PUMPED HYDROELECTRIC ENERGY STORAGE AND SPATIAL DIVERSITY OF WIND RESOURCES AS METHODS OF IMPROVING UTILIZATION OF RENEWABLE ENERGY SOURCES

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B.S., Michigan Technological University, 2003

A thesis submitted to the faculty of the Graduate School of the University of Colorado in partial fulfillment of the requirement for the degree of Master of Science, College of Engineering and Applied Math
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Signature Page

This thesis entitled: Pumped Hydroelectric Energy Storage and Spatial Diversity of Wind Resources as Methods of Improving Utilization of Renewable Energy Sources *written by Jonah G. Levine has been approved for the Interdisciplinary Telecommunications Program, College of Engineering and Applied Science, University of Colorado at Boulder.*

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The final copy of this thesis has been examined by the signatories, and we
Find that both the content and the form meet acceptable presentation standards
Of scholarly work in the above mentioned discipline.

Abstract

Levine, Jonah G (MS. Interdisciplinary Telecommunications Program, College of Engineering and Applied Science)

Pumped hydroelectric energy storage and spatial diversity of wind resources as methods of improving the utilization of renewable energy sources

Thesis directed by Distinguished Professor. Frank S Barnes

Renewable energy generation is becoming more prevalent on today's electric grid. Part of the challenge of increasing the percentage of renewable energy beyond 20% will be dealing with the intermittent nature of renewable sources. The following body of work discusses two methods to integrate intermittent or variable renewable energy in to the electric system. The methods are pumped hydroelectric energy storage and optimizing the capacity development of wind generation utilizing complimentary wind regimes encountered with spatial diversity. The research effort has two general findings.

With regards to pumped hydroelectric energy storage (PHES), Colorado has many sites with different attributes that could be considered for development. Through PHES development, Colorado could manage not only its intermittent power generation but facilitate integration of renewable generation over a much larger geographic region. Opportunities exist in Colorado to utilize infrastructure already in the ground as well as new construction.

With regards to wind generation, if capacity development is optimized utilizing the complimentary production encountered with spatial diversity, some percentage of capacity developed can be utilized as firm power. The analysis herein show 5% of developed capacity is firm over 99% of the year analyzed. In some cases optimized wind power production spends 0.00% of time at zero power generation in the given year. Additionally this analysis may be improved to increase the percentage of capacity which can be counted as firm.

Acknowledgements

The vision and leadership that supported me and this work from start to its current state was Dr. Frank Barnes, thank you Frank.

University of Colorado at Boulder’s *Energy Storage Research Group* received support from the Colorado Energy Research Institute (CERI). Without the generous support of CERI as well as their vision of a more sustainable Colorado this work would not have been possible. Beyond this work the author has gained insight and experience through the reciprocal processes of working, teaching, and learning that will enable not just a better understanding of pumped storage but a stronger grasp of the challenge and potential solutions that are precipitated by intermittent energy generation. Thank you CERI.

University of Colorado at Boulder’s *Energy Storage Research Group* received support from the Colorado Department of Agriculture. This support enabled the study of small scale distributed energy storage applicable to family farm scale applications.

University of Colorado at Boulder’s *Energy Storage Research Group* received support from University of Colorado’s Energy Initiative. This support directly funded the following thesis by supporting the study of potential locations for development of PHES in Colorado. This support also facilitated legal analysis of water and regulatory right relevant to this work.

University of Colorado at Boulder’s *Energy Storage Research Group* received regular collaboration and working support from University of Colorado School of Law’s Energy and Environmental Security Initiative (EESI). The intellectual collaboration between the disciplines of engineering and law bring technical ideas closer to political fruition. Thank you EESI.

Rocky Mountain Institute with support from the Argosy Foundation were helpful in my learning process while this work was developed. Ms. Lena Hansen provided a great deal of intellectual capital around quantifying the results of spatial diversity and optimization of wind power. Together with Lena I look forward to further developing this body of work.

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1. Introduction

Renewable energy generation is becoming more prevalent on today's electric grid. While Colorado's political atmosphere is driving changes in our electric utility industry, the industry is hesitant to change how it has been supplying reliable electric power for nearly a century. Some of the reason for this hesitation is the intermittent or variable nature of renewable sources. For instance, solar electricity is not going to function at night, and likewise wind generation will not generate electricity when the wind is not blowing. This variable energy manifests the challenge times when no output is available, and times when excess output is generated. Additionally, other challenges arise such as momentary faults and decreased ability to manage the real versus reactive power on the electric system. This set of challenges can be classified generally as variable or intermittent generation integration issues. One part of solving the intermittent integration challenge is electrical energy storage.

An effort has been successful increasing the amount of renewable energy in Colorado by raising the current Renewable Portfolio Standard (RPS) from 10% to 20% renewable source generation by the year 2020. This will bring with it both technical and economic consequences. Some positive consequences include bolstering clean energy industries in Colorado, diversifying our generation portfolio, and protecting our environment. Part of the challenge of increasing the percentage of renewable energy (to 20% penetration and beyond) will be dealing with the intermittent nature of renewable sources. Increasing the amount of intermittent sources without ensuring they are available when needed still requires the capital cost investment in conventional generation plants. The net result is an unnecessarily increased cost for electric power. If legislation encourages system wide planning to ensure energy is available when it is needed while minimizing the externalities of fossil fuel generation and maintaining reasonable cost, Colorado has the opportunity to set a positive example of energy systems planning.

What can be done to solve the challenge presented by the need for energy when renewable production is not available? Or conversely, what can be done to handle excess energy created when intermittent generation is high and demand is low? The most effective solution will be an integrated approach, which should include:

1. Diversifying the types and locations of renewable generation sources. This method should be an optimization of spatial diversity and renewable generation sources that minimizes intermittence and cost while maximizing capacity to meet or exceed RPS targets while meeting loads with over 99% reliability.
2. Encouraging demand side management (DSM) to serve as a renewable source of energy, this can be thought of as virtual base load generation many times referred to as the *negawatt.* DSM can also be used to describe the deployment or control of loads.
3. Developing adequate transmission infrastructure to facilitate diversified renewable plant locations.
4. Planning for additional energy storage on Colorado's electric grid that optimizes the utilization of transmission and generation resources minimizing costs and green house gas (GHG) emissions, and allows renewable energy to be dispatched with more flexibility.
5. Formulate legislation that provides incentives for the first four points.

None of the above points are silver bullets to facilitate 20% and greater penetration of renewable power sources. Moreover, if only one of the above strategies is pursued it will be less valuable than if a combination are pursued. Each point will increase the reliability of Colorado's electric grid and have synergistically positive effects on the other points. One alternative to the above mitigating steps is building additional peaking natural gas plants to provide on demand energy in the absence of sun and wind, though this is seemingly contrary to an increased RPS.

Evaluating both the technical and economic ramifications of each of the five mitigating steps will need to be done as efforts move forward with RPS deployment. It is evident that a system analysis for the state as a whole or a larger geographic region will need to be conducted to determine the most effective solution to the challenges poised by intermittent power generation. Legislation needs to be written so that those generating, transmitting and distributing the energy have incentives to optimize the system as a whole. This optimization will enable renewable energy sources to meet as large a fraction as possible of the public's need for reliable power, while concurrently setting the stage for increasing Colorado's renewable generation beyond 20%. To this end, the following body of work will draw on current knowledge and propose future projects to facilitate the integration of intermittent power on to the electric grid.

This thesis will be presented in two major parts. Chapter II deals with the potential for deployment of pumped hydroelectric energy storage (PHES) resources in the state. It includes site analysis of various potential locations for PHES around the state. These sites are analyzed using a model developed to determine expected physical and financial aspects of the sites. Chapter III deals with the optimization of wind generating resources via spatial diversity of the wind generators.

2. Pumped Hydroelectric Energy Storage in Colorado

2.1. Background and Literature Review

Renewable energy generation is becoming more prevalent on today's electric grid. Colorado voters have passed and state legislators have recently increased required renewable generation targets (via our RPS, Amendment 37) for the most significant independent system operators (ISO's), municipal suppliers (MUNI's), and rural electric associations (REA's) in the State. One method for solving the intermittent challenge is electrical energy storage. Figure 2-1 displays the fundamental problem by plotting both a daily load profile and a wind generation profile.

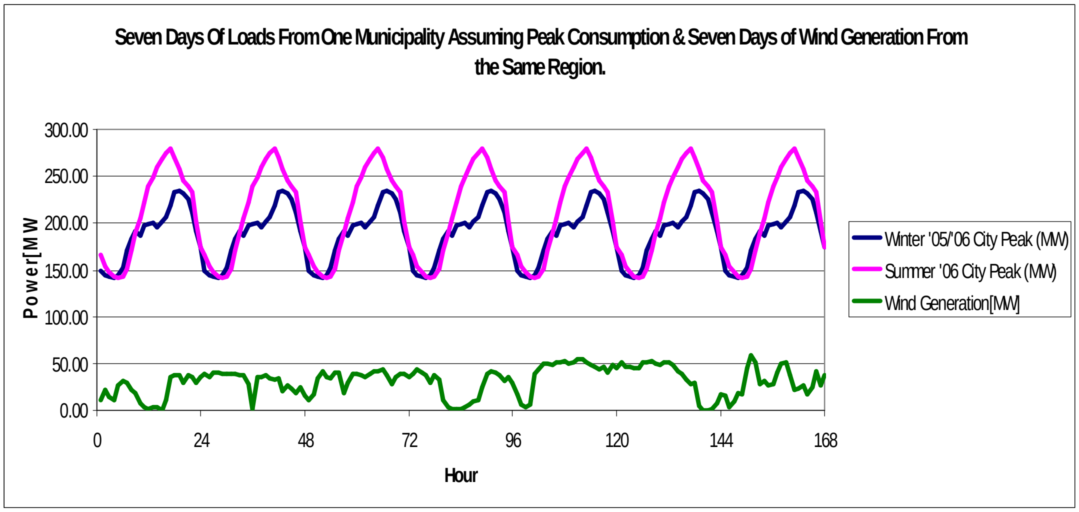

Figure 2-1: Seven Days of Wind Generation and Loads.

The non-zero magnitudes of wind generation can be increased by building additional wind capacity, essentially multiplying current energy generated by the added resource. However, multiplying the zero values by any additional generation will continue to yield a zero energy result. Many of those zero energy time periods align with loads that need to be met. Energy storage and optimization of generation capacity development are fundamental steps in solving the intermittent generation challenge. Electrical energy storage addresses the following aspects of system operation:[1]

1. Dispatchability- Responding to fluctuations in electricity demand.
2. Efficiency- Recovering wasted energy.
3. Regulatory-driven needs- meeting distribution and other transmission capacity expansion requirements.

As the penetration percent of intermittent generation grows on Colorado's electric grid, the need for energy storage to augment electricity generation will become increasingly acute. It was recently shown by Xcel Energy that at and above 20% intermittent generation on Xcel's grid significant economic cost increases will manifest[2] if mitigation techniques are not pursued. With regard to Xcel Energy's electric grid one study points out the cost to integrate renewable generation is as shown in Table 2-1, Table 2-2 and Figure 2-2:

Table 2-1: Gas Cost Impact of wind penetrations with and without storage on Xcel's electric grid

Wind Penetration	10%	15%
$/MWH Gas Impact No Storage Benefits	$2.17	$2.52
$/MWH Gas Impact with storage benefits	$1.26	$1.45

Table 2-2: Cost impact of increasing wind penetration on Xcel's electric grid

Wind Penetration	**Electric Production Cost Impact**	**Gas Supply System Impact**	**Total**
10%	$2.25	$1.26	$3.51/MWH
15%	$3.32	$1.45	$4.77/MWH
20%	$7.47	$2.10	$9.57/MWH

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[1] Tester. 2005. *Chapter 16 Storage, Transportation, and Distribution of Energy in, Sustainable Energy Choosing among Options.*I ed., vol. 1, S. Howe, Ed. Cambridge, Massachusetts: The MIT Press. PP **648,** 648-686.

