An Overview of the Capital Costs of Firming Wind Farms with Pumped Hydro

TABLE OF CONTENTS

List of Tables

List of Annexes

1 SUMMARY

The NSW publication, 'NSW Electricity Infrastructure Roadmap' (the Roadmap)[1] advises that four of the five coal fired power stations will be decommissioned by 2035. According to the Roadmap, NSW has world leading renewable energy and pumped hydro resources. These resources, combined with falls in technology prices, put NSW in a position to have globally competitive energy prices.

The Roadmap's strategy is to construct large Renewable Energy Zones (REZ) consisting of wind and solar farms firmed with some combination of gas turbine, batteries and pumped hydro plants. The Roadmap notes, however, that:

‘**In the future, long duration storage batteries may also become economic’**.

This would suggest that batteries are currently not viewed as viable firming solutions, and this view is confirmed in two papers[2] [3]developed by the authors of this current paper.

Similarly, the Roadmap advises that gas:

'can provide backup to renewable energy, transmission and storage because it is more independent of weather. Gas-fired generation also has the potential to be converted to zero-emissions hydrogen firing as this technology becomes economic.'

Putting aside the obvious commercial challenges of converting gas to hydrogen and then using the hydrogen to fire a gas turbine, the authors have demonstrated[4] that firming wind farms with gas turbines significantly increases the cost of renewable electricity to the point where it becomes uncompetitive with coal fired electricity. This does not accord with the Roadmap's claim that:

'The cheapest prospective sources of generation are large-scale wind and solar farms located in NSW’s Renewable Energy Zones'.

Noting that the NSW Government is also pursuing a net zero emissions policy, the adoption of gas turbine firming appears problematic.

This leaves us with pumped hydro as the preferred firming technology. This paper provides a brief overview of the problems with this strategy, and concludes that the replacement of the four decommissioned coal plants with modern HELE USC coal fired plants is an economically and technically superior solution.

[1] NSW Electricity Infrastructure Roadmap dated November 2020.
[2] An Overview of the Costs of Firming Wind Farms with Batteries dated 10 March 2021
[3] Firming a Renewable Energy Zone with Batteries dated 3 March 2021.
[4] A Review of the Problems with GenCost 2018 dated November 2020.

2 POWER CAPACITY LOSSES DUE TO DECOMMISSIONING

The Roadmap advises that four of the five NSW coal fired plants will be decommissioned before 2035. Table 1 reflects the consequent reduction in nameplate power capacity.

Asset Name	Capacity (MW)[5]
Liddell	2,000 MW
Vales Point B	1,320 MW
Eraring	2,880 MW
Bayswater	2,665 MW
Total Reduction in Power Capacity	8,865 MW

Table 1 Reduction in coal fired power station nameplate capacity

It is imperative that this electrical power capacity is replaced by an equally reliable and dispatchable resource. The Roadmap's strategy is the construction of REZs firmed, potentially, with pumped hydro plants. Hence, not only will 8,865 MW of nameplate power capacity need to be replaced by wind and solar farms, but also 8,865 MW of firming capacity will be required to compensate for wind droughts and unfavourable solar conditions (e.g. at night).

[5] https://www.aemo.com.au/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/forecasting-and-planning-data/generation-information

3 THE SCENARIO

To simplify the analysis, let us assume that wind farms are selected as the preferred technology to replace the coal fired power stations. This is reasonable, as wind farms exhibit a higher Capacity Factor (CF) than solar farms and hence require less firming capacity which reduces the capital costs significantly.

The Sapphire Wind Farm near Glen Innes in NSW is currently the largest in the state and its capital cost, Capacity Factor and nameplate power capacity are well known. The question is, how many Sapphire sized wind farms and at what capital cost are required to replace the decommissioned coal fired plants? Table 2 provides an analysis.

