has led to an extensive network of mines along most of the Australian sea board.

When the dip of the seam is approximately horizontal, underground coal seams are often extracted using a technique called long wall mining. Using specialised equipment, an entire block of the seam is removed by extracting almost all of the material while temporarily supporting the roof of the seam. Once the seam block is extracted, the temporary supports are purposely collapsed to ensure that geotechnical stability is restored. A consequence of the long wall mining technique is that settlement of the surface can cause community concern.

Other unintended consequences are possible, some of which are poorly documented. Collapse of the seam can lead to adjacent facture of the rock mass above. Fissures in the rock mass could potentially lead to disruption of surface water systems by leak formation due to fracturing.

An intriguing possible alternative would be to retain sufficient of the seam to ensure that the roof remains adequately supported. Such an approach would alleviate the impacts of subsurface collapse. Depending on the size of the seam, there is also the possibility that a substantial deep void would be created, suitable for pumped storage.

A suitable surface reservoir would also be required to store water at the surface elevation prior to discharge through a turbine system located deep underground. The use of existing adjacent reservoirs may be possible but the quality of groundwater leaking into the subsurface void must be carefully assessed.

In 2009, Illawarra Coal Holdings were seeking approval to continue mining the Bulli coal seam at the Appin Mine in the Southern Coalfield region. The plans proposed seven extended mining areas with average depths ranging from 300-850 m from the overlying surface. Average seam thickness ranged from 2 - 3 m. In total 127 new long wall mines were proposed with lengths ranging from 525 - 5625 m and the majority of void widths at 310m. Surface contours range from approximately 70-400 m above sea level in the region. On the southern fringes of the region is Cataract Dam, holding 94300ML of water at approximately 290 m above sea level. (MSEC 2009).

A rough estimate of available storage volume in the proposed mines is that a void 200 000ML could be constructed. With an approximate 500 m head differential between the Cataract Dam water surface, a pumped storage network between the two could potentially generate 0.402PJ of stored energy. If Lake Cordeaux, roughly 10 km south, was connected to the system it would become an additional upper storage. Potential stored energy generation would roughly double to 0.801PJ.

Open pit mines could also be converted into upper storages and linked with nearby underground and/or open pit mines to form a pumped storage network in abandoned dense mining regions with the ability to store large volumes of energy.

In 2010, Newcrest was approved development of Australia’s largest underground mine, Cadia East Underground just outside Orange (Mining-Technology, 2012). The mine will use panel caving technique to extract gold and copper ore at depths up to 1500 m below the surface. An estimate of available storage at such depths from this technique requires further study. The existing open pit mine and/or water holding dam could be used as upper storage in a two stage system. Water usage would be required to be minimal and evaporation studies would need to be performed, however underground storage potentially reduces this effect.

With such a strong mining industry, underground pumped storage potential is large in Australia and its application should be thoroughly assessed in such a context, as a matter of importance.

4. ROAM Report on Pumped Storage Modelling for AEMO 100% Renewables Project

During the course of this investigation the author became aware of a relevant report by Roam Consulting (Rose et.al, 2012).

Under the Clean Energy Future Plan, the Department of Climate Change and Energy Efficiency (DCCEE) commissioned the Australian Energy Market Operator (AEMO) to broaden its planning horizon by investigating a National Energy Market approaching a 100% renewable energy scenario. As a part of this study AEMO engaged ROAM Consulting to identify pumped storage sites to be used as input data for AEMO's modelling and the final report is due in May 2013. For this ROAM has presented *ROAM Report* on *Pumped Storage Modelling for AEMO 100% Renewables Project 2012* (Rose et.al, 2012) included in Appendix 4 of AEMO's *Input Assumptions Report* 2012 (AEMO, 2012).

The scope of investigation limited ROAM to consideration of potential pumped storage sites which utilised existing dams and possible elevated seawater storages. ROAM used GIS technology and search criteria to locate sites within the AEMO study region, which in NSW identified 13 existing reservoirs and 4 seawater locations associated with multiple linked potential storages. Rankings of preferred sites were given in terms of cost as $/KWh which considered various capital and operating costs and energy output. Some details of the techniques used are discussed.

The head separation (termed nett head in the ROAM report), was calculated as the absolute elevation difference between the surface of existing dams or seawater(0m) to a pondage minima (local minima in the terrain). It did not consider the depth of water above the reservoir floor. This can lead to potentially significant errors for storages with low elevation separation and high ratio of transfer volume to surface area. These errors impact estimates of efficiency, stored energy and cost.

Efficiency was calculated using a linear extrapolation of nett head between 90 m and 400 m with respective efficiencies of 71% and 80%. This is a reasonable range for cyclic efficiency (Section 2.3), but underestimates the potential storage output which depends solely on generating efficiency. Therefore using the results from their report systematically underestimates potential stored energy output.

In estimating pipe costs ROAM uses approximately horizontal distance (spherical laws of cosine using the earth's radius) without considering slope distance from local terrain. This can significantly underestimate pipeline costs.

The ROAM study gives little potential to areas with flatter terrain suitable for excavated pond types despite many renowned overseas pumped storages utilising this technique including Okinawa Island in Japan, Goldisthal in Germany and Tianhuangping in China (Hino et al. 2012). Broader and perhaps more applicable options to the Australian environment such as potential underground storages are also ignored. The ROAM study also failed to identify sites in NSW from earlier studies completed in the 1970's, particularly those mentioned in earlier sections of this report.

Despite a number of shortcomings a digital mapping assessment of pumped storage potential has been well overdue. Sites identified by ROAM may well have significant pump storage potential should they be reassessed more accurately. However full pumped storage potential in the National Energy Market (particularly NSW in this case) should not be limited to the results of this report.

5. Conclusions and Recommendations

This investigation has reviewed the potential of pumped storage to play a significant role in the supply of energy in NSW.

Pumped storage hydro power in meeting peak demands, can significantly reduce and stabilise power generation capacity concurrent with providing resilience to the electricity grid. New pumped storage hydro plants can be designed to integrate most effectively with a range of future power grid demand load curves.

There is a growing need to match intermittent energy generation with variable energy demand quickly and reliably. A further study in conjunction with the *NSW Draft Renewable Energy Action Plan* should quantify how much storage is required within various planning horizons.

Pumped storage is well understood and extensively developed in foreign energy markets but full potential is not utilised in the Australian Energy Market.

Environmental considerations are critical in design and pumped storage offers some new and novel ways of managing large dams.

Locations for pumped storage in NSW could utilise existing dams, seawater storages or underground mines to produce storages of varying capacities.

Pumped storage offers significant opportunities when combined with flood mitigation proposals found in the *NSW Government State Infrastructure Strategy December 2012*.

The future of hydroelectricity in Australia is not exhausted. In the light of younger generation renewable developments, pumped storage provides promising potential for a hydropower industry. As pumped storage, hydroelectricity can continue to provide a critical role as storage infrastructure in NSW and the Australian National Energy Market.

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