[2] Oakleaf. RMEL 2006 Renewables Conference: New Developments in Applications. Nov 29, 2006. http://www.rmel.org

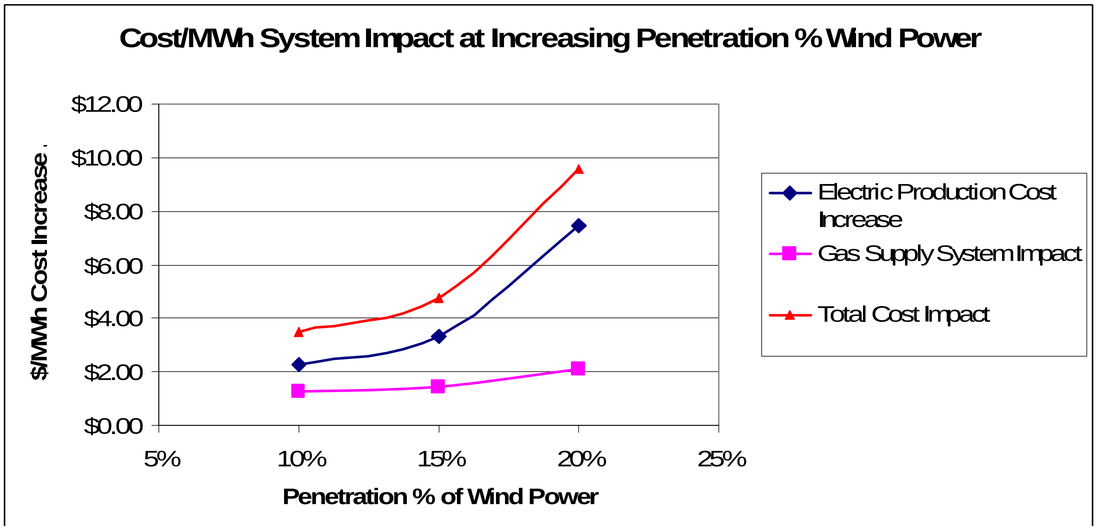

Figure 2-2: Increasing system cost over increasing penetration of wind power on Xcel Energy's electric grid.

Figure 2-2 shows an increasing cost of electric energy over an increasing penetration of wind power. This increasing cost has 324 MW of pumped storage available on the system which illustrates the effect of the increasing costs. Table 2-1 shows that natural gas cost increases will take place without the use of energy storage on the system.

Pumped hydroelectric energy storage (PHES) is a mature technology that has been deployed for over a century.[3] Examples of installed PHES systems as early as 1890 can be found in both Italy and Switzerland. PHES does not generate electricity, rather is a storage mechanism.[4] PHES uses electricity to pump water uphill to be stored, then energy is later recaptured when the water released back down hill through a turbine PHES systems are highly efficient, capable of reaching and surpassing 80-85% round-trip efficiencies. The

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[3] Lawrence. 2006. *Hydropower.* Lecture noteSYST6820(2006)online http://leeds-faculty.colorado.edu/Lawrence/SYST6820/Lectures/Hydropower.ppt

[4] In the case that the forebay collects precipitation in its natural watershed via drainage the power generated is generation because it has not been pumped. This scenario is a very small amount of the total capacity of any PHES unit.

scale of PHES this paper addresses is suited to the functional ability of the Francis turbine.[5] The Francis turbine is capable of reversible operation, utilizing a single unit that acts as a motor-pump or a turbine-generator. Figure 2-3 shows a basic schematic of the PHES installation at Raccoon Mountain owned and operated by the Tennessee Valley Authority (TVA).

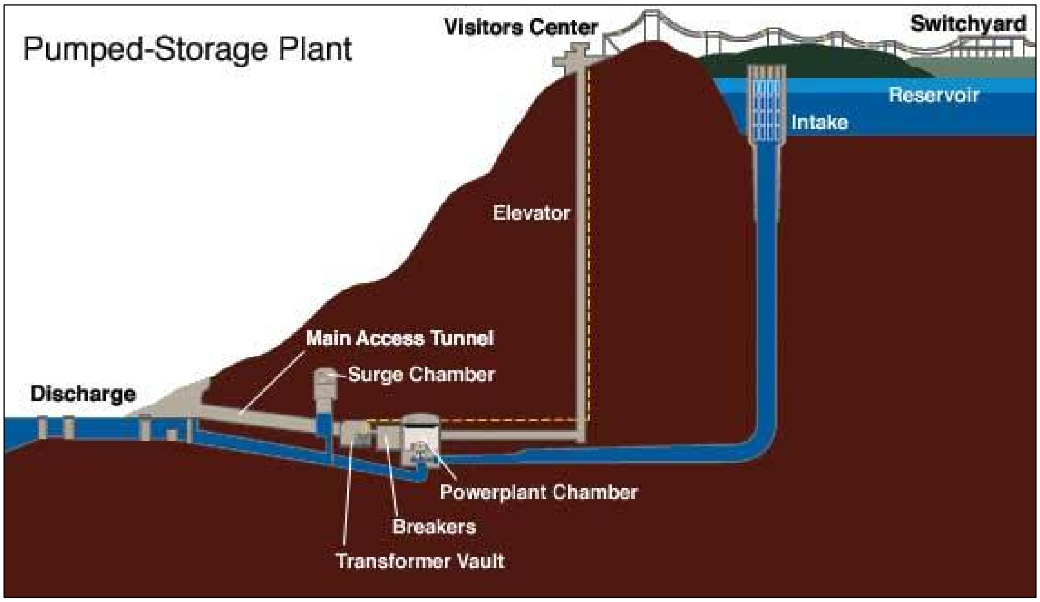

Figure 2-3: A basic schematic of the pumped hydro installation at Raccoon Mountain

The Raccoon Mountain Pumped-Storage Plant[6] is a widely cited example of PHES. Plant construction began in 1970 and was complete in 1978. The generating capacity of Raccoon Mountain is about 1,600 megawatts and it can run for 22 hours to supply 35,200 MWh of electricity.

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[5] J. W. Tester, "Chapter 12 Hydropower." in, *Sustainable Energy Choosing among Options* ,I ed., vol. 1, S. Howe, Ed. Cambridge, Massachusetts: The MIT Press, 2005, pp. 529.

[6] More information for Raccoon Mountain can be found at http://www.tva.gov/sites/raccoonmt.htm

Armstrong and Mermel in 1974[7] compiled a series of papers from a conference into a text titled *Converting Existing Hydro-Electric Dams and Reservoirs into Pumped Storage Facilities*. This text is valuable in covering many topics including sections on siting potential, equipment, innovations, construction, and environmental problems and solutions.

Wood and Wollenberg in 1996[8] published a text titled *Power Generation, Operation, and Control* this text covers operational techniques for power generation including pumped hydroelectric plants (page 230).

Stone and Webster Consultants in December of 1988[9] put out a report titled *Colorado Joint Planning Study Economic Potential of Pumped Storage.* This report defines the expected loads and the generation needed to meet those loads. It explores the potential of pumped storage to facilitate future planning as well as the timing the deployment of PHES resources.

The US Department of Interior Bureau of Reclamation has a number of older documents on this topic. Web based resources for the Bureau are referenced throughout this document but two resources of note are: *Wind-hydroelectric Energy project- Wyoming*[10], September 1984. This document looks at a wind and hydroelectric integrated project but does not make any significant conclusion due to difficulties with the wind machines at the time of the study. The second document of note is entitled: *Potential Power Additions To The*

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[7] Armstrong E. Mermel T. 1974. *Converting Existing Hydro-Electric Dams and Reservoirs into Pumped Storage Facilities.* American Society of Civil Engineers. New York, NY.

[8] Wood A. Wollenberg B. 1996. *Power Generation, Operation, and Control.* Wiley-Interscience Publication, John Wiley and Sons, Inc. New York NY.

[9] Stone & Webster Management Consultants. 1988. *Colorado Joint Planning Study Economic Potential of Pumped Storage*. Colorado, Denver

[10] US Department of the Interior Bureau of Reclamation. 1984. Wind Hydroelectric Energy Project Wyoming: Status Report on System Verification Units.

Colorado-Big Thompson Project Pick-Sloan Missouri Basin Program Colorado[11] published in 1978. This document covers a potential PHES location on the Colorado Big Thompson Project.

Dr. David Harpman with the Bureau of reclamation has contributed to this pool of knowledge through a number of efforts. Some of his work can be seen at his web site at: http://mysite.du.edu/~dharpman/profdownload.html. Included at this website is a paper titled *Exploring the Economic Value of Hydropower in the Interconnected Electricity System.*[12] This paper was influential in quantification of ancillary services in the following pumped hydroelectric economic modeling.

Chiu, L Et Al wrote *Mechanical Energy Storage Systems: Compressed Air and Underground Pumped Hydro* in 1978.[13] This paper looks at the costs for development of CAES as well as underground PHES. This work was presented at an AIAA meeting in Alabama in January, 1978.

Bueno and Carta wrote *Wind Powered Pumped Hydro Storage Systems, a means of increasing the penetration of renewable energy in the Canary Islands* in 2006.[14] This paper looks at the sizing of a PHES application to meet the needs of a specific island energy system.

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[11] US Department of the Interior Bureau of Reclamation. April 1978. *Potential Power Additions To The Colorado-Big Thompson Project Pick-Sloan Missouri Basin Program Colorado*

[12] Harpman D. 2006. Exploring the Economic Value of Hydropower in the Interconnected electricity System. Available online at: http://mysite.du.edu/~dharpman/profdownload.html. Also available from NTIS

[13] Chiu, L Et Al. 1978. *Mechanical Energy Storage Systems: Compressed Air and Underground Pumped Hydro.* AIAA. Huntsville Alabama.

[14] Buena C. Carta J. October 2006. *Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands.* Renewable and Sustainable Energy Reviews. 312-340

Between 2005 and 2006, Van Kooten et. al. have produced a series of papers looking at the dynamic between different generation and storage resources on the grid versus the increasing penetrations of renewable energy.[15] [16] [17]

2.2. Methods

To address the potential for PHES systems in Colorado, locations had to be identified and then assessed for their technical and economic applicability. The methods for this analysis were designed to be able to assess multiple sites around the state at a high level. If further interest is sparked in any of the sites suggested in this body of work, a more detailed analysis should be performed.

To identify locations for PHES additions in Colorado, locations were looked for that utilized infrastructure already in the ground. To this end, US Bureau of Reclamation (USBR) hydro projects in Colorado were surveyed. Those projects are the Colorado Big Thompson and the Frying Pan Arkansas. Additionally a meeting was held with the Senior Power Liaison Mr. Michael Roluti, of the US Department of Interior Bureau of Reclamation to discuss PHES potential on the USBR system. After the USBR projects were surveyed PHES sites were looked for that had good characteristics for development. Favorable site characteristics include:

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[15] P. Benitez, L. Dragulescu and C. Van Kooten. (2006). "The Economics of Wind Power with Energy Storage," *Resource and Environmental Economics and Policy Analysis (REPA) Research Group,* pp. 1-38, 2006.

[16] P. Lawrence, G. Cornelis van Kooten, Murray Love and Ned Djilali, "Utility-Scale Wind Power: Impacts of Increased Penetration": Paper No. IGEC-097 in *Proceedings of the International Green Energy Conference*, June 12-16, 2005, Waterloo, Ontario, Canada.

[17] Liu, Jia, G. Cornelis van Kooten and Lawrence Pitt. June 2005. *Integrating Wind Power in Electricity Grids: An Economic Analysis.* Paper No. IGEC-1-017 in Proceedings of the International Green Energy Conference. Waterloo, Ontario, Canada. Available: http://www.iesvic.uvic.ca/publications/library/IGEC_Pitt.pdf

- High head potential
- Water availability
- Areas conducive for forebay and afterbay construction or utilization
- Adjacent to transmission or distribution lines
- Utility right of ways
- Renewable generation development
- Strong wind or solar potential
- A road

A model has been developed that analyzes both economic and technical characteristics of each site. This model is run in a series of tabs in a Microsoft Excel workbook. The tabs are as follows:

1. Power and Capacity
2. Revenue
3. Cost
4. Payback

2.2.1. Power and Capacity

To calculate the technical specifications of a pumped hydroelectric site, a basic fluid power equation is used. The inputs to the equation that change based on the location are head, flow, and efficiency. Head is given by the upper elevation minus the lower elevation. A more in-depth feasibility study of PHES would specify the effective head, and effective head is not given in this work. Effective head is the elevation differential adjusted to account for efficiency. The flow rate in this analysis can be entered in one of two ways. Most of the sites in this analysis have flow dictated by the expected volumetric area of the limiting reservoir divided by the desired storage time to yield the available flow, minus a 15% reservoir operating cushion. If water ways are already in place or there is another reason flow rate is known, that flow rate can be directly entered into the calculator.