Item No	Parameter	Data
1	Total capacity to be replaced at 95% Capacity Factor (8,865 MW * 0.95)	8,422 MW
2	Total energy to be replaced per annum (8,422 MW * 365 d * 24 h)	73,776,720 MWh
3	Sapphire Wind Farm Nameplate Power Capacity	270 MW
4	Sapphire Wind Farm Cost[6]	AUD 590 Million
5	Sapphire Wind Farm Capacity Factor	34%
6	Total energy supplied by one Sapphire Wind Farm per annum at 34% Capacity Factor (270 MW * 365 d * 24 h * 0.34)	804,168 MWh
7	No of Sapphire Wind Farms to replace coal fired plants (73,776,720 MWh/804,168 MWh))	Approx 92
8	Total Capital Cost of Wind farms (92*$590 million)	**Approx AUD 54 Billion**

Table 2 Capital Costs of Wind Farms to replace decommissioned coal plants

Note that the above costs do not include the requirement for firming by gas, pumped hydro or batteries which, of course, would drive the capital costs very much higher. It is not possible to operate wind farms independently and it is essential that they are firmed with dispatchable generators. Page 5 of the Roadmap advises that:

'**In this respect, the Roadmap is expected to attract $32 billion of timely and coordinated private sector investment by 2030 in large-scale generation, storage and transmission to maintain a reliable, secure and affordable supply'**.

The $32 billion expected to be attracted would therefore appear to be significantly underestimated.

[6] https://en.wikipedia.org/wiki/Sapphire_Wind_Farm

4 PUMPED HYDRO CAPITAL COSTS

Page 30 of the Roadmap states that:

’Pumped hydro projects can make a substantial contribution to NSW’s future electricity storage needs, but they require bespoke design, face long lead times and are capital intensive, which creates high barriers to their development’.

The Australian National University has identified approximately 8,600 potential pumped hydro sites in NSW[7]. NSW currently has two pumped hydro assets, Shoalhaven and Tumut 3. The Shoalhaven asset was considered for the development of a second pumped hydro generator, using the existing upper and lower storages; however, a study[8] conducted by Origin Energy determined that:

‘the expansion of the scheme is not commercially feasible in the current economic and regulatory conditions. While there are opportunities to capture the arbitrage value in the NEM, particularly with the increasing penetration of non-dispatchable renewable energy, and benefits of utilising existing pumped hydro and dam infrastructure at Shoalhaven to develop a competitive “brownfield” opportunity, these did not outweigh the commercial risks of the Project. Of note, the capital costs of the Project were significantly higher than predicted in the Pre-Feasibility Study and are subject to exchange rate fluctuations. Furthermore, revenue generated by PHES projects in the NEM is likely to be significantly impacted by the development of Snowy 2.0 alongside the impact of batteries in the FCAS markets’.

The challenges that contributed to the decision not to proceed are summarised as follows:

- Construction costs were estimated to be much higher than expected, driven largely by the high cost of civil works, pipeline development and tunnelling
- High-cost volatility in relation to proposed tunnelling works, particularly across varied geotechnical ground conditions
- Increased difficultly in undertaking the required grid modelling necessary for the grant of a Connection Approval by AEMO and TransGrid given the high number of applications for intermittent generation in NSW
- The significant impact Snowy Hydro 2.0 will have on the NSW energy, ancillary and energy storage markets

[7] An atlas of pumped hydro energy storage; 21 September 2017.
[8] Shoalhaven Pumped Hydro Scheme Knowledge Sharing Report dated May 2020.

- Increased volatility, and decreased value of the Australian Dollar against the US Dollar and the Euro, which are generally used to purchase PHES hardware

- Increased volume of civil works being undertaken across Australia has reduced the availability and increased timeframes for securing quality EPC resources and materials, driving up costs and challenging construction durations

- Approval process to complete the Project Environmental Impact Statement, as defined by the NSW Department of Planning, proved more onerous than originally anticipated

- Complexities associated with the control requirements for works within the Water NSW "Special Zone" to ensure water quality in the system is maintained to required standards

- Limited Tunnel spoil disposal options when considering community impacts due to the lack of major road networks

- Lack of clarity in relation to Water NSW requirements on the waterway and future scheme use.

Note that Shoalhaven is a 'brownfield' site, hence the availability of existing upper and lower reservoirs should reduce costs. This was not the company's experience, which suggests that the construction of greenfield pumped hydro generators in NSW will be commercially problematic.

5 CAPITAL COSTS OF PUMPED HYDRO PLANTS

According to the Tasmanian Hydro-Electric Corporation (the Entura Report),[9] pumped hydro capital costs for six hours storage vary between AUD 1.4 million/MW and AUD 1.6 million/MW in NSW. The paper does not estimate the costs for eight hours storage required by the Roadmap, but suggests that AUD 1.7 million/MW is reasonable for 12 hours of storage. A capital cost of AUD 1.5 million/MW will therefore be used in Table 3.

