Pumped hydro energy storage (PHES)

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Summary and recommendations

*PHES comprises **95% of energy storage** in the NEM. Batteries provide substantial storage power (GW), but most of the energy storage (GWh) is supplied by PHES. It is important to get the cost of PHES right, to avoid excess investment in higher-cost batteries and gas.*

PHES capital cost is strongly influenced by geography. Large head, large water-rock ratio, large scale, short tunnels and aqueducts can reduce capital costs by a factor of 10. The ANU global pumped hydro atlas is the best comprehensive source of accurate geographical data. It is difficult to adequately cost PHES without detailed reference to the best sites in the ANU atlas.

There are dozens of premium (cost-class AA) sites close to Brisbane-Sydney-Melbourne transmission. These match Snowy 2.0 on paper but have lower risk and higher construction speed because tunnels are 4-10X shorter and because Snowy 2.0 has upskilled Australian pumped hydro personnel.

We submit that there are substantial inadequacies in the draft 2024 PHES cost estimates:

1. *160-hour PHES storage (like Snowy 2.0) should be modelled in addition to 10, 24 and 48 hrs, noting that the marginal cost of converting a 48hr storage to 160hrs is usually very low (adding more rock to the reservoir walls while all other costs remain unchanged).*
2. *Aurecon appears to have undertaken a generic costing process using cost-class A or B sites and overlooked the scores of Class AA sites in the ANU PHES atlas that are close to Brisbane-Sydney-Melbourne transmission. Aurecon should explicitly focus on premium sites.*
3. *Aurecon should resolve the substantial cost-inconsistencies noted below, all of which fall on the high side.*
4. *AEMO, CSIRO and Aurecon should work with ANU and others to address our concerns.*

Our concerns

Reference: tables B.7 and B.8 in the document "GenCost202425ConsultDraftApxTables_20241127"

- *PHES with **160 hours of storage** should be costed.*
  1. Aurecon modelled 10, 24 and 48 hours of PHES storage. This is based on the highly questionable supposition that only 48 hours of storage in the NEM is worth modelling. The main role of PHES is energy storage for overnight, several days, and seasonal.
  2. By far the largest storage in the NEM (Snowy 2.0, 350 GWh, 2.2 GW) has **160** hours of storage.
  3. The absence of modelling of 160 hours of PHES storage causes an inappropriate focus on pumped hydro with high power (GW) and low energy (GWh) rather than the converse.

- *The Aurecon cost estimates look to be substantially too high*

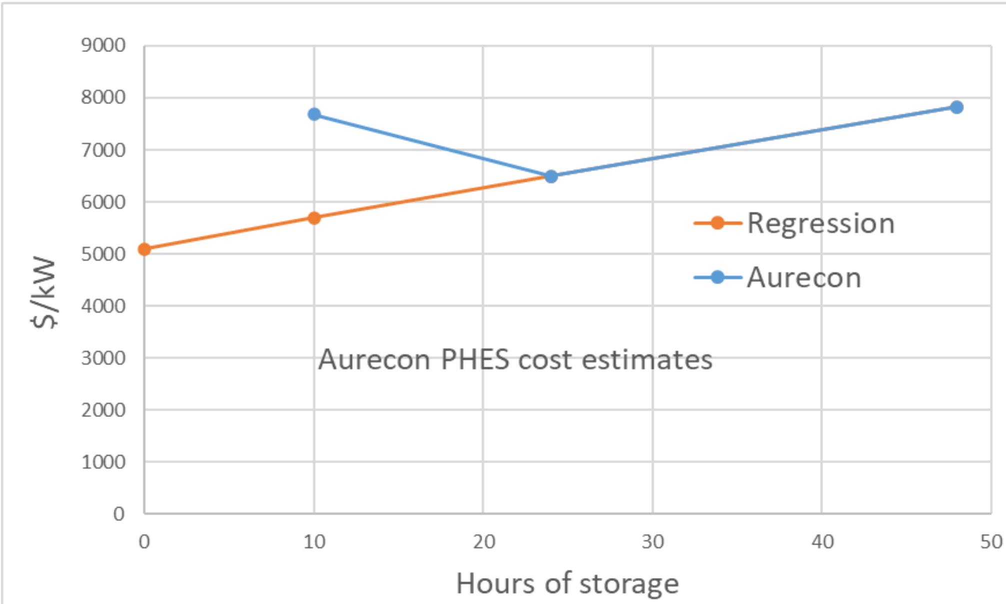
The Aurecon cost estimate for PHES 48 hours is $163/kWh, or equivalently $7822/kW (48hr*$163/kWh) which is substantially higher than comparators. The large discrepancies noted below should be resolved.

