Will Pumped-Hydro Energy Storage Business Models Work for Peak Shaving Use?

Andreas Helwig and Akshay Sahay
School of Mechanical and Electrical Engineering, University of Southern Queensland, Toowoomba, QLD 4350, Australia
E-mail: Andreas.Helwig@usq.edu.au, Akshay.Sahay@usq.edu.au

***Abstract*—** The desire for improved environmental sustainability continues to reduce reliance on fossil carbon based energy usage, while increasing installation of renewable energy sources in Australia and in the Pacific region. Pumped hydro energy storage systems (PHESS) are a technology that can be used to improve network stability where high penetration of renewable energy sources exist. However current participation in the Australian Electricity Market by PHESS does not match international participation in other electricity markets. This paper reviews international CAPEX costs and cos oft recharge energy for PHESS to better understand its potential use in the Australia national energy market. Deep sea PHESS as a conceptual emerging technology is also compared. PHESS and DSPHESS modelling in Australia and Fiji are developed to assess the final cost of energy from these sources in relation to peak shaving application. Part of each model is a sensitivity study of final cost of electricity produced from PHESS systems based on CAPEX costs and recharge energy costs.

***Index Terms*—**Hydroelectric Power generation, Electricity Supply Industry, Energy Storage.

Glossary

PHESS = Pumped Hydro Energy Storage System
NEM = National Electricity Market (of Australia)
AEMO = Australian Electricity Market Operator
CAPEX = Capital Expenditure
HVDC = High Voltage Direct Current

I. Introduction

THERE is much debate about the role and relationship between the need for energy storage systems to that of renewable energy generation penetration in a large distribution network such as the Australian National Electricity Market. One of the current topics under academic, political and commercial review is pumped hydro energy storage systems (PHESS). This is a well-defined land based technology, and a deep sea-based version of this will develop over the coming decades. In the USA, PHESS underwent rapid green field development in the 1970's to increase energy storage. Environmental and concerns over water and land management in the 1980's then curtailed development. In 2015, OAK RIDGE National Laboratory completed a study report [1] into modulized USA PHESS systems that are based on capacities less than 100MW. Here the revenue streams for the energy market, ancillary services, peak shaving and frequency control were explored for three different case studies. The conclusion of this report cited that existing transmission infra-structure must be available for PHESS to keep initial CAPEX costs competitive. The second conclusion was that a hybrid business model of combination of energy market and ancillary services is required to be viable. The SANDIA REPORT of 2015 Handbook of Energy Storage [2] reports typical present value $USD cost of installed capacity in this diverse and continental network of $5,500-$8,200/kW installed capacity. The associated present value in $USD of the leveled cost of electricity produced by PHESS is generally $155 - $220/MWh. In 2017, USA had a nominal cumulative PHESS capacity while the EU has 47.44 GW. By 2020 another 15GW of PHESS is expected to be installed in Europe [2] [3]. A review by UK University of Sheffield in 2016, gives a capital cost for PHESS in Europe and Asia of $2,000-$4,400/kW installed capacity based on much denser energy network footprints. The lower end of this range (i.e. $2,000/kW) refers to pumped back storage in an existing facility, while if a reservoir requires construction, then the upper limit of $4,400/kW results.

In contrast to this in Australia, currently there is nominally 2.8 GW of PHESS in operation, i.e. 2.2GW in the current Snowy Hydro system, with 0.57GW capacity in the CS-Energy Wivenhoe PHESS in Queensland. There is up to another 9GW potential PHESS to be developed in both Tasmania's hydro-generation network and also all over the NEM Eastern Australia as reported by Stocks *et.al* [5]. However in the their report (Submission 35 to the [Australian Government] Select Committee into resilience of Electricity Infrastructure in a Warming World) Stocks *et.al* [4] use a much more over-optimistic $870AUD/kW installed capacity for PHESS. This cost per installed kW capacity is an order of magnitude less than that reported in USA [2], and at least 60% lower than best lowest capital costs reported for Europe and Asia [4]. This optimistic Australian cost of PHESS installation may apply to micro pumped hydro systems, but for any installation based on normal hydro-electricity capacity of 100MW up to 1GW. In the long thin continental Australian NEM network, it is suspected that the USA or upper European/Asian CAPEX figures would tend to be more applicable for sites in Eastern Australia that do not have direct access to the backbone EHV network and require water storage poundage created. The exceptions to this would be the Tasmanian Hydro-Commission's planned retro-fit of pump-back being added to current hydro-storage dams to add an additional 2.5GW capacity; and the planned potential Snowy 2.0 scheme to add an additional 2GW of PHESS. For these two proposed projects, existing AEMO network access and storage dams already exist.