Given hydraulic head, an upper bound on flow rate, and efficiency of the plant, the power generation capacity of a pumped hydroelectric installation can be calculated with the following equation:

$$P = Q \cdot H \cdot r \cdot g \cdot h$$

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 multiplied by run time. Run time is a function of flow rate and reservoir volume.

2.2.2. Revenue

Revenue is calculated as described in this section. Power as well as energy are imported as a link from the ***power and capacity*** page of the model worksheet. The revenue is calculated via multiple revenue streams:

1. kWh purchase and sales differential
2. Avoided peak generation cost
3. CO_2 value
4. SO_2 value

Other revenue streams do exist and may be viable contributions to these projects although they will not always apply and have not been included here. These other steams include ancillary services, transmission development deferral, capital cost deferral for other types of fast response plants, capacity values and a multitude of revenue streams associated with the storage of water.

2.2.3. Energy Purchase and Sales Differential

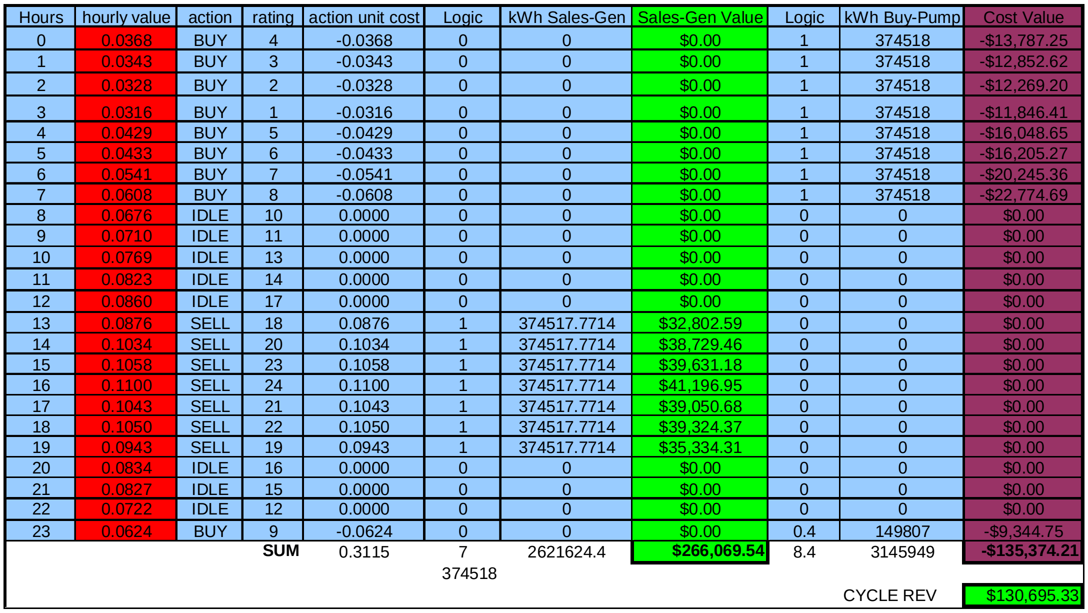
PHES must pull energy from the grid and then return energy to the grid when it is called for. Efficiency losses will mean that approximately 20% of the energy pumped into the system will be lost and not returned out of the system. But, due to the fact that during peak demand times or other times when energy is lacking (such as a situation where the wind power drops off) the value of a kWh increases. Thus, the efficiency loss per kWh can be compensated financially by a higher value for the timely delivery of that next unit of energy. If energy costs $0.03 kWh and the energy is sold for $0.13 kWh with an 80% round trip efficiency, the kWh differential is $0.08. If a PHES plant is rated at 100 MW and can run for 5 hours per day, that day with the differential described above would yield:

(($0.13 * 100,000kW * 5 hours) - ($0.03 * 100,000kW * 5 hours)) * 0.80 = $40,000.00.

In the case that this cycle would run 5 days per week and 52 weeks per year, the annual value of the kWh differential would be:

$40,000.00/revenue cycle * 5day/week * 52weeks/year = $10,400,000.00 annual kWh purchase and sales differential

Unfortunately kWh revenue streams do not work out that simply. In a functioning energy market the purchase price and the sales price fluctuate with the market. This is a basic function of supply and demand. The model calculates kWh differential by varying the both the purchase price and the sales price of the kWh over time of day. When the demand is high the value of the kWh is high and when the demand is low the value of the kWh is low. The model uses a set of nested if/then statements to make the decision to purchase when the cost is lowest and sell when the price is highest. These choices are kept within the constraints of the system. The constraints of the system force the PHES plant to run a full cycle of all dispatchable energy but do not allow the system to over-pump the capacity of either reservoir. The model also requires that the days per week and weeks per year the system will function be specified by the user. A typical output for kWh purchase and sales differential is displayed below in Figure 2-4:



Hours	hourly value	action	rating	action unit cost	Logic	kWh Sales-Gen	Sales-Gen Value	Logic	kWh Buy-Pump	Cost Value
0	0.0368	BUY	4	-0.0368	0	0	$0.00	1	374518	-$13,787.25
1	0.0343	BUY	3	-0.0343	0	0	$0.00	1	374518	-$12,852.62
2	0.0328	BUY	2	-0.0328	0	0	$0.00	1	374518	-$12,269.20
3	0.0316	BUY	1	-0.0316	0	0	$0.00	1	374518	-$11,846.41
4	0.0429	BUY	5	-0.0429	0	0	$0.00	1	374518	-$16,048.65
5	0.0433	BUY	6	-0.0433	0	0	$0.00	1	374518	-$16,205.27
6	0.0541	BUY	7	-0.0541	0	0	$0.00	1	374518	-$20,245.36
7	0.0608	BUY	8	-0.0608	0	0	$0.00	1	374518	-$22,774.69
8	0.0676	IDLE	10	0.0000	0	0	$0.00	0	0	$0.00
9	0.0710	IDLE	11	0.0000	0	0	$0.00	0	0	$0.00
10	0.0769	IDLE	13	0.0000	0	0	$0.00	0	0	$0.00
11	0.0823	IDLE	14	0.0000	0	0	$0.00	0	0	$0.00
12	0.0860	IDLE	17	0.0000	0	0	$0.00	0	0	$0.00
13	0.0876	SELL	18	0.0876	1	374517.7714	$32,802.59	0	0	$0.00
14	0.1034	SELL	20	0.1034	1	374517.7714	$38,729.46	0	0	$0.00
15	0.1058	SELL	23	0.1058	1	374517.7714	$39,631.18	0	0	$0.00
16	0.1100	SELL	24	0.1100	1	374517.7714	$41,196.95	0	0	$0.00
17	0.1043	SELL	21	0.1043	1	374517.7714	$39,050.68	0	0	$0.00
18	0.1050	SELL	22	0.1050	1	374517.7714	$39,324.37	0	0	$0.00
19	0.0943	SELL	19	0.0943	1	374517.7714	$35,334.31	0	0	$0.00
20	0.0834	IDLE	16	0.0000	0	0	$0.00	0	0	$0.00
21	0.0827	IDLE	15	0.0000	0	0	$0.00	0	0	$0.00
22	0.0722	IDLE	12	0.0000	0	0	$0.00	0	0	$0.00
23	0.0624	BUY	9	-0.0624	0	0	$0.00	0.4	149807	-$9,344.75
			SUM	0.3115	7	2621624.4	**$266,069.54**	8.4	3145949	**-$135,374.21**
					374518					
									CYCLE REV	$130,695.33

Figure 2-4: kWh sales and purchase differential

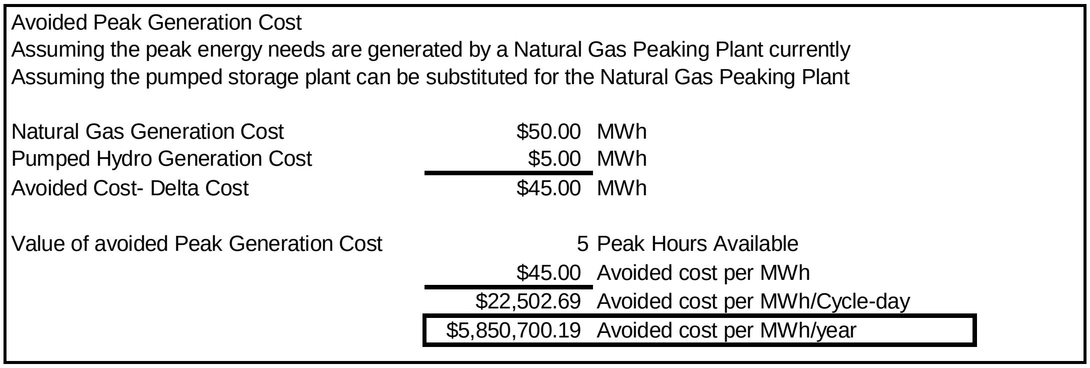
The equation for kWh differential revenue generation is as follows:

> (kWh sales value * power * time at that value and power) - (kWh cost value * power * time at that value and power) * Efficiency of the plant = kWh differential value

2.2.4. Avoided Peak Generation Cost

Peak generation costs are costs avoided by running a PHES plant rather than running a Natural Gas Peaking plant (NG). The most significant cost difference between a PHES plant and an NG plant is that a PHES does not have a fuel cost where NG plants have significant fuel costs. It should be kept in mind that a natural gas plant is its own primary energy driver whereas a PHES plant needs another primary driver. This revenue is in the form of cost arbitrage, and assumes that: Peak energy needs are currently generated by a natural gas peaking plant and that PHES can be substituted for the NG peaking plant. This calculation adds the avoided operational and maintenance costs into the revenue stream. Additionally one may in some circumstances add an additional revenue stream by not having to build the NG plants. That negated capital cost is not included in any of the examples shown in this paper. Although that negated cost would in many cases be significant.

Figure 2-5 below shows avoided peak generation cost for a 100 MW plant running 5 hours per day, 260 days out of the year to meet peak loads.



Avoided Peak Generation Cost
Assuming the peak energy needs are generated by a Natural Gas Peaking Plant currently
Assuming the pumped storage plant can be substituted for the Natural Gas Peaking Plant

Natural Gas Generation Cost	$50.00	MWh
Pumped Hydro Generation Cost	$5.00	MWh
Avoided Cost- Delta Cost	$45.00	MWh
Value of avoided Peak Generation Cost	5	Peak Hours Available
	$45.00	Avoided cost per MWh
	$22,502.69	Avoided cost per MWh/Cycle-day
	$5,850,700.19	Avoided cost per MWh/year

Figure 2-5: An example of avoided peak generation cost calculation

2.2.5. CO_2 value & SO_2 value

In the case that the primary driver behind the PHES plant is a generation source that does not emit CO_2 and/or SO_2 there would be a revenue stream for that lack of GHG emissions. What the primary driver is behind the energy storage and how that is calculated by a regulating body will enable or disable this revenue stream. If this revenue stream can be valued a conservative set of values comes from the Chicago Climate Exchange[18] at the time this model was built CO_2 was trading at $5/ton and SO_2 was trading at $600/ton.