It appears that Aurecon has costed Class A or Class B sites and **overlooked** the many dozens of premium (Class AA and AAA) sites that are close to Brisbane-Sydney-Melbourne transmission

1. Snowy 2.0 (2.2 GW, 350 GWh) has a public cost estimate of $12 billion.
    a. This translates to $34/kWh (**21%** of Aurecon 48hr) or equivalently $5,500/kW (**70%** of Aurecon 48hr)
    a. Snowy 2.0 could be transformed from a 160-hour storage to a 51-hour storage by the addition of five 1 GW, 4-hour batteries (350 GWh +20 GWh divided by 2.2 GW + 5 GW = 51 hours). The total cost would be $20.5 billion ($12 billion for Snowy 2.0 + $8.5 billion for 5*4-hour batteries). The capital cost of this **hybrid system** is $55/kWh (**34%** of Aurecon 48hr) or equivalently $2800/kW (**36%** of Aurecon 48hr).
2. The P50 cost estimate for the abandoned Pioneer-Burdekin site in far north Qld for Option 2 (2.5 GW, 120 GWh, 48 hours of storage) is $142/kWh (**87%** of Aurecon 48hr) or equivalently $6,800 per kW (**87%** of Aurecon 48hr). Pioneer-Burdekin re-designed as a 160-hour storage would have been considerably cheaper.
3. In October 2024 ANU provided Aurecon with details of a premium Class AA PHES site near **Dungowan** (150 GWh, 3 GW, 50 hours of storage) as well as 10 other good sites. Aurecon reverted with a hypothetical cost estimate which is far below tables B.7 and B.8. Details are discussed in Appendix A2.
    a. Aurecon reverted with a hypothetical cost estimate of $15 billion which corresponds to $100/kWh (**61%** of Aurecon 48hr) or equivalently $5,000/kW (**64%** of Aurecon 48hr).
    b. We modified the Aurecon Dungowan cost model to have 160 hours of storage (to match Snowy 2.0) rather than 50 hours of storage. This entails raising the height of dam walls by a small amount at low marginal cost by scooping more rock out of the bed of the reservoirs. All other costs remain the same. The revised cost is $36/kWh (**22%** of Aurecon 48hr) or equivalently $5,700/kW, (**73%** of Aurecon 48hr) which is close to the published cost of Snowy 2.0 and far below Aurecon's estimate.
    c. We applied the Aurecon Dungowan model to Snowy 2.0 which yielded a capital cost of $25 billion, which is **double** the published cost of $12 billion. The discrepancy is mainly caused by a 3-fold difference in assumed tunnelling costs per km. The use of aqueducts at Dungowan would substantially further reduce the cost of the water conveyance.
    d. It appears that Aurecon has modelled class A and class B sites **rather than Class AA like Dungowan**.
4. The 10hr, 24hr and 48hr costs are inconsistent as shown in the graph below.
    a. PHES 10hr should be cheaper than PHES 24hr for constant power capacity.
    b. Furthermore, extrapolating the 24 and 48hr datapoints in the graph below to zero hours of storage suggests a PHES price excluding reservoirs of $5100/kW. This is inconsistent with Snowy 2.0: Snowy 2.0 has a published price of $5500/kW and there is zero reservoir cost (they already exist). However, Snowy 2.0 includes a very long (27 km) tunnel, which forms most of the total cost. Most Class AA sites in the ANU Atlas have tunnel length that is 4-10 times shorter (2-6 km); many can use aqueducts to further reduce tunnel length; and none are located in a remote alpine national park with