The question under investigation, is given the varying CAPEX costs reported from several sources, and the current AEMO operational legislation forcing PHESS to be classed as

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generating sources, will the initial CAPEX cost of PHESS green field establishment and recharge energy costs significantly impact PHESS in a negative way to participate in the Australian peak load electricity market as renewable generation source penetration increases? This is an important commercial aspect of PHESS planning and operation that impacts the Australian NEM operation. Island nations such as Fiji also need energy storage where renewable energy reliance is being driven by the cost of traditional hydro-carbon fuel import costs as well as local potential bio-mass thermal-steam energy availability. As stated in the OAK RIDGE National Report for modulized PHESS, to be successful in the USA, PHESS business modelling has indicated the need to be competitive both in the peak shaving energy market and not just in the Ancillary Services market.

II. Justification & Background information

This research question is based on the example of the difference in utilization of the Australian Wivenhoe Power (from the CS-Energy 2016/17 Annual Report [6]) and the EU PHESS data [3] to benchmark market penetration. Table 1 shows the difference in market penetration of PHESS in the Australian and EU electricity markets. The question arises why the Wivenhoe PHESS is not utilised more. Is this due to its $COE/MWh despatch costs not being competitive AEMO generator versus the peak demand market spot price?

TABLE I
Comparison of CS-Energy Wivenhoe PHESS and EU PHESS Market Penetration (Data reference)

CS-Energy Wivenhoe (Aust) 0.50GW PHESS	Annual GWh despatched	Hrs/yr Electricity Market Despatch	% of daily 3hr peak shaving market /annum
2016/17	66	132	12.0%
2015/16	86	172	15.7%
2014/15	17	34	3.1%
2013/14	14	28	2.6%
2012/13	23	46	4.2%
Germany 5.66GW PHESS	6240	1102	100.6%
Italy 3.6GW PHESS	2544	707	64.5%
Portugal 1.79GW PHESS	804	449	41.0%
SPAIN 3.28GW PHESS	3024	922	84.1%

There are also other market indicators, for Australia with future climate swings that could limit the competitiveness of the Snowy Hydro and Tasmanian Hydro-Commission competitiveness in the market. From the AER (Australian Electricity Regulator) 2017 report on the NSW electricity market [6], it is noted, though the Snowy Hydro had 19% of the summer generation capacity it only produced 4% of the total dispatched generation during 2016-17. In this report's ensuing analysis, there is a note that "*From 2017 capacity that the Snowy Hydro previously offered from $0-$30/MWh was offered at higher prices, including between $150-$300/MWh"*. This is commented in the report that the cost of water purchase (fuel for the hydro-scheme) had to now take into account environmental flow agreements, water storage levels, contract levels and competing bids from thermal generators in a market with reduced competitiveness due to the closure of the Hazelwood thermal-steam power station. As previously reported in the USA, in the 1980's, environmental concerns limited large PHESS development. So also potential climate swings in Australian rainfall and snowfall, with associated agricultural and environment implications, could limit the ability of the PHESS planned projects based in the Snowy and Tasmanian Hydro to increase their future PHESS capacity. Droughts and limited snowfalls are significant risk factors for the capacity of these proposed two new PHESS to always participate in an Australian energy market as more renewable energy sources come online.