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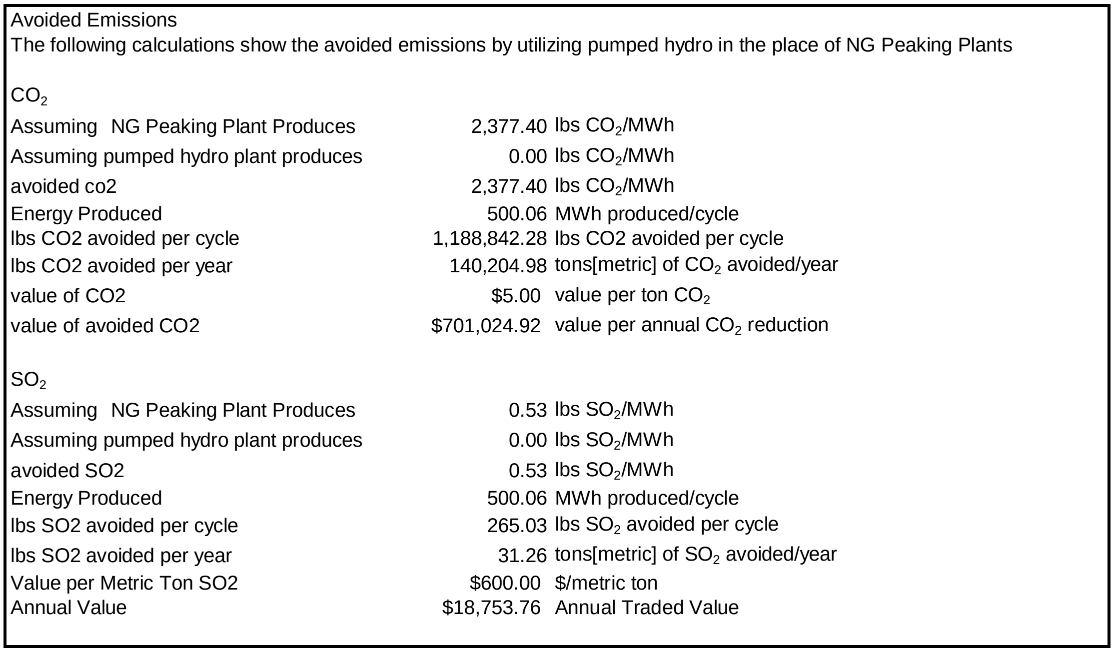
[18] The Chicago Climate Exchange is available online at: http://www.chicagoclimatex.com/

Figure 2-6 below shows an emissions reduction value of CO_2 and SO_2 as traded on the Chicago Climate Exchange for a 100 MW plant running 5 hours per day, 260 days out of the year. This reduction was only calculated for the NG peaking plant not running. Other reductions would be expected as the PHES plant would allow additional wind and solar energy onto the grid due to the economic boost of a firm resource and dispatchability attained through the PHES infrastructure.



Avoided Emissions

The following calculations show the avoided emissions by utilizing pumped hydro in the place of NG Peaking Plants

CO_2		
Assuming NG Peaking Plant Produces	2,377.40	lbs CO_2/MWh
Assuming pumped hydro plant produces	0.00	lbs CO_2/MWh
avoided co2	2,377.40	lbs CO_2/MWh
Energy Produced	500.06	MWh produced/cycle
lbs CO2 avoided per cycle	1,188,842.28	lbs CO2 avoided per cycle
lbs CO2 avoided per year	140,204.98	tons[metric] of CO_2 avoided/year
value of CO2	$5.00	value per ton CO_2
value of avoided CO2	$701,024.92	value per annual CO_2 reduction
SO_2		
Assuming NG Peaking Plant Produces	0.53	lbs SO_2/MWh
Assuming pumped hydro plant produces	0.00	lbs SO_2/MWh
avoided SO2	0.53	lbs SO_2/MWh
Energy Produced	500.06	MWh produced/cycle
lbs SO2 avoided per cycle	265.03	lbs SO_2 avoided per cycle
lbs SO2 avoided per year	31.26	tons[metric] of SO_2 avoided/year
Value per Metric Ton SO2	$600.00	$/metric ton
Annual Value	$18,753.76	Annual Traded Value

Figure 2-6: CO_2 and SO_2 emissions reduction value example calculation

2.2.6. Cost

The capital cost determined by the model for each potential PHES site is calculated with an overnight cost estimate. That estimate scales down in capital cost as the capacity of a plant scales up. Additionally, the overnight capital cost is broken out into constituent costs of bringing a plant online. Table 2-3 displays the overnight capital cost per MW of power as it scales with size. Table 2-4 breaks out the constituent costs of a plant as a percent of those

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total costs. In the case that a potential site will not need any individual cost of the eight costs broken out, those costs can be removed from the calculation by a function in the model.

Table 2-3: Overnight capital cost per MW of PHES plant max rated size

	Sizing of Plant	Overnight Cost	
Mini	< 1MW	$5,000,000	$/MW
Small	>1MW, < 10 MW	$3,500,000	$/MW
Medium	>10MW, < 50 MW	$2,500,000	$/MW
Large	>50MW, <200 MW	$1,800,000	$/MW
Extra Large	>200 MW	$1,300,000	$/MW

Table 2-4: Constituent costs of a PHES plant as a percent of the total overnight capital cost estimate

Item	% of Capital Cost
land and land rights	2.05%
Power Station structures and improvements	8.73%
Reservoirs and Water Ways	22.15%
Pumps Turbines Valves Governors	9.22%
Generator Motors and Static Starting Equipment	6.40%
Accessory Electrical Power plant Substation Equipment, Roads	10.17%
Contingencies Engineering and Overhead	14.16%
Allowance for funds during construction	27.12%
TOTAL	100.00%

2.2.7. Payback

A time valued payback is used as the metric by which these PHES sites are fiscally measured. Each of the revenue streams as well as each of the costs described in this body of work can be valued or not valued within the model. The payback tab drives out the capital costs with an interest rate over specified period of construction. During the specified period of construction no revenues are garnered although interest accrues. When the construction period passes the annual revenue starts paying back the financed balance. Operation and management (O and M) costs are figured at ½ of one percent of the initial capital cost per year. In the case of a 200 MW plant the capital cost would be calculated at 1.3 million dollars per MW for a total of 260 million dollars. That hypothetical 200 MW plant would have an annual O and M budget of 1.3 million dollars. Additionally, an annual percentage increase in costs and revenues in assumed (typically 1%). The annual percentage increase will affect the O and M cost and the revenue streams.

The payback model functions in the following order. First, capital costs are brought into the model. Second, the financed capital costs are divided over the specified years of construction. Third, after the completion of construction, O and M costs as well as revenues begin to run at the plant on an annual or otherwise specified periodic basis. Each period the revenue streams are first applied to the O and M costs, then the balance of the revenue is applied to the financed balance. Fourth, the remaining financed balance is increased by the specified interest rate. Fifth, the interest and balance is sent into the next period where step three begins again. This continues until the plant is paid off and the payback period is exposed.

One site location, West Gypsum, includes a sensitivity analysis. This analysis shows the changing payback period with regards to percentage changes of the kWh margin between the purchase price and the sales price. The margin is increased in two steps as well as decreased in two steps. This is further discussed in the results section for West Gypsum.

Each site proposed that will require significant infrastructure will have a descriptive summary table which shows the itemized revenues as well as the itemized costs and how the two reconcile via a payback horizon. Interest rates, construction time, and annual increase in costs are also displayed in the summary tables.

2.3. Results and Discussion of PHES Sites in Colorado

2.3.1. New Management of Imbedded Infrastructure

Colorado has pumped hydroelectric energy storage infrastructure in the ground today that may be utilized to facilitate the integration of renewable generation onto our electric grid. Due to its magnificent topographic relief, Colorado presents multiple locations for the development of additional pumped hydroelectric energy storage sites. Prior to development of new infrastructure all current infrastructure should be utilized for, as Gifford Pinchot would say, "the greatest good, for the greatest number, for the greatest amount of time." That greatest good may now insist that pumped hydroelectric storage sites in the ground today not only function to serve our peaking demands, but also function to integrate intermittent renewable energy generation. Infrastructure currently in the ground is outlined in Table 2-5 and followed by a brief discussion.

Table 2-5: PHES in Colorado with Developed or Partially Developed Infrastructure

Site Name	Ownership	Capacity	Head	Supporting Documents
Mt. Elbert	USBR	200 [MW]	438 [ft]	[19]
Flat Iron Pumping Plant	USBR	8.5 [MW]	240 [ft]	[20]
Horsetooth College Lake	USBR	10 [MW]	200 [ft]	[21]
Pinewood Carter	USBR	108 [MW]	840 [ft]	[22]

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[19] US Department of the Interior Bureau of Reclamation. *Mount Elbert Pumped Storage Power Plant.* Available online at: http://www.usbr.gov/power/data/sites/mtelbert/mtelbert.html

[20] US Department of the Interior Bureau of Reclamation. *Colorado-Big Thompson Project Engineering Data*. Available online at: http://www.usbr.gov/dataweb/html/gpcbtengdata.html

[21] Levine & Barnes. 2007. *Potential Pumped Hydroelectric Energy Storage Sites in Colorado.* EESAT Conference Proceedings Paper. Available online at: http://www.colorado.edu/engineering/energystorage/files/EESAT2007/EESAT_Colorado_PHES_Sites_Paper.pdf

[22] US Department of the Interior Bureau of Reclamation. April 1978. *Potential Power Additions To The Colorado-Big Thompson Project Pick-Sloan Missouri Basin Program Colorado*

Cabin Creek	Xcel Energy	324 + 35 [MW]	1,226 [ft]	[23]
Phantom Canyon	Private Developer	390 [MW]	800 [ft]	[24]
Total		1,075.5 [MW]		

Mount Elbert Pumped Hydro is located outside of Twin Lakes Colorado. It has a capacity of 200[MW], which is achieved by utilizing two 100[MW] turbines. This plant was completed by the Bureau of Reclamation (USBR) as part of the Fryingpan-Arkansas Project under Public Law 87-590 (77 Stat. 393), signed by the President on August 16, 1962.[25] Construction of the Mt Elbert plant was Completed 1981. The 2005 capacity factor[26] for Mt Elbert was 15.14%. This low capacity factor is indicative of potential to more fully utilize the potential at Mt Elbert. This facility is run by the Bureau of Reclamation whose primary objective with regards to water works infrastructure is to ensure the delivery of water not the delivery of electricity. As generation intermittence grows on Colorado's grid it may be beneficial for USBR to take a more aggressive stance toward energy storage and timely deployment. As stated by USBR "The Mt. Elbert power generation and transmission system is connected to the Public Service Company of Colorado transmission system at the Malta substation near Leadville. This interconnection with Public Service Company enables Fryingpan-Arkansas Project power to be marketed to Colorado customers through the Western Area Power Administration."[27] Why this resource is not being utilized more is not

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[23] *Hugh W Hight. Jan 1971. Cabin Creek Pumped Storage Hydroelectric Project.* Journal of the Power Division. Proceedings of the American Society of Civil Engineers.

[24] Morley, Mark. 2007. Personal Communication. Supported by the Washington Group International.

[25] Bureau of Reclamation, "MT. ELBERT PUMPED-STORAGE POWERPLANT". Available online at: http://www.usbr.gov/power/data/sites/mtelbert/mtelbert.html

[26] US Department of the Interior Bureau of Reclamation. Available online at: http://www.usbr.gov/dataweb/html/fryark.html

known. It would be prudent for a State sponsored -or other- effort to facilitate efforts aimed at this resource.

The Flat Iron Pumping Plant part of the Colorado-Big Thompson project is a fully operational pumped hydroelectric facility. This pumping plant is not deployed to integrate wind power and to my knowledge is not used to address peak loads. As described to me by a USBR communications officer out of the USBR Loveland field office this plant only pumps to balance water delivery. Many challenges may stop this pumping plant from providing integration services such as; increased wear and tear on the plant, water delivery and power delivery timing conflicts, and imbedded management strategies or long term contracts. Other challenges many also effect the decision to not deploy this plant for integration or peak power production. But, if this is the case USBR should ensure with further study that this infrastructure is being deployed to the best interest of the taxpayers who financed its development. With a listing of duty cycles, operational constraints, drawings, and open dialogue this pumping plant may be able to facilitate integration of renewable power onto Colorado's -and WECC's- electric grid.

