Potential Pumped Hydroelectric Energy Storage Sites In Colorado

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Introduction

Wind and solar energy generation are being developed in Colorado. Both wind and solar energy are intermittent by nature but electricity must remain reliable. Mitigating the intermittent nature of renewable generation sources will require a system-wide integrated planning and development approach. One piece of the integration puzzle will include energy storage. Pumped hydroelectric storage is well understood and deployable in Colorado, with two existing facilities in the State. Contrary to traditional hydroelectric generation, which is thought to be nearing the end of potential development sites, pumped hydroelectric locations exist. This paper presents two potential locations in detail along with a listing of other potential locations in the State of Colorado –see Table 1.

Pumped hydroelectric energy storage has potential for further development in Colorado as well as around the country. The August 2007 *Hydro Review* points out that 23 GW of identified potential traditional hydro generation can be developed without the need for new dams. How much of that could be used as pumped storage as well as traditional hydro generation? Two pumped hydroelectric plants currently operate in Colorado-Cabin Creek and Mt. Elbert. The economic benefit of Cabin Creek on the utility system as it relates to the integration of wind power is well documented [1]. Mt Elbert does not provide the same benefit due to a different management strategy. Colorado's vast mountains provide many additional opportunities for pumped hydroelectric sites. Table 1 outlines a listing of potential PHES locations in Colorado.

Table 1: Colorado PHES; Locations, Power, Capacity, Payback Period, and Comments

Site Name	Power [MW]	Capacity [MWh]	Payback [years]	Comments
Cabin Creek as calculated	329	1317	39	Plant in operation this site was used to check the assumptions used for calculations
Bellyache Ridge	310	2167	21	Adjacent to transmission and water
West Gypsum	375	2622	21	Adjacent to transmission and water
Horsetooth College	15	75	27	Forebay and Afterbay currently in place
Davis Pt	548	2739	25	Adjacent to water and 1km from an oil shale plant
Schoolhouse Pt	630	3148	25	Adjacent to water
Peetz Bluffs	43	213	Does not payback in base calculation	Adjacent to Colorado's North Eastern Wind Plants
Gunnison Hydro	641	3846	22	Afterbay in place Utility right of way exists

Methods

A model has been developed that analyzes both economic and technical characteristics of each site. To calculate the technical specifications of a pumped hydroelectric site, a basic fluid power equation is used. Given hydraulic head, system efficiency, and an upper bound on flow rate, the power generation capacity of a pumped hydroelectric installation can be calculated with the following equation:

[1] EnerNex Corporation. May 2006. *Wind Integration Study for Public Service Company of Colorado.* Prepared for Xcel Energy Denver Colorado. Page 78.

$$P = Q \cdot H \cdot \rho \cdot g \cdot \eta$$

Where P = generated output power in Watts [W]
Q = fluid flow in cubic meters per second [m^3/s]
ρ = fluid density in kilograms per cubic meter [kg/m^3] = 1000 [kg/m^3] for water
H = hydraulic head height in meters [m]
g = acceleration due to gravity [m/s^2] = 9.81 [m/s^2]
η = efficiency

Next, given the power capacity of the plant, the limiting volume of the upper or lower reservoir dictates the energy capacity. Potential energy generation or Kilowatt hours [kWh] are calculated by power output (capacity) multiplied by run time. Run time is a function of flow rate and reservoir volume. Financial analysis is based on capital cost estimations as well as estimations of the volatile price of energy on the open market. Interest rates, construction times, the value of CO_2 avoidance, and other factors are taken into account in the financial analysis of Colorado PHES sites. This set of methods is effective for a expedient look at multiple potential sites. If development is still under consideration after this process a more rigorous methodology should be used to yield a more detailed analysis.