As an alternative to terrestrial based PHESS, deep-sea PHESS or DSPHESS is in its conceptual stage with development and testing at this time [7]. There are significant engineering challenges for DSPHESS systems, but sea-based systems have the future advantage that climate swings do not limit the available PHESS capacity as it can do on land. It is also possible in future generations as sustainable engineering develops, that DSPHESS will connect regions of the world for renewable energy transfer based on HVDC undersea links. HVDC is estimated to cost an additional ~$3.65 million / km [8] for dual submarine cables for 0.5–1GW energy transmission. DSPHESS potential sites are easily identified in Australia using Google PRO Maps. These are located at the edge of narrow continental shelf areas and with over 4,000 metre hydraulic heads suitable for 0.5 – 1GW DSPHESS at:

- South of Albany in West Australia (requiring a 140km ~$511 million HV DC link);
- South of the border between Victoria and South Australia requiring a 200 km ~$730 million HVDC link);
- East of the coast of NSW town of Nowra on the South NSW Coast (requiring a 110km ~$401.5 million HVDC link).

As another example location, in Fiji there is a 2,000 metre hydraulic seabed head available to the south of Suva the capital, where a DSPHESS would require a 45km ~$32.85 million 10MW HVDC underwater link. HVDC links decrease the efficiency of any DSPHESS system, and this was investigated by Xu [9] by using a Simulink model to provide the general data for energy losses versus length of HVDC as plotted in figure 1. From figure 1, it can be seen that for HVDC links under 500km in length, that nominally there are another additional 3% losses that slightly reduce the standard range of PHESS efficiencies of 70-86% [2] [3].

III. Methodology

Based on the significant disparity in USA, EU and Australian PHESS data, usage and electricity markets application, HOMER Energy Software models are developed

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based on CAPEX costs for both terrestrial and deep-sea PHESS to see the impact on the cost of electricity ($COE) production.

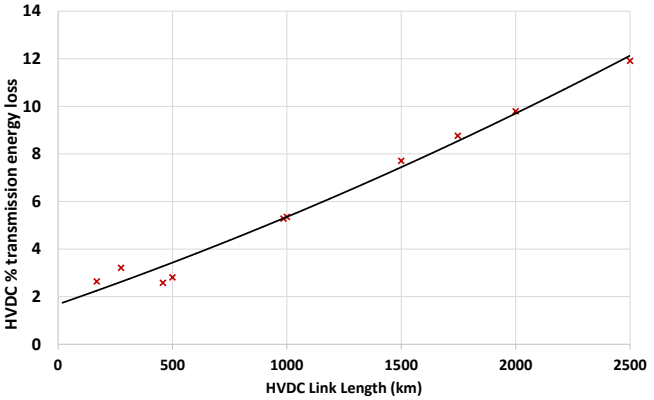

Fig. 1. HVDC Link %Losses versus Length of Link

An initial sample survey was undertaken from AEMO data for NSW to benchmark average demand and average $COE over a daily period. The sample period is August 2017 to July 2018 inclusive, and figure 2 provides the averaged daily curve for demand and cost of electricity. For this annual period, this shows the three main daily averages:

- Off-peak: $60/MWh,
- Average Daytime: $72/MWh,
- Average Peak Maximum: $115/MWh.

Delving into the statistics further using the above three benchmark values, it was found for this year period there were:

- 241 hours of operation at COE[>$115 but <$150]/MWh or 22.0% or ~80 days/annum peak shaving operation during the three hour peak period.
- 168 hours of operation at COE[>$150 but<$320]/MWh or 15.3% or ~60 days/annum peak shaving operation during the three hour peak period.
- 2 hours of operation at COE[>$2,400]/MWh.