Horsetooth College Lake is an example of the presence of both a forebay and an afterbay that represents the possibility of pumped storage without the need to develop new reservoirs. This example is of interest both because of its imbedded infrastructure and the fact that the afterbay lies on the property of Colorado State University (CSU). This example could facilitate experiential education as well as 10 [MW]s of pumped storage potential. As CSU looks to develop wind power at Maxwell Ranch they could look to develop PHES to firm that power. This example is fully covered in the new infrastructure section of this document.

Pinewood Carter was a potential pumped storage addition to the Colorado Big Thompson discussed in the late 1970's. This development was sited to produce 108 [MW] of storage capacity and has reservoirs in place. Additionally the USBR concluded[22] that this project was financially viable with a 1.1 to 1 cost benefit ratio including a cost for lost recreation at Pinewood Reservoir. The loss or reduction of recreation ability at Pinewood Reservoir would be a significant challenge. Stakeholders would need to be engaged in the beginning of a discussion to identify what would allow this project to proceed. Suggestions may include but are not limited to increased recreation ability in other areas, management of the PHES development in such a way that minimal recreation impacts are felt, full disclosure of the benefits of a PHES development preserving the greater natural landscape at the loss of a specific site. Swimming is not currently allowed at the site but no wake boating, fishing, and camping are allowed. With a larger scope of thought in mind this challenge of recreation versus PHES sites will be an issue with many of the PHES plants suggested. It is in the best interest of society to bring stake holders together as early as possible and attempt to proceed with projects in a way that benefits all involved.

Cabin Creek located just outside of Georgetown Colorado operates at a rated 324 [MW]. Xcel Energy is currently making efficiency upgrades to the plant, which will yield approximately 35 additional [MW] which will total 359 [MW]. This plant is operated to facilitate wind integration and also run to address peak loads. Cabin Creek pumped hydro is located outside of Georgetown Colorado. It has a capacity of 324[MW] by running two, 162[MW] turbines. Construction of the plant was originally conceived of by Dr. Lawrence M. Robertson, construction was completed in 1967. This plant is owned and operated by Xcel Energy which was formerly Public Service Company of Colorado. Xcel uses this plant to meet among other things peak demands. Generally in Colorado’s Front Range the most challenging peak demands are summer time air conditioning loads. Having Cabin Creek available is a great advantage to the ratepayer of Xcel’s service territory. It would be prudent in many situations to reduce peak loads with efficiency upgrades to free up Cabin Creek for more integration ability. The afore mentioned air conditioning load could be reduced significantly by evaporative cooling, awnings, improved building envelopes, and other techniques.

Large coal plants are difficult to ramp up and down -in power output- Cabin Creek is able to use excess coal energy at night (in times of low demand) and redeploy that energy during daytime peaking demands. In recent years as wind power has been developed on Xcel's grid they can choose to mitigate that intermittence with the storage contained at Cabin Creek. While Cabin Creek is a good resource its capacity is spread thin by attempting to meet peaking loads and also coping with increasing wind (intermittence) on Xcel Energies grid.

Phantom Canyon is a proposed PHES site that is gaining traction. This site would add 390 MW of pump back storage to the grid. This project was originally conceived of to assist the agricultural industry in SE Colorado manage water resources. The energy storage that Phantom Canyon may provide once developed will be a valuable resource to Colorado as it brings additional intermittent power online.

2.3.2. New infrastructure

Assessing Colorado for new PHES developments many locations can be found. A diverse sampling of locations is reported below. Table 2-6 lists the site names, power, capacity and payback period along with brief comments. Each of the listed potential sites has a discussion and technical/economic out put below.

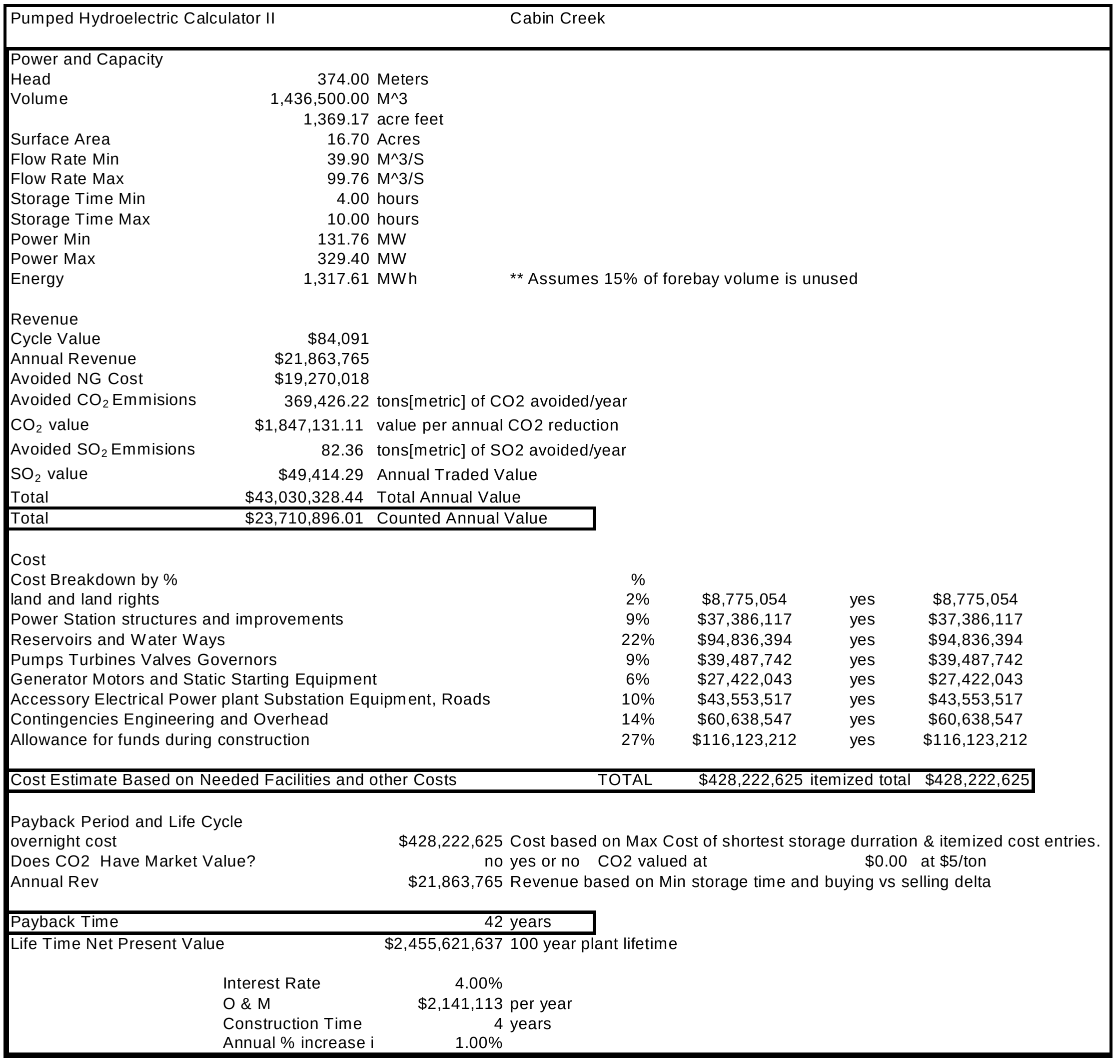
Table 2-6: A sampling of new infrastructure PHES sites in Colorado

Site Name	Power [MW]	Capacity [MWh]	Payback [years]	Comments
Cabin Creek as calculated	329	1318	42	Plant in operation this site was used to check the assumptions used for calculations results for both power and energy were within 1.6% of technical specifications
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	15	Adjacent to water and 1km from an oil shale plant
Schoolhouse Pt	630	3148	15	Adjacent to water
Peetz Bluffs	43	213	31	Adjacent to Colorado’s North Eastern Wind Plants
Gunnison Hydro	282	1692	22	Afterbay in place Utility right of way exists
S1- White River	407	4075	35	Rio Blanco County Adjacent to Oil Shale development- high flow site
S2- Cathedral	435	4356	35	Rio Blanco County Adjacent to Oil Shale development- high head site

Cabin Creek as calculated

The figures displayed in this portrayal of Cabin Creek are not an output of Xcel Energy the current operator of Cabin Creek Station. These figures are the output of the environmental constraints of the system along with the economic assumptions of the model. The output in this case has been used to verify the accuracy of the model. In the case of Cabin Creek the Power and Capacity figures resultant from the model are within 1.5% and 1.6% of the true technical output of the PHES station. The economic figures are based on the power and capacity but are yet another step from reality. Thus it would follow that the economic outputs from the model are less accurate then 1.5% and 1.6% for the economic calculations. The economics of Cabin Creek are not public information and are not verifiable.



Pumped Hydroelectric Calculator II		Cabin Creek	
Power and Capacity			
Head	374.00	Meters	
Volume	1,436,500.00	M^3	
	1,369.17	acre feet	
Surface Area	16.70	Acres	
Flow Rate Min	39.90	M^3/S	
Flow Rate Max	99.76	M^3/S	
Storage Time Min	4.00	hours	
Storage Time Max	10.00	hours	
Power Min	131.76	MW	
Power Max	329.40	MW	
Energy	1,317.61	MWh	** Assumes 15% of forebay volume is unused
Revenue			
Cycle Value	$84,091		
Annual Revenue	$21,863,765		
Avoided NG Cost	$19,270,018		
Avoided CO_2 Emmisions	369,426.22	tons[metric] of CO2 avoided/year	
CO_2 value	$1,847,131.11	value per annual CO2 reduction	
Avoided SO_2 Emmisions	82.36	tons[metric] of SO2 avoided/year	
SO_2 value	$49,414.29	Annual Traded Value	
Total	$43,030,328.44	Total Annual Value	
Total	$23,710,896.01	Counted Annual Value	

Cost				
Cost Breakdown by %	%			
land and land rights	2%	$8,775,054	yes	$8,775,054
Power Station structures and improvements	9%	$37,386,117	yes	$37,386,117
Reservoirs and Water Ways	22%	$94,836,394	yes	$94,836,394
Pumps Turbines Valves Governors	9%	$39,487,742	yes	$39,487,742
Generator Motors and Static Starting Equipment	6%	$27,422,043	yes	$27,422,043
Accessory Electrical Power plant Substation Equipment, Roads	10%	$43,553,517	yes	$43,553,517
Contingencies Engineering and Overhead	14%	$60,638,547	yes	$60,638,547
Allowance for funds during construction	27%	$116,123,212	yes	$116,123,212
Cost Estimate Based on Needed Facilities and other Costs	TOTAL	$428,222,625	itemized total	$428,222,625

Payback Period and Life Cycle				
overnight cost	$428,222,625	Cost based on Max Cost of shortest storage durration & itemized cost entries.		
Does CO2 Have Market Value?	no	yes or no CO2 valued at	$0.00	at $5/ton
Annual Rev	$21,863,765	Revenue based on Min storage time and buying vs selling delta		
Payback Time	42	years		
Life Time Net Present Value	$2,455,621,637	100 year plant lifetime		
Interest Rate	4.00%			
O & M	$2,141,113	per year		
Construction Time	4	years		
Annual % increase i	1.00%			

Figure 2-7: Cabin Creek as Calculated technical and economic output

Bellyache Ridge

The Bellyache Ridge site is located in Eagle County to the North East of the town of Eagle, Colorado. This location showed potential due to high head, water availability, transmission right of way, and significant seasonal load requirements do to the tourist draw of ski resorts. It has been concluded by the author that recent housing developments in the area may NIMBY (Not in my backyard) this option off the table. This location's forebay is along a high ridge and the afterbay would sit along side the Eagle River in the I-70 corridor. This site has a potential hydraulic head of 615 meters. With a surface area potential of about 16 acres for the upper reservoir, Bellyache Ridge could have an energy storage capacity of 2,167 MWh deployable in 7 hours at 310 MW.

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 $33,700,315 plus an additional $21,728,454 in avoided natural gas and natural gas turbine operation costs. Also this plant could enable the avoidance of 728,975 tons of CO_2 for a value of $3,644,873 when valued at $5/ton. The above revenues and avoided costs set against the time valued capital cost yield a payback of 21 years.