Results and Discussion

West Gypsum Site

The West Gypsum site is located in Eagle County to the West of the town of Gypsum, Colorado. This location's forebay is along a high ridge owned by the Bureau of Land Management (BLM) and the afterbay would sit along side the Eagle River in the I-70 corridor. This site has a potential hydraulic head of 393 meters with areas for development at the top and bottom for reservoirs, the bottom reservoir would be more difficult to site due to both a major interstate and the river which would serve as a water source. With a surface area potential of about 40 acres for the upper reservoir, West Gypsum could have an energy storage capacity of 2,620 MWh deployable in 7 hours at 374 MW. Currently Colorado has 324 MW of pumped storage capacity in use actively managed to mitigate wind intermittence. This would more then double the assets within the state in both capacity and energy to pump water for energy storage. This doubling may be the scale of development that is necessary as Colorado has doubled its renewable portfolio standard from 10% to 20%. The vast majority of that generation will come in the form of wind generation. Xcel Energy has reported that the cost of integration of Renewables at 10% penetration is reasonable with current assess, but the 20% level will be challenging. Doubling the PHES storage assets on Colorado's grid may allow the additional 10% plus set Colorado up for additional clean energy gains.

Economic analysis of this system assumes an overnight capital cost of $1300 per installed kW, a construction time of 5 years, an interest rate of 4.9%, and a CO_2 avoidance value of $5 per ton of CO_2. This yields estimated annual energy sales of $40,776,944 plus an additional $26,291,148 in avoided natural gas and natural gas turbine operation costs. Also this plant could enable the avoidance of production of 882,049 tons of CO_2 for a value of $4,410,249 when valued at $5/ton. The above revenues and avoided costs set against the time valued capital cost yield a payback of 21 years.

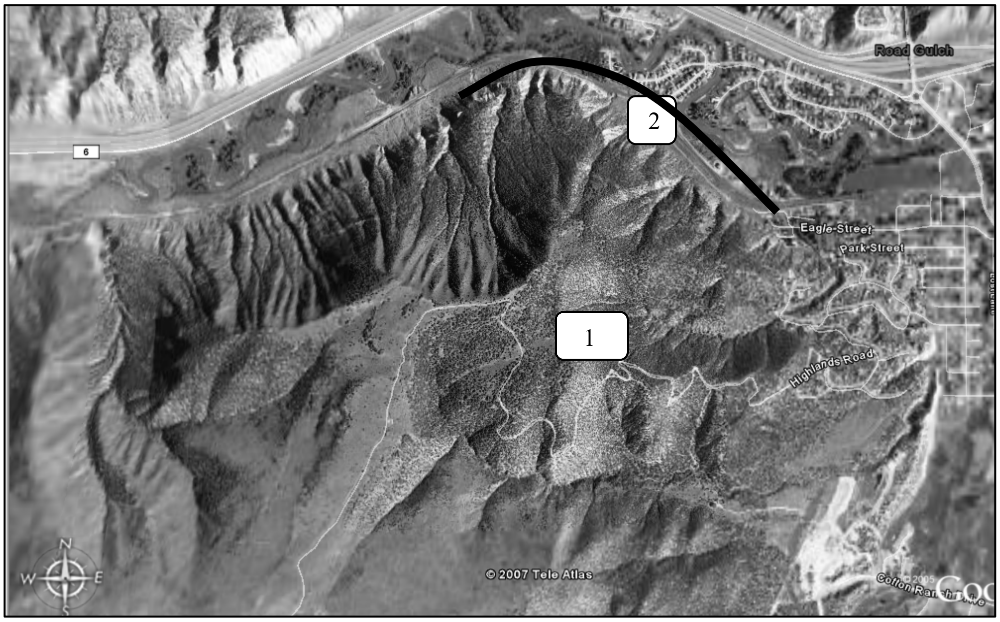

Figure 1: View of the West Gypsum Potential Site; 1-Aproxamate forebay location, 2-Afterbay may be located anywhere along the Eagle River I-70 corridor to facilitate siting. Eagle River I-70 corridor is marked in a bold black line.