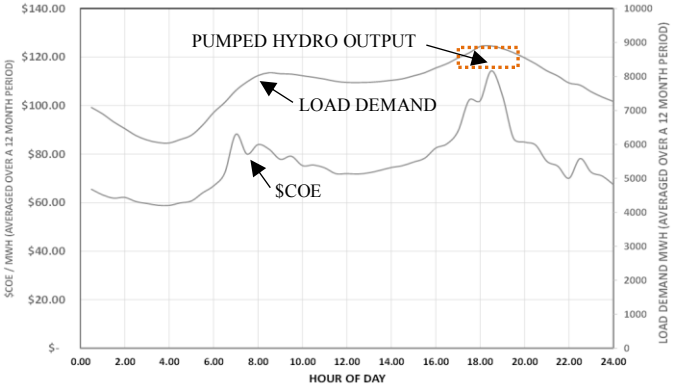

Fig. 2. AEMO NSW Average Yearly Daily Demand (*upper trace*) and Average $COE[Aug2017 to July 2018 Inclusive](*lower trace*), with the indicated hatch-filled rectangle estimating peak shaving load demand of 1. 5 GWh av. / day.

For Fiji, the daily load schedule is significantly different to that experienced in Australia. Figure 3 shows the impact of air conditioning load, with a twin peak of power at 12 noon, and around 2:30pm. The current Fiji domestic tariff with VAT is $0.3608/kWh in Fiji dollars (or ~$0.233AUD/kWh).

A. Homer Energy Software Modelling Inputs

For generic energy modelling, a 10MW and 500MW PHESS and DSPHESS systems were chosen. The larger unit is similar in size to the Australian CS-Energy Wivenhoe scheme in current operation, while the small unit is matched to demand in Fiji. Here the Monasavu Wailoa hydro-generation plant would be redeveloped with a 10MW pumped back hydro-generation system added to utilise biomass energy sources in Fiji [10].

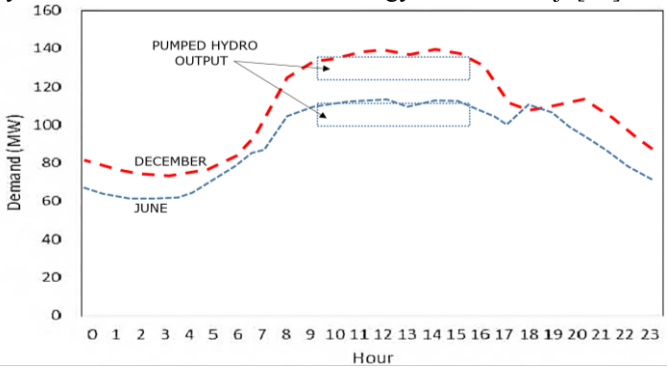

Fig. 3. Mean Daily Load Curve (Weekday) of Viti Levu in 2013. [10] Here the transparent box indicates a peak load shaving market of 10 MW nominally over 5.5 hours from 10 am to 3.30 pm.

For PHESS, the capital costs were varied from the minimum costs of European and Asian based of $2,000/kW capacity in a denser energy network, to the minimum USA based costs of $5,500/kW capacity for a dispersed network with allowance to build a water poundage. [2] [3]. This provides a CAPEX cost input range of $1billion to $2.75 billion for the 500MW unit, and $20million for the smaller 10MW PHESS unit that could be developed. Inflation shall be set at 2.8% to 5%, while interest for funds borrowed 6.5% to 10% to give some range of optimistic versus pessimistic global economic influences.

The overall efficiency of output will be taken from within the mid-range of values as 77% turn-around of the energy input. Given the electrical generator efficiency of 90% (accounting for parasitic load), this means the pump efficiency is set at 86% efficiency, which means at least 14% or more energy is needed to recharge the energy storage, than it can deliver to the grid. Recharge is assumed to be by PV energy and this load demand on the grid to recharge the energy storage system will be spread over the period from 10:30am to 3:30 pm to match the typical AEMO Power photovoltaic generation maximum output time. For Fiji this would be reversed to take advantage of off peak baseload bio-mass energy between 11:30 pm and 5:30 am.

For the DSPHESS, costs shall be assumed to be twice the costs of terrestrial based applications, to account for the engineering challenge of constructing small 17–50M-litre storage spheres at 2,000 – 4,500m depths for the chosen listed examples t the Nowra NSW and Fiji. Similarly challenges also exist for the mechanical pump required for the evacuation of the sphere's water when re-charging the system against the static head at these depths as well as operating inside the sphere at low partial pressures. Energy efficiency shall be nominally 65% to account for the HVDC link losses, as well as the additional energy costs for the deep sea sphere evacuation pump operation. Assuming the hydro-generator efficiency in these extreme conditions is 85%, then the pump efficiency is set at 76.5%. Therefore 23.5% or more recharge energy is required. The additional HVDC link costs are added as a CAPEX cost.