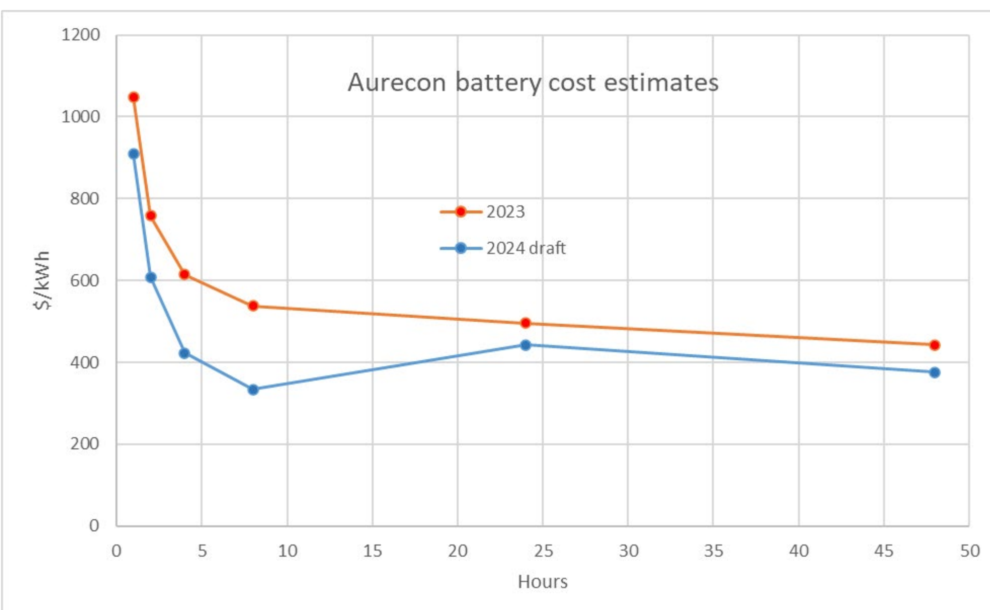
expensive roads, workcamps and transmission. This means that cost excluding reservoirs is far below \$5100/kW for consistency with Snowy 2.0.

c. The imputed reservoir cost (comparing the 24hr and 48hr costs) is \$57/kWh which implies a Class A or Class B site rather than Class AA.



- *Batteries*

The cost estimates for batteries in the 2024 draft are inconsistent. The chart shows the 2023 and the 2024 (draft) estimates by graphing cost (\$/kWh) against hours of storage. Cost should decline continuously for larger-energy battery systems (assuming constant battery power).



APPENDIX

A1. Explore the PHES Alases

The Atlas link (Green, Blue, Brownfield, Turkey nest Atlases) is here. Within the Atlas, you can pan, zoom, rotate and tilt. Look for sites with stars (cost class AAA) or triangles (class AA). Clicking on a reservoir or a tunnel route produces different information popups containing 26 items of detailed information. Different sizes can be selected in the lefthand pane. There are about 180 Cost-class AA 150 GWh sites in Australia (see appended spreadsheet) and many more in other size ranges (2-5000 GWh).

PHES_Shortlist.csv

A2. Dungowan test site

We presented a PHES site near Dungowan for costing with the Aurecon cost model. Aurecon reverted with a cost estimate, which is reproduced in the appended spreadsheet. As noted above, the Aurecon Dungowan cost model is **notably inconsistent** with tables B.7 and B.8. Perhaps tables B.7 and B.8 apply to Class A and B sites rather than Class AA sites. Australia has hundreds of Class AA sites which is far more than would ever be needed, and these should form the basis of cost estimates – not more-expensive class A and B sites.

250105 Aurecon Dungowan.xlsx

Spreadsheet dropbox url is here.

Features of the Dungowan site are:

- Power: 3 GW.
- Energy: 150 GWh.
- Duration: **50** hours.
- Head: 612 m
- Separation of the reservoirs: 6.2 km
- Aqueducts or low-pressure pipes convey water from deep points in each reservoir to the upper and lower edges of the escarpment to minimise the length of the expensive tunnel.
- A short pressure tunnel and underground powerhouse connects the two aqueducts/pipes without intruding upon wooded land along the escarpment.
- Water-Rock ratio: 16 (so that 16 Gigalitres of water is impounded per GL of rock in the dam wall)
- The dam walls are assumed to comprise rock removed from the bed of the reservoir. They are modelled according to a 3:1 batter on each face. The crest width is 10 m, and the freeboard is 1.5 m. A full description is here.
- Flooded area is 13 km^2, all outside national parks.
- Distance to 500kV transmission is 17 km.
- The Atlas URL for this site is here. Distance to Tamworth: 52km
- There is substantial opportunity to share transmission cost with new solar & windfarms.

Applying Aurecon Dungowan 50-hours cost model to Snowy 2.0 and to Dungowan 160-hours

The main differences applied for Snowy 2.0 were (i) the length of 10m diameter tunnel is increased from 6 km to 27 km; (ii) the cost of reservoirs was deleted (they already exist); and (iii) the cost of the powerhouse was reduced by the ratio of the power outputs (2.2 GW rather than 3.0 GW).

The difference applied to convert Dungowan from 50 to 159 hours of storage (to match Snowy 2.0) are to escalate the cost of the water reservoirs by the ratio 159/50.

In the Aurecon cost model, overhead charges amount to 53% of total cost, comprising (i) General costs, (ii) Indirect costs, (iii) Owner's costs and (iv) and Contingencies.