Power and Capacity							
Head	393.00	Meters					
Volume	2,720,000.00	M^3					
	2,592.51	acre feet					
Surface Area	39.52	Acres					
Flow Rate Min	50.37	M^3/S					
Flow Rate Max	107.94	M^3/S					
Storage Time Min	7.00	hours					
Storage Time Max	15.00	hours					
Power Min	174.77	MW					
Power Max	374.52	MW					
Energy	2,621.62	MWh	** Assumes 15% of forebay volume is unused				
Revenue							
Cycle Value	$130,695						
Annual Revenue	$40,776,944						
Avoided NG Cost	$26,291,148						
Avoided CO_2 Emissions	882,049.96	tons[metric] of CO2 avoided/year					
CO_2 value	$4,410,249.81	value per annual CO2 reduction					
Avoided SO_2 Emissions	196.64	tons[metric] of SO2 avoided/year					
SO_2 value	$117,982.62	Annual Traded Value					
Total	$71,596,323.61	Total Annual Value					
Total	$45,187,193.44	Counted Annual Value					
Cost							
Cost Breakdown by %				%			
land and land rights				2%	$9,976,908	yes	$9,976,908
Power Station structures and improvements				9%	$42,506,616	yes	$42,506,616
Reservoirs and Water Ways				22%	$107,825,432	yes	$107,825,432
Pumps Turbines Valves Governors				9%	$44,896,085	yes	$44,896,085
Generator Motors and Static Starting Equipment				6%	$31,177,837	yes	$31,177,837
Accessory Electrical Power plant Substation Equipment, Roads				10%	$49,518,719	yes	$49,518,719
Contingencies Engineering and Overhead				14%	$68,943,759	yes	$68,943,759
Allowance for funds during construction				27%	$132,027,747	yes	$132,027,747
Cost Estimate Based on Needed Facilities and other Costs				TOTAL	$486,873,103	itemized total	$486,873,103
Payback Period and Life Cycle							
overnight cost		$486,873,103	Cost based on Max Cost of shortest storage durration & itemized cost entries.				
Does CO2 Have Market Value?		yes	yes or no	CO2 valued at		$4,410,249.81	at $5/ton
Annual Rev		$40,776,944	Revenue based on Min storage time and buying vs. selling delta				
Payback Time		21	years				
Life Time Net Present Value		$8,251,156,548	100 year plant lifetime				
	Interest Rate	4.90%					
	O & M	$2,434,366	per year				
	Construction Time	5	years				
	Annual % increase	1.00%					

Figure 2: Technical and Economic outputs for West Gypsum

Figure 2 legend-
Cycle value = The value of running the PHES plant for one cycle of pumping and generating 2,622 MWh
Annual Revenue = Cycle value times 6 days times 52 week per year
Avoided Natural Gas (NG) Cost = Assuming NG Peaking plant costs $50/MWh to operate and PHES plants cost $5/MWh to operate, each MWh the PHES plant operates as opposed to the peaking NG plant the system gain $45/MWh. This value was limited to 5 hours/day.
Avoided CO_2 Emissions = Assuming NG peaking plants can be run less due to the use of the PHES plants each MWh the model calculates operation for the PHES plants -limited to 5 hrs/day- avoids 2,377.4 lbs of CO_2. CO_2 was valued at $5/ton.
Avoided SO_2 Emissions = Assuming NG peaking plants can be run less due to the use of the PHES plants each MWh the model calculates operation for the PHES plants -limited to 5 hrs/day- avoids .53 lbs of SO_2. SO_2 was valued at $600.00/ton.

Horsetooth-College
The Horsetooth-College site is located on the western edge of Fort Collins Colorado between Horsetooth Reservoir and College Lake displayed in Figure 3 . The current analysis uses 65 meters for the hydraulic head and uses an energy storage capacity of 65MWh deployable in 5 hours at 13 MW. Economic analysis of this installation assumes an overnight (capital) cost of $2500 per installed kW, a construction time of 2 years, an interest rate of 4.9%, and a CO_2 avoidance value of $5 per ton of CO_2. This yields estimated annual energy sales of $1,245,382 plus an additional avoided cost of $913,166 avoided natural gas and gas turbine costs also the avoidance of production of 25,249 tons of CO_2 for a value of $109,414. The above revenues and avoided

costs pay the financed capital cost back in approximately 27 years. The payback period is significantly effected by the interest rate assumed as well as the choice to include or not include the avoided cost of natural gas generation as revenue. The capacity presented in the above calculation requires flow rates not currently passable by the water works in place. While the reservoirs are useable the penstocks can not pass more then 65 cfs and the capacity design point presented here is more then a factor of 10 over that allowance.