Equations (1) and (2) govern pumping recharge energy and

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available potential energy in falling water for hydro-generation.

$$P_{h(kW)} = q\,\rho\,g\,h\,/\,(3.6 \times 10^6) \quad (1)$$

Where: $P_{h(kW)}$ = hydraulic power (kW)
q = flow capacity (m^3/h)
ρ = density of fluid (kg/m^3)
g = gravity (9.81 m/s^2)
h = differential head (m)

$$P_{th} = \rho\,q_f\,g\,h_f\,/1000 \quad (2)$$

Where: P_{th} = power theoretically available (kW)
q_f = water flow (m^3/s)
h_f = falling height, head (m)

TABLE 2
HOMER Software Model Input Data Summary

Input (Aust)	PHESS 1	DSPHESS 1
Capacity (MW)	500	
Inflation low (%)	2.8	
Inflation high (%)	5	
Interest low (%)	6.5	
Interest high (%)	10	
Efficiency (%)	77	65
Energy recharge input factor	1.14	1.235
CAPEXlow ($million)	1000	2000
CAPEX high ($million)	2750	5500
HVDC Link km	-	110
HVDC Link ($million)	-	401.5
Hydraulic Head (m)	230 *	4000
Hydro flow rate (m^3/s)	235	19.2
Pump Recharge efficiency (%)	86	76.5
Hydro-generation efficiency (%)	90	85
PHESS turn-around efficiency	77%	65%
6 hour storage capacity (G-litre)	5.076	0.41472
Recharge time of day (E.Aust PV Solar Energy)	10:30 - 15:30	10:30 - 15:30
Input (Fiji)	**PHESS 2**	**DSPHESS 2**
Capacity (MW)	10	
Inflation low (%)	2.8	
Inflation high (%)	5	
Interest low (%)	6.5	
Interest high (%)	10	
Efficiency (%)	77	65
Energy recharge input factor	1.14	1.235
CAPEXlow ($million)	20	40
CAPEX high ($million)	(N/A)	92
HVDC Link (km)	-	45
HVDC Link ($million)	-	32.85
Hydraulic Head (m)	625 **	2000
Pump Recharge efficiency (%)	86	76.5
Hydro-generation efficiency (%)	90	85
PHESS turn-around efficiency	77%	65%
Hydro flow rate (m^3/s)	2.19	0.790
6 hour storage capacity (G-litre)	0.047304	0.017064
Recharge time of day (off-peak bio-mass)	23:30 - 05:30	23:30 - 05:30
* Based on Jindabyne Lift Head in Snowy Mountains Hydro		
** Based on Monasavu Wailoa Hydro hydraulic static head		
Input Recharge Energy Costs Sensitivity Study		
Low Cost of recharge energy $/kWh (i.e. no cost switchable load)	$ -	$ -
Step 1 recharge costs $/kWh	$ 0.03	$ 0.03
Step 2 recharge costs $/kWh (i.e. nom. Min. PV feed-in tariff.	$ 0.06	$ 0.06
Step 3 recharge costs $/kWh	$ 0.10	$ 0.10
Step 4 recharge costs $/kWh (i.e. nom. Off-peak Australian tariff)	$ 0.14	$ 0.14

For both PHESS and DSPHESS model, the available pumping time was uploaded from CSV file, which contains only three hours of available water discharge at the peak evening period in Australia (i.e. 4:30 pm to 7:30 pm). This acts as a switch in HOMER Energy software to control when the hydro-model is available to input energy.

Similarly, the evening peak grid COE rates are manipulated in the Homer software grid link time of day tariff, and raised until the electrical energy during peak period (for peak shaving) is supplied by the pumped hydro energy system discharging. From the data generated, in the extended annual plot of energy demand and $COE graph, this shall is expanded to show the COE for a given period of the day, taking note of the COE in peak period which is equal to the PHESS or DSPHESS $COE.