Significant cost savings are possible in the Aurecon cost model for Dungowan

For the hypothetical test site near Dungowan (and in many other premium sites):

1. Construction of a Snowy 2.0 look-alike will be considerably easier because the site is not in a national park, nor remote, nor alpine.
2. An aqueduct can substitute for most of the tunnel, allowing large cost savings.
3. Geotechnical risk is low because the required tunnel is 10X shorter than Snowy 2.0.
4. Speed of construction is high because the tunnel is 10X shorter than Snowy 2.0.
5. Cost of interconnection is likely to be shared by new solar and windfarms.
6. The cost of temporary works could be small because the site is only 52km from Tamworth. In contrast, Lobs Hole (and also Tantangara) hosts a large workcamp within a national park that is about 90 minutes from Cooma (where the Snowy Hydro offices and the concrete plant are located) by a winding road that is subject to winter snow.
7. Increasing the energy storage from 150 GWh to 350 GWh (to match Snowy 2.0) is merely a matter of increasing the dam wall heights (at low cost) using additional rock from the bed of the reservoirs. The capital cost of energy storage ($/kWh) is thereby halved. The marginal capital cost of energy storage is very low.

Additional sites

Information and links for additional sites is shown in the Table for 150 GWh sites. Other sizes in the range 2-5000 GWh are available in our Atlases. None intrude on National Parks. In most cases, an aqueduct or low-pressure pipeline can substantially shorten the pressure tunnel. In most cases, new solar and wind farms would share the cost of transmission. Most have good road and water access. Most have many options to optimise the design of the reservoirs and pressure tunnel.

Location	Size (GWh)	Head (m)	W/R	Slope	View	Type
Talbingo & Blowering	150	Many options			URL	Bluefield
Lithgow	150	672	17	7%	URL	Greenfield
Belinger	150	740	17	12%	URL	Greenfield
Stanthorpe	150	541	17	15%	URL	Greenfield
Tamworth	150	612	16	10%	URL	Greenfield
Tenterfield	150	640	13	11%	URL	Greenfield
Brown Mtn	150	860	16	9%	URL	Greenfield
Araluen	150	539	13	11%	URL	Greenfield
Armidale	150	553	10	10%	URL	Greenfield
Yallourn	150	446	14	3%	URL	Brownfield

A3. Hybrid PHES/battery systems – the case for 160-hours of PHES storage

PHES **with 160 hours of storage** (like Snowy 2.0) is usually a better configuration than 10, 24 or 48 hours.

PHES is very cheap for energy ($20-40/kWh) due to low marginal cost of heightening reservoir walls (scooping more rock from the reservoir beds). This is 10-15X cheaper than batteries. On the other hand, batteries are cheaper for power ($/kW). A hybrid system offers both cheap energy and cheap power.

In a hybrid system, the batteries can be trickle charged by a PHES system for 24 hours every day during a week with repeated high peak power prices. During a week with repeated negative prices, batteries can charge themselves around noon every day and then trickle-charge PHES for the next 20 hours.

During a stressful week, Snowy 2.0 (2.2 GW, 350 GWh, 160-hour) could continuous trickle-charge at 2 GW the following loads:

- Every day: 12 GW of four-hour utility batteries OR
- Every day: 24 GW of home batteries (5 million homes) from 20-90% (10 kWh each) OR
- Once: 10 million EVs from 20-90% (50 kWh each).

Thus, during a stressful period there may be an energy shortfall, but there is unlikely to be a power shortfall. **The key point is that Snowy 2.0 and other 160hrs PHES systems can trickle-charge high-power storage, as well as supply loads directly.**

If wind and transmission prove to be more difficult to build than solar farms, then more storage than expected will be required., and stressful periods for the grid will also be longer. This is the role for 160 hours of storage (like Snowy 2.0).

A4. PHES sites

We offer to update the locational cost factors for AEMO as we have a much better database than the Entura 2018 report (and similar approaches for cost estimation). A reasonable approach could be to use the cost of existing projects (Snowy 2.0) as benchmark. We provide regional factors by using our Atlas and our cost model to compare the average cost of several premium systems in a region vs the cost of the benchmark system.

From GenCost: "*It is important to note that PHES has a wider range of uncertainty owing to the greater influence of site-specific issues. Batteries are more modular and as such costs are relatively independent of the site. As an indicator of the influence of site costs, we have included the cost of Tasmania pumped hydro for 24 and 48 hours duration. AEMO provides state and regional cost adjustment factors for PHES and other technologies as part of the Inputs and Assumptions Workbook publication.*" "PHES Tasmania" is taken from the 2018 Entura report.