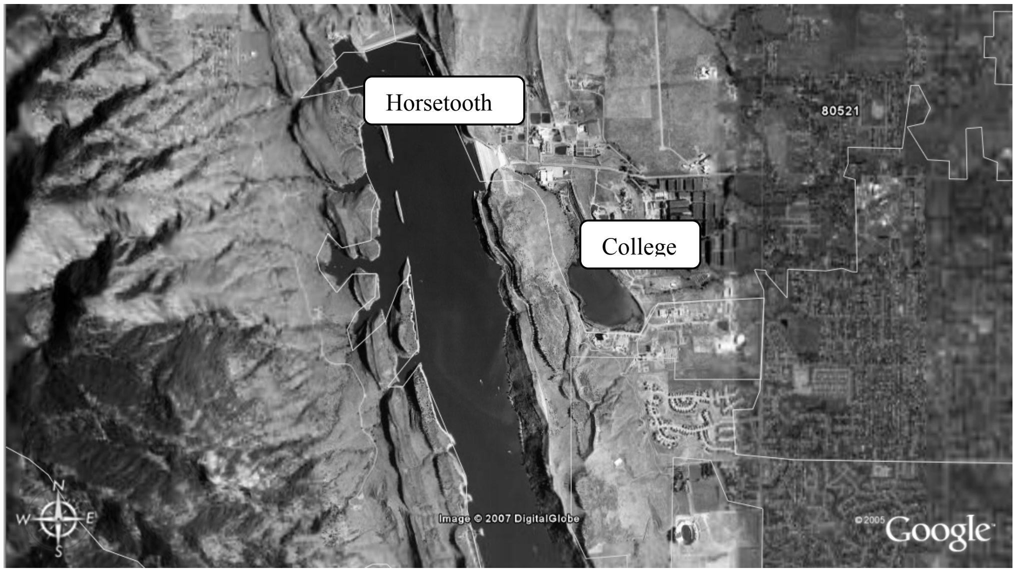

Figure 3: View of Horsetooth reservoir and College Lake on the western edge of Ft Collins Colorado and the CSU campus.

A summary sheet is displayed below in Figure 4 showing a set of outcome cost and technical outputs.

Power and Capacity							
Head	65.00	Meters					
Volume	408,000.00	M^3					
	388.88	acre feet					
Surface Area	79.04	Acres					
Flow Rate Min	22.67	M^3/S					
Flow Rate Max	22.67	M^3/S					
Storage Time Min	5.00	hours					
Storage Time Max	5.00	hours					
Power Min	13.01	MW					
Power Max	13.01	MW					
Energy	65.04	MWh					
Revenue							
Cycle Value	$3,992						
Annual Revenue	$1,245,382						
Avoided NG Cost	$913,166						
Avoided CO_2 Emissions	21,882.92	tons[metric] of CO2 avoided/year					
CO_2 value	$109,414.59	value per annual CO2 reduction					
Avoided SO_2 Emissions	4.88	tons[metric] of SO2 avoided/year					
SO_2 value	$2,927.05	Annual Traded Value					
Total	$2,270,889.35	Total Annual Value					
Total	$1,354,796.48	Counted Annual Value					
Cost							
Cost Breakdown by %				%			
land and land rights				2%	$666,397	no	$0
Power Station structures and improvements				9%	$2,839,182	yes	$2,839,182
Reservoirs and Water Ways				22%	$7,202,080	yes	$7,202,080
Pumps Turbines Valves Governors				9%	$2,998,784	yes	$2,998,784
Generator Motors and Static Starting Equipment				6%	$2,082,489	yes	$2,082,489
Accessory Electrical Power plant Substation Equipment, Roads				10%	$3,307,548	yes	$3,307,548
Contingencies Engineering and Overhead				14%	$4,605,022	yes	$4,605,022
Allowance for funds during construction				27%	$8,818,647	yes	$8,818,647
Cost Estimate Based on Needed Facilities and other Costs				TOTAL	$32,520,150	itemized total	$31,853,753
Payback Period and Life Cycle							
overnight cost		$31,853,753	Cost based on Max Cost of shortest storage durration & itemized cost entries.				
Does CO2 Have Market Value?		yes	yes or no	CO2 valued at		$109,414.59	at $5/ton
Annual Rev		$2,158,548	Revenue based on Min storage time and buying vs. selling delta				
Payback Time		27	years				
Life Time Net Present Value		$321,527,840	100 year plant lifetime				
	Interest Rate	4.90%					
	O & M	$159,269	per year				
	Construction Time	2	years				
	Annual % increase	1.00%					