A nominal average peak shaving load of 1.5GWh is used in the model as the demand curve over the peak evening three hour period for the 500MW systems. For the Fiji based system, a 10MW unit would operate for 5.5 hours to handle the mid-morning to mid-afternoon air conditioning peak load. In all of the models, variable time steps of up to 20% are allowed for changes in onset/finish of the peak demand period, plus a similar variability of 20% in the peak load demand level is allowed on a daily basis.

B. Sensitivity Impact Study of Recharge Energy Costs

Energy for hydro pumping energy storage recharge will be varied in cost from considering the various pumped hydro systems as a *switchable load*, i.e. they receive excess base load electricity at any time of the day for free, to an off peak value of electricity of $60/MWh in steps of $20/MWh.

For this study, operational and maintenance costs shall be assumed to be covered by payments for ancillary services (i.e. scheduled and unscheduled frequency control, standby scheduled and unscheduled load control and black start source).

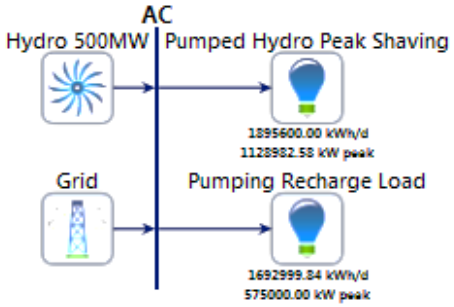

Fig.4 Typical HOMER Energy model for pumped-hydro systems; this specific example is DWPHESS (NSW) low inflation, low discount rate and lowest CAPEX costs.

Table 2 summarizes the HOMER software model inputs, and sensitivity study for energy purchase costs to recharge the PHESS and DSPHESS. The life of the plant for this modelling was set for 50 years for both types of pumped hydro-generation systems. Figure 4 shows a typical HOMER Energy model. This example is the case for DWPHESS low inflation, low discount rate, lowest capital costs (but including the HVDC link costs).

IV. Results

The results of the HOMER Energy models are collated in table 3, and then graphically displayed in figure 5 for the NSW Australian and figure 6 for the Fiji models.

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TABLE 3
HOMER Software Model Input Data Summary

	PHESS-LLL-NSW	PHESS-HHH-NSW
Recharge $/MWh	$COE $/MWh Av.	$COE $/MWh Av.
$ -	$ 89.70	$ 340.00
$ 30.00	$ 103.10	$ 352.50
$ 60.00	$ 117.00	$ 365.00
$ 100.00	$ 135.00	$ 381.50
$ 140.00	$ 154.00	$ 398.50
	DSPHESS-LLL-NSW	**DSPHESS-HHH-NSW**
Recharge $/MWh	$COE $/MWh Av.	$COE $/MWh Av.
$ -	$ 122.00	$ 447.50
$ 30.00	$ 136.00	$ 460.50
$ 60.00	$ 150.00	$ 472.50
$ 100.00	$ 168.00	$ 489.50
$ 140.00	$ 186.00	$ 506.00
	PHESS-LLL-FIJI	***PHESS-HHH-FIJI not applicable, as this is a pump-back situation for an existing hydro dam.***
Recharge $/MWh	$COE $/MWh Av.	
$ -	$ 59.10	
$ 30.00	$ 74.55	
$ 60.00	$ 89.95	
$ 100.00	$ 110.50	
$ 140.00	$ 144.00	
	DSPHESS-LLL-FIJI	**DSPHESS-HHH-FIJI**
Recharge $/MWh	$COE $/MWh Av.	$COE $/MWh Av.
$ -	$ 83.55	$ 149.00
$ 30.00	$ 99.30	$ 164.50
$ 60.00	$ 115.00	$ 180.50
$ 100.00	$ 136.00	$ 201.50
$ 140.00	$ 157.00	$ 222.00