Empirical data can be sourced from the Genex Power Limited (Genex) Kidston pumped hydro project in Queensland. According to Energy Storage News[10] and PV Magazine Australia[11], the Genex Power Kidston project data are as follows, noting that the costs could be potentially greater as the existing upper and lower reservoirs are available and do not need to be constructed:

- Nameplate power capacity – 250 MW
- Generation duration – 8 hours
- Capital cost – AUD 666 million
- Transmission capital costs – AUD 257 million
- Cost per MW (AUD 666 million/250 MW) – AUD 2,664,000/MW

The feasibility study[12] undertaken by Origin Energy to support its Shoalhaven pumped hydro extension project determined the following data, again noting that the costs could be potentially greater as the existing upper and lower reservoirs are available and do not need to be constructed:

- Nameplate power capacity - 235 MW
- Capital cost - AUD 570 million to AUD 630 million

Table 3 captures the range of capital costs for pumped hydro plants.

Source	Nameplate Power Capacity	Capital Cost	Capital Cost per MW
Entura Report			AUD 1.5 Million/MW
Kidston Pumped Hydro Plant	250 MW for 8 hours generation (,2000 MWh)	AUD 666 Million	AUD 2.664 Million/MW

[9] Pumped Hydro Cost Modelling dated 7 December 2017.
[10] https://www.energy-storage.news/news/first-new-pumped-hydro-plant-in-australia-for-nearly-40-years-approaches-fi
[11] https://www.pv-magazine-australia.com/2021/03/24/genex-pours-115-million-into-queensland-pumped-hydro-plant/
[12] Shoalhaven Pumped Hydro Scheme Knowledge Sharing Report dated May 2020.

Source	Nameplate Power Capacity	Capital Cost	Capital Cost per MW
Shoalhaven Pumped Hydro Extension	235 MW	AUD 570 Million to AUD 630 Million	AUD 2.425 Million/MW to AUD 2.680 Million/MW

Table 3 Capital Costs per MW for Pumped Hydro Plants

6 THE PUMPED HYDRO FIRMING SOLUTION

Having identified the requirement to construct 92 wind farms to replace the four coal-fired power stations, the next step is to determine the number and associated capital costs of the firming pumped hydro plants.

Annex A demonstrates that wind drought durations can be as much as 74 hours in the National Electricity Market. The requirement, therefore, is to construct a system of wind farms and pumped hydro plants sufficient to continue to supply power for 74 hours. Table 4 provides an analysis using data from the Kidston pumped hydro project as the reference, noting that the project is designed for eight hours storage and that the costs have been identified.

Item No	Parameter	Data
1	Total reduction in nameplate power due to wind drought	8,422 MW
2	Nameplate power rating per pumped hydro plant	250 MW
3	Number of 250 MW pumped hydro plants required to compensate for total reduction of wind power capacity (8,422 MW/250 MW)	Approx 34
4	Duration of wind drought	74 hours
5	Specified storage capacity of each pumped hydro station	8 hours[13]
6	Number of pumped hydro plants required to provide nameplate power capacity for 74 hours (34 * 74/8)	Approx 315
7	Capital cost for one 250 MW pumped hydro plant (250 * AUD 2.664 Million)	AUD 666 Million
8	Total capital costs for 315 pumped hydro plants (315 * AUD 666 Million)	**AUD 209.8 Billion**

Table 4 Calculations to determine number and capital costs of firming pumped hydro plants

In the scenario at Table 4, as the first ‘bank’ of 34 pumped hydro plants discharges its capacity over eight hours, the next bank takes the load and so on until all the pumped hydro plants are exhausted. Of course, if massive solar power capacity is available, it might be diverted to recharging the banks of pumped hydro plants. Note that this would be restricted to daylight hours in favourable solar conditions which is a very high-risk proposition.

[13] NSW Electricity Infrastructure Roadmap key parameters.