Power and Capacity			
Head	615.00	Meters	
Volume	1,436,500.00	M^3	
	1,369.17	acre feet	
Surface Area	16.70	Acres	
Flow Rate Min	26.60	M^3/S	
Flow Rate Max	57.00	M^3/S	
Storage Time Min	7.00	hours	
Storage Time Max	15.00	hours	
Power Min	144.44	MW	
Power Max	309.52	MW	
Energy	2,166.65	MWh	** Assumes 15% of forebay volume is unused
Revenue			
Cycle Value	$108,014		
Annual Revenue	$33,700,315		
Avoided NG Cost	$21,728,454		
Avoided CO_2 Emissions	728,974.74	tons[metric] of CO2 avoided/year	
CO_2 value	$3,644,873.68	value per annual CO2 reduction	
Avoided SO_2 Emissions	162.51	tons[metric] of SO2 avoided/year	
SO_2 value	$97,507.35	Annual Traded Value	
Total	$59,171,150.56	Total Annual Value	

Cost				
Cost Breakdown by %	%			
land and land rights	2%	$8,245,467	yes	$8,245,467
Power Station structures and improvements	9%	$35,129,812	yes	$35,129,812
Reservoirs and Water Ways	22%	$89,112,883	yes	$89,112,883
Pumps Turbines Valves Governors	9%	$37,104,601	yes	$37,104,601
Generator Motors and Static Starting Equipment	6%	$25,767,084	yes	$25,767,084
Accessory Electrical Power plant Substation Equipment, Roads	10%	$40,925,001	yes	$40,925,001
Contingencies Engineering and Overhead	14%	$56,978,925	yes	$56,978,925
Allowance for funds during construction	27%	$109,115,012	yes	$109,115,012
Cost Estimate Based on Needed Facilities and other Costs	TOTAL	$402,378,785	itemized total	$402,378,785

Payback Period and Life Cycle					
overnight cost	$402,378,785	Cost based on Max Cost of shortest storage durration & itemized cost entries.			
Does CO2 Have Market Value?	yes	yes or no	CO2 valued at	$3,644,873.68	at $5/ton
Annual Rev	$33,700,315	Revenue based on Min storage time and buying vs. selling delta			
Payback Time	21	years			

Interest Rate	4.90%	
O & M	$2,011,894	per year
Construction Time	5	years
Annual % increase i	1.00%	

Figure 2-8: Bellyache Ridge

West Gypsum

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 assets, but the 20% level will be challenging. Doubling the PHES storage assets on Colorado's grid may allow the additional 10% of wind generation 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 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. This payback period was also analyzed with a sensitivity analysis. The most significant revenue for any of the proposed sites in this body of work is the kWh sales and purchase margin. With specific regards to this location that margin was increased as well as decreased and the resulting changes in payback period were attained. When the margin was decreased by 12% and 25% the resulting payback periods were 25 and 33 years respectively. When the margin was increased by 12% and 25% the payback periods were 16 and 18 years respectively. The decreasing margin has a proportionally larger effect on the payback period due to the time value of money. The relationships described above are displayed below in Figure 2-9.

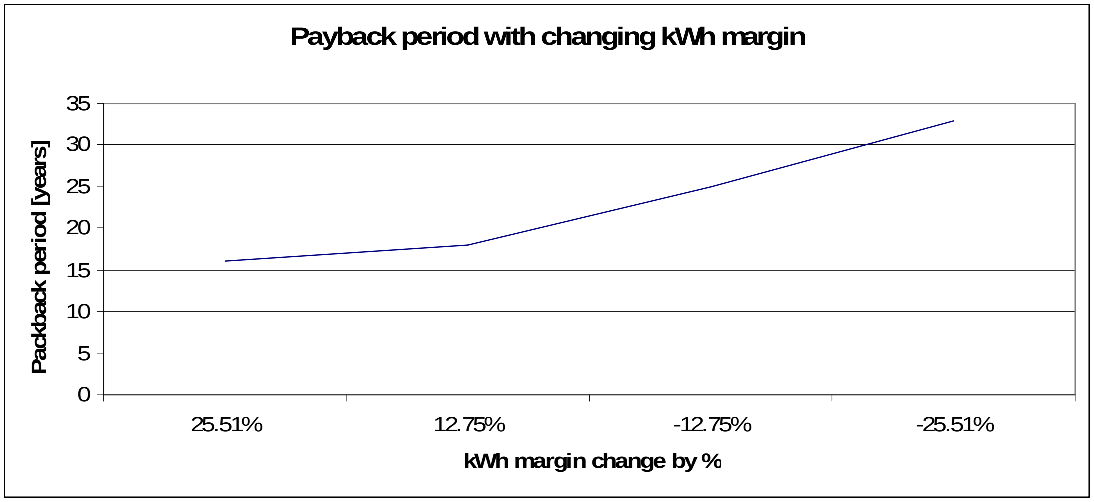


Figure 2-9: Payback period sensitivity analysis with changing kWh price margin

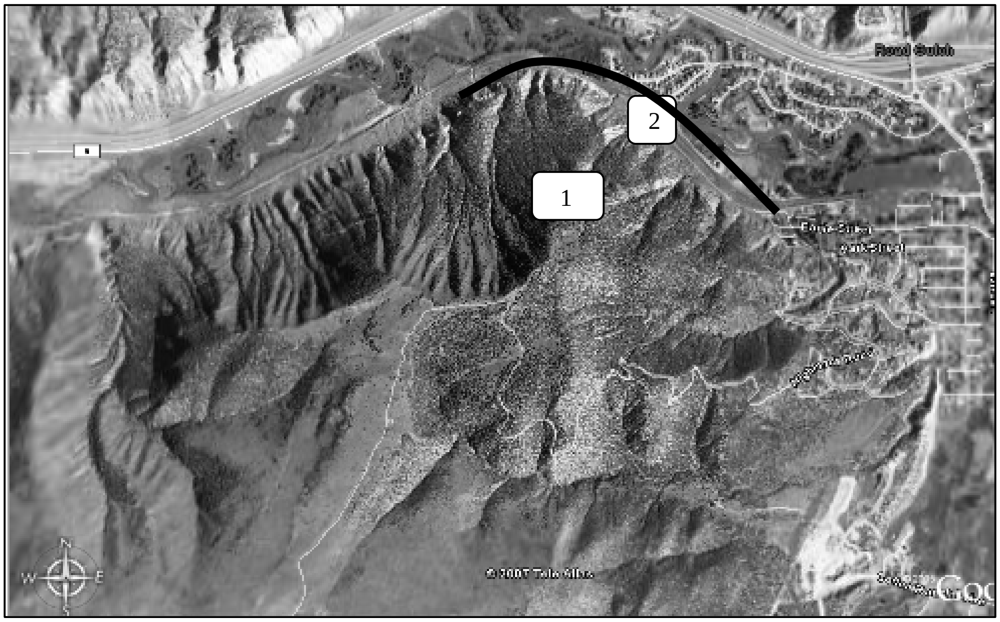
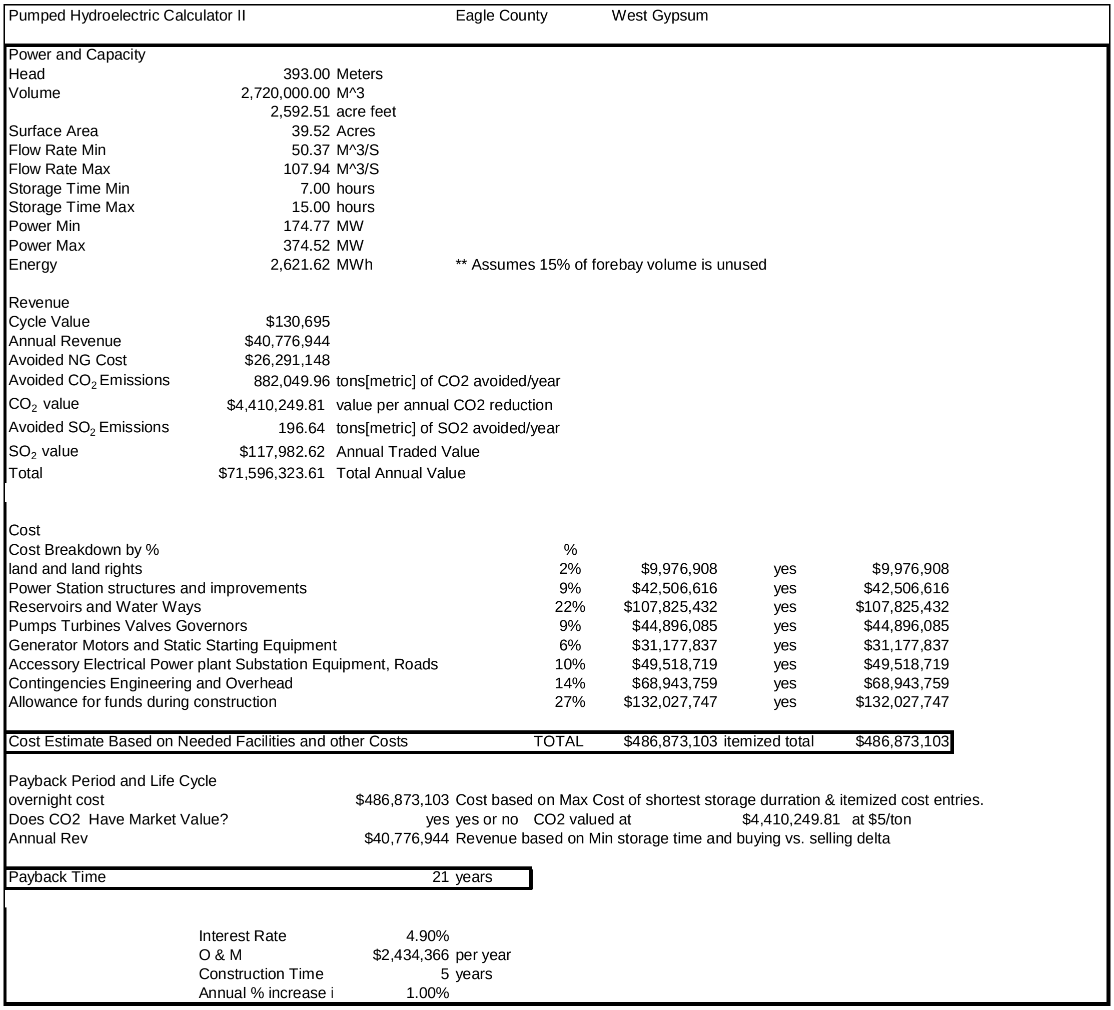


Figure 2-10: View of the West Gypsum Potential Site; 1-Aproxamate forebay location, 2-Afterbay may be located anywhere along the Eagle River I-70 corridor to facilitate siting. Eagle River I-70 corridor is marked in a bold black line.



Pumped Hydroelectric Calculator II			Eagle County	West Gypsum

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

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

Interest Rate	4.90%	
O & M	$2,434,366	per year
Construction Time	5	years
Annual % increase i	1.00%	

Figure 2-11: West Gypsum Technical and Economic Summary Output

Figure 2-11 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 2-12 . 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 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.