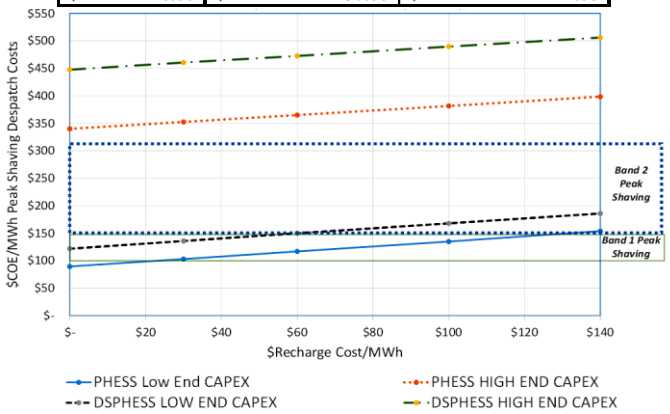

Fig.5 NSW (Australia) 500MW PHESS and DSPHESS Peak Shaving $COE/MWh versus recharge energy costs $/MWh. Band 1 peak shaving is ~80 day/year, and Band 2 peak shaving is ~60 days/year based on NSW 2017 electricity cost survey from AEMO data.

V. Conclusion

Reflecting on these predicted results in NSW, there is a place for PHESS with low end CAPEX costs (e.g. retro-install of pumped hydro to existing hydro facilities). To compete in Band 1 of the peak shaving, recharge costs for such facilities would have to nominally be half the $COE/MWh despatch bid. The best result is attained if PHESS is considered a switchable load to control load demand when other generation capacity exceed load demand during the day. For green field PHESS to even compete in the Band 2 peak shaving bidding, CAPEX costs would have to be below $2,900/kW of installed capacity, and energy recharge costs ranging from nil cost as a switchable load, or up to a maximum of 50% of the bidding costs in this less frequent peak shaving market. This is not as optimistic an outcome compared to those predicted by the ANU report [5]. Careful site selection for PHESS is required to keep CAPEX costs to acceptable levels, i.e. available access the HV network would be a primary concern. Currently DSPHESS looks promising to compete in Band 2, but again CAPEX costs would have to be $2,900/kW of installed capacity. Technology development has to catch up with conceptual evaluation to implement this technology in the future.

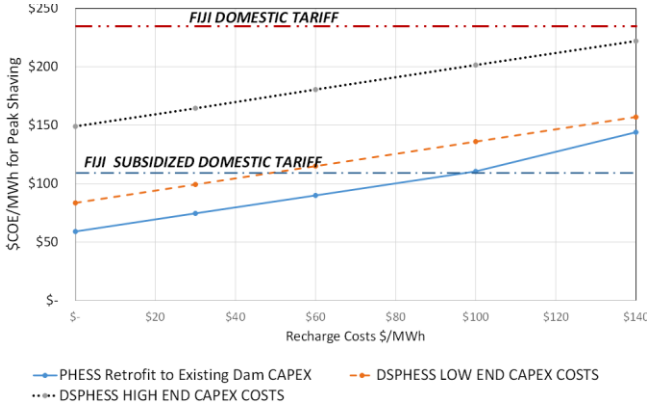

Fig.6 Fiji 10MW PHESS and DSPHESS peak shaving $COE/MWh versus recharge costs, compared to subsidized and normal domestic tariff.

Referring to figure 6, for isolated island grids like Fiji with no electricity market, both PHESS retrofit to any current hydro-schemes, as well as modular 1–20MW DSPHESS look feasible. Here these devices would be switchable load devices, as well as peak shaving generation sources.

Both example business case models give better definition to interactions of CAPEX cost limits for retrofit, or new proposed PHESS. AEMO and its legislative framework should also consider whether PHESS and DSPHESS should have special duel status as a peak shaving generation source, but also as a switchable load to receive recharge energy at no costs when excess generation capacity exists from renewable sources in particular. This would help develop increased energy storage in this market sector. Future work for DSPHESS includes modifying the model to include the impact of the HVDC link inverter LCA costs, to see the impact of this shorter life sub-component on system despatch $COE costs.

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