7 COST COMPARISON WITH HELE USC COAL FIRED GENERATORS

The capital costs to replace the four coal fired power stations is the addition of the wind farms (AUD 56 Billion) and the pumped hydro generators (AUD 209.8 Billion) giving a total of **AUD 265.8 Billion**. A separate paper by the authors[14]noted that Germany had recently constructed a HELE USC 1050 MW coal fired power station at a cost of **AUD 2.5 Billion**. Hence the four coal fired power stations due to be decommissioned could be replaced by nine HELE USC plants at a total of AUD **22.5 Billion** which is significantly less than the pumped hydro firmed wind farm strategy. The NSW Government could, of course, fund and own the HELE coal plants and contract their operation and maintenance to private industry under a profit-sharing incentive arrangement. Should that strategy be adopted, the following advantages would accrue:

- The capital cost is significantly less thus better serving the financial interests of the NSW taxpayers
- NSW would be provided with reliable, affordable and dispatchable electrical energy which is not weather dependent
- The HELE USC coal plants could be constructed in the same location as the existing coal plants thus providing easy access to fuel, water and transmission facilities
- Wind droughts cease to be an issue
- The requirement to construct pumped hydro assets would be obviated
- The requirement to construct the 11,000 km of transmission lines identified in the Roadmap would be obviated
- The requirement to compensate land owners for the construction of wind farms would be obviated.

[14] ‘A Review of the Problems with GenCost 2018

8 CONCLUSIONS

Over the next 15 years, NSW will decommission four of its five coal fired power stations which will dramatically reduce the availability of reliable and dispatchable electrical power.

According to the NSW Government, the reduced capacity will be replaced by wind and solar farms firmed with batteries, gas and pumped hydro. This paper has demonstrated that renewables firmed by pumped hydro is massively expensive and high-risk commercially and technically.

The most cost-effective and technically feasible solution is to replace the four decommissioned coal fired power stations with modern HELE USC coal plants which would deliver significant advantages over the firmed renewables strategy.

Authors:

Michael Bowden; IEng(Electronics-UK);CPL;CQP

Craig Brooking; MBA; BE(Civil); FAIC, Dip; formerly FIEAust; CPEng

Sydney, NSW, 18 April 2021

ANNEX A
Additional Reference Data

A.1 Wind Farm Outage Data

Table 5 records significant wind farm outages across the NEM over a decade.

Start Date Time	End Date Time	Duration (Hours)	Average CF	Average MWh
27/05/2011 5:00	30/05/2011 6:00	74	3%	76
2/06/2017 10:00	5/06/2017 9:00	72	5%	205
3/07/2012 2:00	5/07/2012 20:00	67	5%	127
12/08/2011 3:00	14/08/2011 17:00	63	4%	85
22/08/2016 2:00	24/08/2016 14:00	61	6%	232
2/06/2018 10:00	4/06/2018 18:00	57	6%	297
16/06/2013 22:00	19/06/2013 3:00	54	5%	169
6/05/2011 5:00	8/05/2011 9:00	53	4%	93
15/06/2017 11:00	17/06/2017 14:00	52	4%	183
29/04/2013 1:00	1/05/2013 3:00	51	6%	185
5/10/2011 12:00	7/10/2011 12:00	49	5%	111
2/05/2017 22:00	4/05/2017 21:00	48	6%	261
27/06/2013 14:00	29/06/2013 13:00	48	4%	138
16/04/2014 1:00	17/04/2014 22:00	46	4%	162
26/04/2012 0:00	27/04/2012 21:00	46	5%	120
30/04/2011 8:00	2/05/2011 5:00	46	6%	134
10/05/2017 8:00	12/05/2017 1:00	42	3%	149
28/03/2014 0:00	29/03/2014 16:00	41	4%	153
19/06/2019 8:00	20/06/2019 23:00	40	7%	424
18/07/2015 8:00	19/07/2015 22:00	39	5%	179
21/07/2014 8:00	22/07/2014 20:00	37	3%	115
8/04/2014 22:00	10/04/2014 10:00	37	6%	220
14/09/2012 21:00	16/09/2012 9:00	37	4%	109
19/04/2012 10:00	20/04/2012 22:00	37	5%	136
26/06/2017 7:00	27/06/2017 18:00	36	5%	238
20/07/2012 7:00	21/07/2012 18:00	36	3%	91
15/05/2012 11:00	16/05/2012 22:00	36	5%	138
28/08/2014 8:00	29/08/2014 18:00	35	5%	173
4/06/2014 9:00	5/06/2014 18:00	34	5%	169
29/04/2017 11:00	30/04/2017 19:00	33	5%	236
30/08/2015 10:00	31/08/2015 18:00	33	7%	270