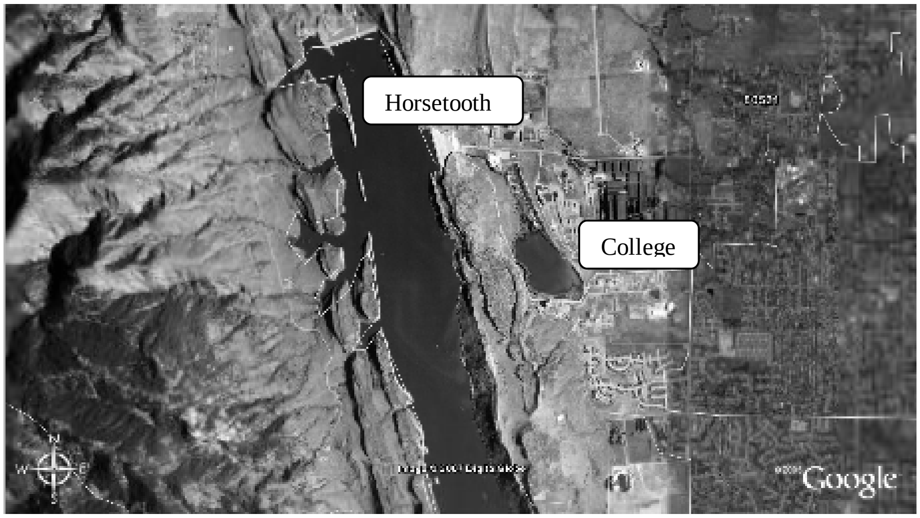
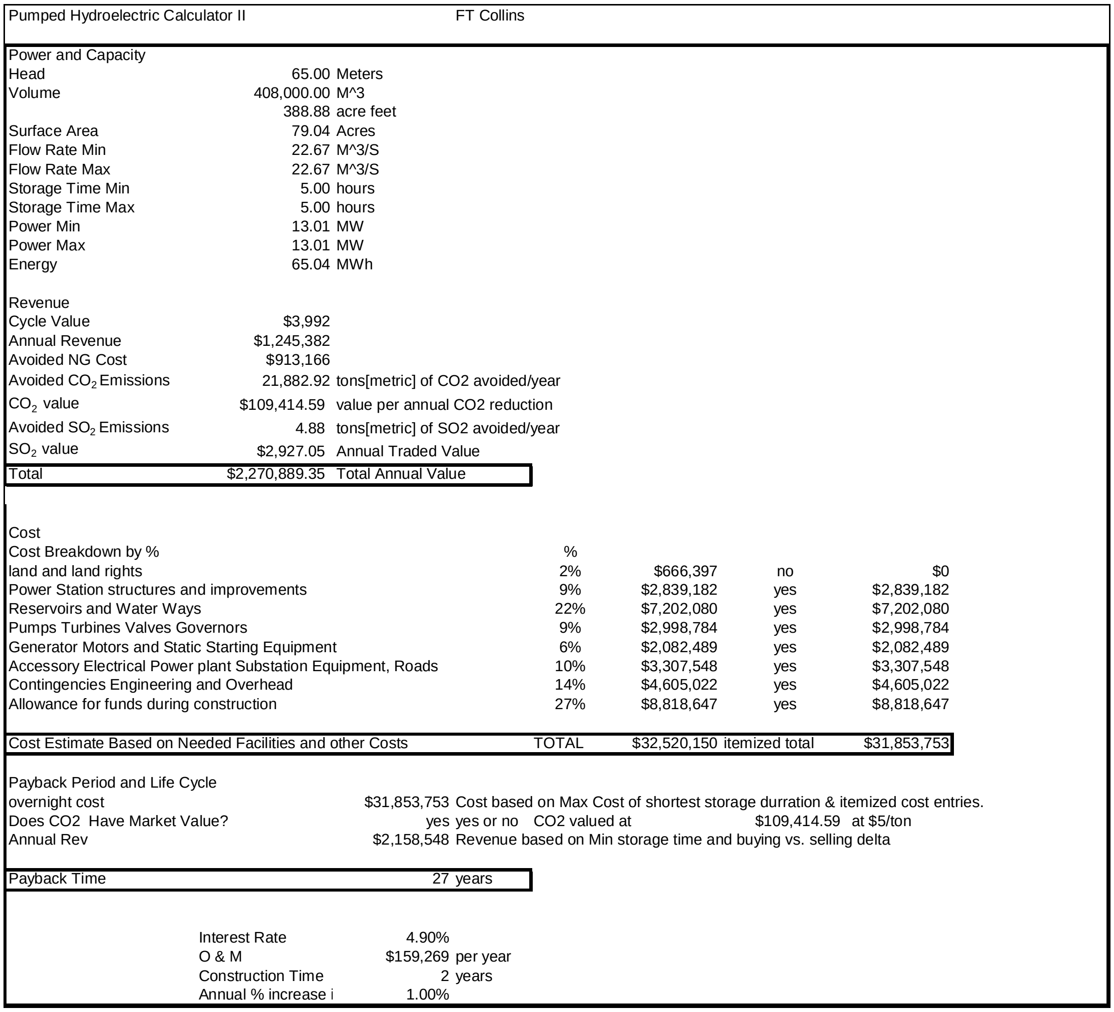


Figure 2-12: View of Horsetooth reservoir and College Lake on the western edge of Ft Collins Colorado and the CSU campus.

A summary sheet is displayed below in Figure 2-13 showing a set of cost and technical outputs.



Pumped Hydroelectric Calculator II		FT Collins				
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				
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				
Interest Rate	4.90%					
O & M	$159,269	per year				
Construction Time	2	years				
Annual % increase i	1.00%					

Figure 2-13: Horsetooth reservoir and College Lake

Figure 2-13 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.

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.

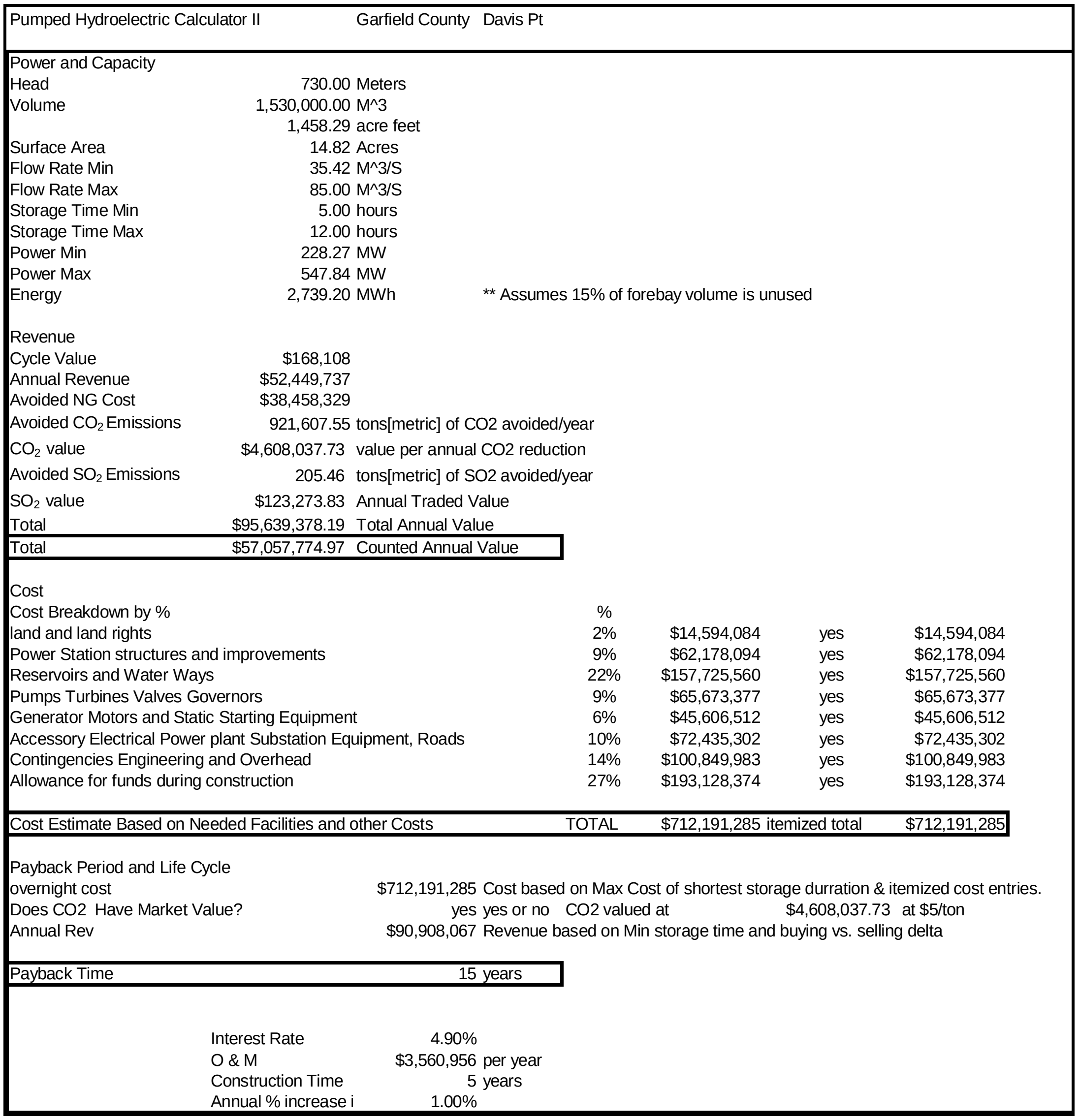
This pumped hydroelectric site may be an opportunity to firm intermittent wind power under consideration by Colorado State University (CSU). CSU is actively pursuing the development of wind power on Maxwell Ranch north of the University. The property is located in the robust South-central Wyoming wind 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 pond 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 attributes 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 mitigated due to the fact that they are already in place.
4. This would serve the University students of Colorado training the leaders of tomorrow a multitude of skills.

Davis Pt

The Davis Pt site is located in Garfield County to the West of the town of Rifle Colorado. Davis Pt is adjacent to the former Naval Oil Shale Reserve close to the Bureau of Mines Oil Shale Experiment Station. This site has a potential hydraulic head of 730 meters with areas for development at the top and bottom for reservoirs. With a surface area potential of about 15 acres for the upper reservoir, Davis Pt could have an energy storage capacity of 2,739 MWh deployable in 5 hours at 548 MW.

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 $52,449,737 plus an additional $38,458,329 in avoided natural gas and natural gas turbine operation costs. Also this plant could enable the avoidance of 921,607 tons of CO_2 for a annual value of $4,608,038 when valued at $5/ton. The above revenues and avoided costs set against the time valued capital cost yield a payback of 15 years.