Figure 4: Horsetooth reservoir and College Lake

Figure 4 legend
Cycle value = The value of running the PHES plant for one cycle of pumping and generating 2,622 MWh
Annual Revenue = Cycle value times 6 days times 52 week per year
Avoided Natural Gas (NG) Cost = Assuming NG Peaking plant cost $50/MWh to operate and PHES plants cost $5/MWh to operate, each MWh the PHES plant operates as opposed to the peaking NG plant the system gain $45/MWh. This value was limited to 5 hours/day.
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This pumped hydroelectric site may be an opportunity to firm intermittent wind power under consideration by Colorado State University (CSU). CSU is actively pursuing the development of wind power on Maxwell Ranch north of the University. The property is located in the robust South-central Wyoming wind regime. The electric and water providers for the Ft Collins and CSU area are Fort Collins Municipalities as well as the Platt River

Power Authority. Due to the municipal nature of the providers and both the land for the wind development and the lake for the lower reservoir are owned and operated by CSU. The bureaucratic hurdles of development are partially minimized. Additionally, an effort known as the Colorado Energy Collaboration has recently been set up between the University of Colorado, Colorado State University, the Colorado School of Mines, and the National Renewable Energy Laboratory which creates an inter-institutional entity that may have interest in the development of such a project. This potential site for development is not the largest nor is it the quickest to payback economically. But, this site has many strong attribute which make it a good candidate for further investigation for development including:

1. Forebay and afterbay are already in place.
2. Two entities capable of managing such a development and operation are co-located to the development site and they either own the land or operate facilities on the land; Colorado State University –own- and Ft Collins Municipal Hydro Department -operates.
3. Environmental concerns due to the development of additional reservoirs and water ways are mitigate due to the fact that they are already in place.

Challenges that still need to be solved include:

1. Reservoir draw-down in Horsetooth reservoir throughout the year decrease the power available and the reliability of the system. This should be addressed by looking at operating conditions throughout the year with historical data. This should also be addressed by looking at the Colorado Big Thompson project as a whole –which feeds the water into Horsetooth Reservoir- to see if draw-down can be minimized through different management strategies.
2. If water is pumped back from College Lake into Horsetooth Reservoir the water quality of both reservoirs will be changed. Horsetooth reservoir is a drinking water source for the City of Ft Collins and can not be compromised without the ability to insure safe drinking water.
3. The water way between Horsetooth reservoir and College Lake is not of sufficient size to pass the flow rate necessary for the design point on the order of ten Megawatts. New water ways would have to be constructed for a project of this size or the water way in place may need significant augmentation.

Conclusions

The two examples shown in this paper are pulled out of a set of seven. Those seven sites are not the full set of potential locations in Colorado. As Colorado, the American West, and the US as a whole develop more intermittent generation capacity there will need to be plans in place to deliver energy when it is needed as opposed to when it is generated. Energy storage is not a silver bullet to renewable energy integration, other steps will be necessary including:

1. An optimization of spatial distribution to minimize intermittent output and maximize energy production of wind generation.
2. Diversification of renewable generation sources, to minimize intermittence.
3. Virtual storage technology such as demand response and virtual baseload through efficiency improvements.
4. Energy storage on multiple time scales.

Given that there will be continued interest in intermittent generation, significant resistance to pumped hydroelectric development, and a need to compromise between the two. The presence of this body of work showing multiple options to solve a variety of challenges will be of increasing importance to Colorado’s electrical utilities, ratepayers, and various other stakeholders. The larger energy storage examples are significant to not only Colorado but the Western interconnect as a whole. To facilitate the four steps listed above aiming to integrate larger penetration percents of renewable energy onto electric grids policy should be put into place that: Enables access to intermittent generation production figures; Provides incentives for the optimization of capacity build-out of generation systems; and supports the development of appropriate virtual and traditional energy storage technology.

Furthering the PHES examples in future work can be done through:

1. The Ft Collins Horsetooth College lake example can be improved through further discussion with the entities in control of the facilities in place.
2. Improved cost modeling though the use of direct cost estimates.
3. Revenue numbers can be improved through the use of real time MWh purchase price data from within the Colorado region.