12/06/2017 16:00	13/06/2017 22:00	31	6%	256
14/04/2016 6:00	15/04/2016 11:00	30	5%	209
14/08/2015 21:00	16/08/2015 2:00	30	4%	146
11/05/2014 14:00	12/05/2014 19:00	30	7%	235
15/07/2013 14:00	16/07/2013 19:00	30	6%	177
28/08/2017 8:00	29/08/2017 12:00	29	5%	238
19/06/2015 18:00	20/06/2015 22:00	29	5%	210
16/06/2015 4:00	17/06/2015 8:00	29	7%	259
19/05/2012 23:00	21/05/2012 3:00	29	6%	157
7/06/2017 9:00	8/06/2017 12:00	28	7%	334
14/04/2017 23:00	16/04/2017 2:00	28	6%	285
27/09/2015 3:00	28/09/2015 6:00	28	5%	209
4/05/2012 19:00	5/05/2012 22:00	28	6%	166
21/06/2018 3:00	22/06/2018 5:00	27	5%	257
29/03/2014 18:00	30/03/2014 20:00	27	6%	212
25/06/2012 19:00	26/06/2012 21:00	27	4%	117
11/08/2014 9:00	12/08/2014 10:00	26	7%	269
19/04/2014 5:00	20/04/2014 6:00	26	5%	193
24/03/2012 19:00	25/03/2012 20:00	26	4%	101
26/07/2019 12:00	27/07/2019 12:00	25	5%	335
7/07/2016 21:00	8/07/2016 21:00	25	7%	272
7/08/2015 4:00	8/08/2015 4:00	25	7%	268
28/03/2015 3:00	29/03/2015 3:00	25	8%	289
31/08/2012 21:00	1/09/2012 21:00	25	7%	191
9/06/2018 3:00	10/06/2018 2:00	24	4%	222
7/07/2015 8:00	8/07/2015 7:00	24	5%	198
30/07/2013 8:00	31/07/2013 7:00	24	5%	161
9/03/2013 16:00	10/03/2013 15:00	24	6%	184
15/04/2012 7:00	16/04/2012 6:00	24	6%	162
10/07/2017 22:00	11/07/2017 20:00	23	4%	202
20/07/2016 2:00	21/07/2016 0:00	23	5%	201
3/05/2015 0:00	3/05/2015 22:00	23	6%	216
28/05/2014 20:00	29/05/2014 18:00	23	6%	232
30/04/2014 13:00	1/05/2014 11:00	23	4%	151
17/09/2012 20:00	18/09/2012 18:00	23	5%	123
27/06/2018 0:00	27/06/2018 21:00	22	6%	348
31/07/2017 20:00	1/08/2017 17:00	22	4%	163

27/01/2017 9:00	28/01/2017 6:00	22	7%	337
7/08/2014 8:00	8/08/2014 5:00	22	5%	171
8/07/2013 8:00	9/07/2013 5:00	22	5%	157
1/04/2012 0:00	1/04/2012 21:00	22	6%	163
24/04/2018 19:00	25/04/2018 15:00	21	6%	321
23/10/2017 3:00	23/10/2017 23:00	21	7%	326
29/03/2015 21:00	30/03/2015 17:00	21	7%	281
13/10/2012 6:00	14/10/2012 2:00	21	7%	193
10/09/2012 11:00	11/09/2012 7:00	21	5%	144
28/03/2012 8:00	29/03/2012 4:00	21	5%	131
13/04/2020 2:00	13/04/2020 21:00	20	5%	385
21/04/2017 5:00	22/04/2017 0:00	20	9%	397
29/01/2017 3:00	29/01/2017 22:00	20	6%	255
2/08/2014 4:00	2/08/2014 23:00	20	7%	252
16/09/2012 21:00	17/09/2012 16:00	20	5%	138
3/04/2012 20:00	4/04/2012 15:00	20	6%	151

Table 5 AEMO Wind Farm Outage Data

A.1.1 Alternative Calculation to Determine Number of Pumped Hydro Plants

Item No	Parameter	Data
1	Total energy lost during 74-hour wind drought (8,422 MW * 74 h)	623,228 MWh
2	Energy storage capacity per pumped hydro plant (250 MW * 8 h)	2000 MWh
3	Number of pumped hydro plants required to compensate for 74-hour wind drought (623,228 MWh/ 2000 MWh)	Approx 312