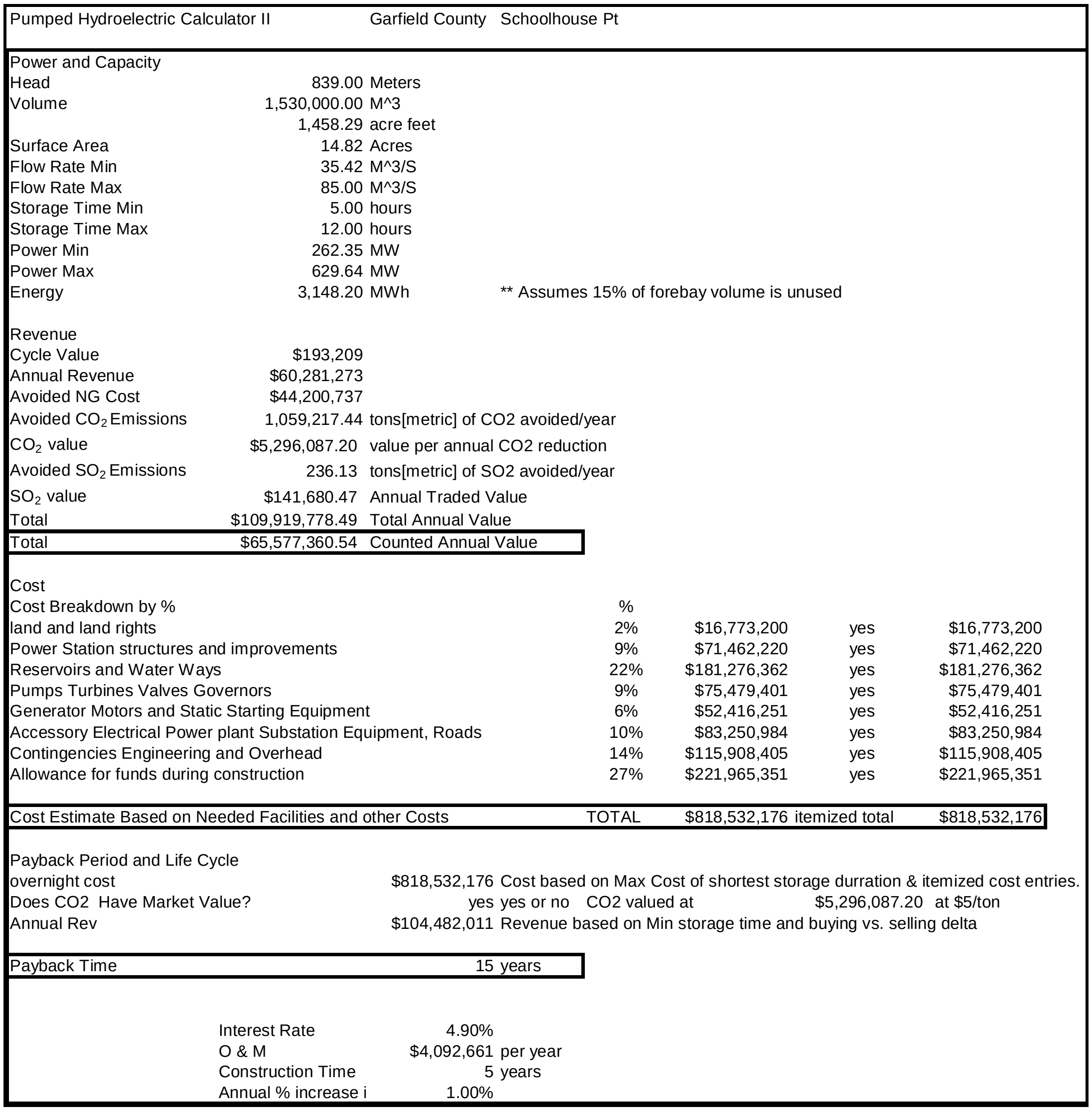
Pumped Hydroelectric Calculator II		Garfield County	Davis Pt				
Power and Capacity							
Head	730.00	Meters					
Volume	1,530,000.00	M^3					
	1,458.29	acre feet					
Surface Area	14.82	Acres					
Flow Rate Min	35.42	M^3/S					
Flow Rate Max	85.00	M^3/S					
Storage Time Min	5.00	hours					
Storage Time Max	12.00	hours					
Power Min	228.27	MW					
Power Max	547.84	MW					
Energy	2,739.20	MWh	** Assumes 15% of forebay volume is unused				
Revenue							
Cycle Value	$168,108						
Annual Revenue	$52,449,737						
Avoided NG Cost	$38,458,329						
Avoided CO_2 Emissions	921,607.55	tons[metric] of CO2 avoided/year					
CO_2 value	$4,608,037.73	value per annual CO2 reduction					
Avoided SO_2 Emissions	205.46	tons[metric] of SO2 avoided/year					
SO_2 value	$123,273.83	Annual Traded Value					
Total	$95,639,378.19	Total Annual Value					
Total	$57,057,774.97	Counted Annual Value					
Cost							
Cost Breakdown by %				%			
land and land rights				2%	$14,594,084	yes	$14,594,084
Power Station structures and improvements				9%	$62,178,094	yes	$62,178,094
Reservoirs and Water Ways				22%	$157,725,560	yes	$157,725,560
Pumps Turbines Valves Governors				9%	$65,673,377	yes	$65,673,377
Generator Motors and Static Starting Equipment				6%	$45,606,512	yes	$45,606,512
Accessory Electrical Power plant Substation Equipment, Roads				10%	$72,435,302	yes	$72,435,302
Contingencies Engineering and Overhead				14%	$100,849,983	yes	$100,849,983
Allowance for funds during construction				27%	$193,128,374	yes	$193,128,374
Cost Estimate Based on Needed Facilities and other Costs				TOTAL	$712,191,285	itemized total	$712,191,285
Payback Period and Life Cycle							
overnight cost		$712,191,285	Cost based on Max Cost of shortest storage durration & itemized cost entries.				
Does CO2 Have Market Value?		yes	yes or no	CO2 valued at		$4,608,037.73	at $5/ton
Annual Rev		$90,908,067	Revenue based on Min storage time and buying vs. selling delta				
Payback Time		15	years				
	Interest Rate	4.90%					
	O & M	$3,560,956	per year				
	Construction Time	5	years				
	Annual % increase i	1.00%					

Figure 2-14: David Pt technical and economic output

Schoolhouse Pt

The Schoolhouse Pt site is located in Garfield County to the West of the town of Rifle Colorado. Schoolhouse Pt is adjacent to the former Naval Oil Shale Reserve close to the Bureau of Mines Oil Shale Experiment Station. This site has a potential hydraulic head of 839 meters with areas for development at the top and bottom for reservoirs. With a surface area potential of about 15 acres for the upper reservoir, Schoolhouse Pt could have an energy storage capacity of 3,148 MWh deployable in 5 hours at 630 MW.

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 $60,281,273 plus an additional $44,200,737 in avoided natural gas and natural gas turbine operation costs. Also this plant could enable the avoidance of 1,057,217 tons of CO_2 for a annual value of $5,296,087 when valued at $5/ton. The above revenues and avoided costs set against the time valued capital cost yield a payback of 15 years.



Pumped Hydroelectric Calculator II		Garfield County	Schoolhouse Pt
Power and Capacity			
Head	839.00	Meters	
Volume	1,530,000.00	M^3	
	1,458.29	acre feet	
Surface Area	14.82	Acres	
Flow Rate Min	35.42	M^3/S	
Flow Rate Max	85.00	M^3/S	
Storage Time Min	5.00	hours	
Storage Time Max	12.00	hours	
Power Min	262.35	MW	
Power Max	629.64	MW	
Energy	3,148.20	MWh	** Assumes 15% of forebay volume is unused
Revenue			
Cycle Value	$193,209		
Annual Revenue	$60,281,273		
Avoided NG Cost	$44,200,737		
Avoided CO_2 Emissions	1,059,217.44	tons[metric] of CO2 avoided/year	
CO_2 value	$5,296,087.20	value per annual CO2 reduction	
Avoided SO_2 Emissions	236.13	tons[metric] of SO2 avoided/year	
SO_2 value	$141,680.47	Annual Traded Value	
Total	$109,919,778.49	Total Annual Value	
Total	$65,577,360.54	Counted Annual Value	

Cost				
Cost Breakdown by %	%			
land and land rights	2%	$16,773,200	yes	$16,773,200
Power Station structures and improvements	9%	$71,462,220	yes	$71,462,220
Reservoirs and Water Ways	22%	$181,276,362	yes	$181,276,362
Pumps Turbines Valves Governors	9%	$75,479,401	yes	$75,479,401
Generator Motors and Static Starting Equipment	6%	$52,416,251	yes	$52,416,251
Accessory Electrical Power plant Substation Equipment, Roads	10%	$83,250,984	yes	$83,250,984
Contingencies Engineering and Overhead	14%	$115,908,405	yes	$115,908,405
Allowance for funds during construction	27%	$221,965,351	yes	$221,965,351
Cost Estimate Based on Needed Facilities and other Costs	TOTAL	$818,532,176	itemized total	$818,532,176

Payback Period and Life Cycle					
overnight cost	$818,532,176	Cost based on Max Cost of shortest storage durration & itemized cost entries.			
Does CO2 Have Market Value?	yes	yes or no	CO2 valued at	$5,296,087.20	at $5/ton
Annual Rev	$104,482,011	Revenue based on Min storage time and buying vs. selling delta			
Payback Time	15	years			

Interest Rate	4.90%	
O & M	$4,092,661	per year
Construction Time	5	years
Annual % increase i	1.00%	

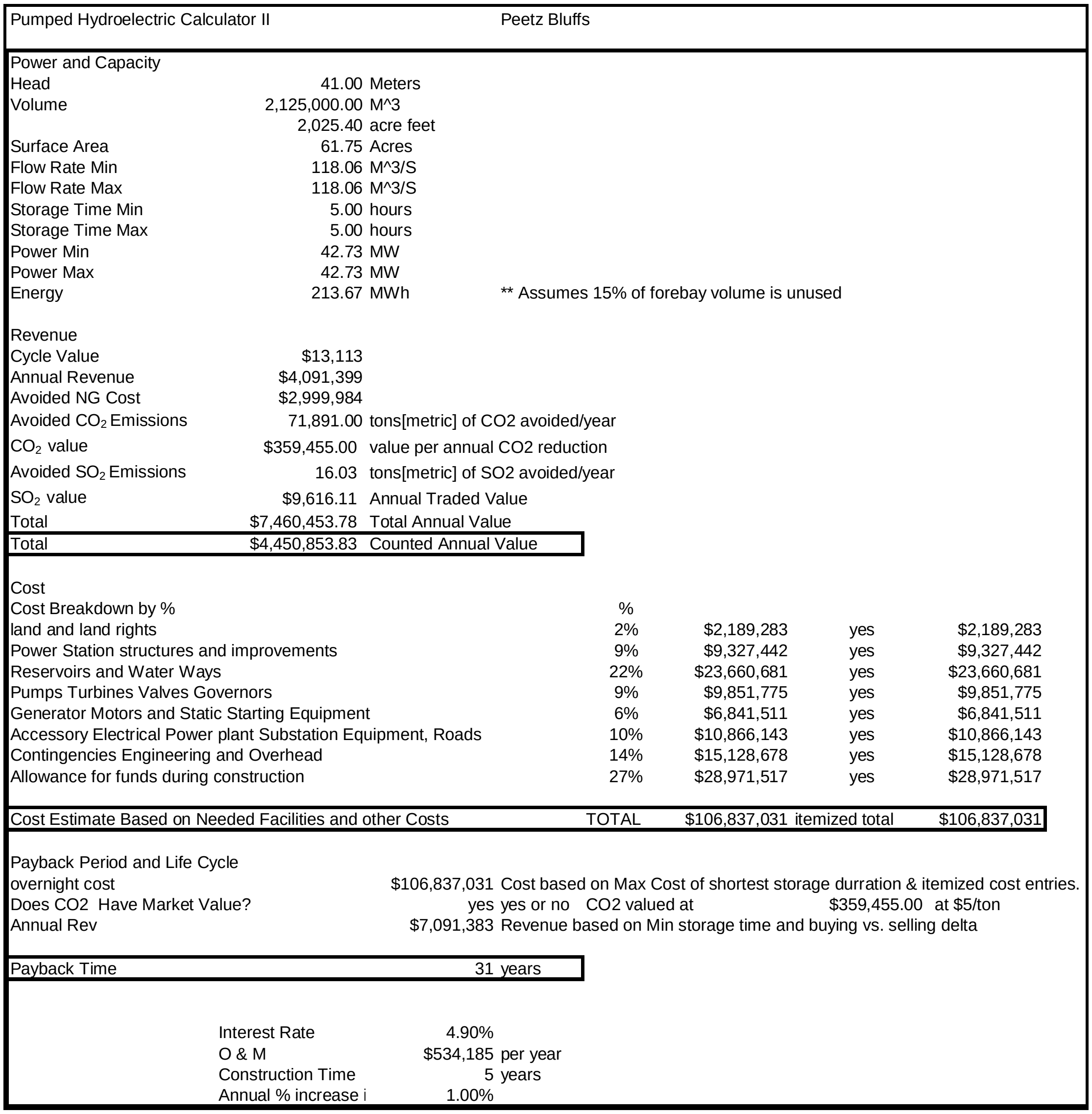
Figure 2-15: Schoolhouse Pt technical and economic output

Peetz Bluffs

The Peetz Bluffs site is located in Logan County to the North of the town of Sterling, Colorado. This location's forebay is along a bluff privately owned and is currently functioning as ranch land. The afterbay would sit also on privately owned ranch land below the rim of the bluff. This site is located close to the significant wind development in north eastern Colorado. This site would facilitate higher capacity value of wind by wire from the NE of the state.

This site has a potential hydraulic head of 41 meters with areas for development at the top and bottom for reservoirs. With a surface area potential of about 61.75 acres for the upper reservoir, Peetz Bluffs could have an energy storage capacity of 213 MWh deployable in 5 hours at 43 MW. Water rights and technical water availability would be a significant challenge for this development.

Economic analysis of this system assumes an overnight capital cost of $2,500 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 $4,091,399 plus an additional $2,999,984 in avoided natural gas and natural gas turbine operation costs. Also this plant could enable the avoidance of 71,891 tons of CO_2 for a value of $359,455 when valued at $5/ton. The above revenues and avoided costs set against the time valued capital cost yield a payback of 31 years.



Pumped Hydroelectric Calculator II			Peetz Bluffs
Power and Capacity			
Head	41.00	Meters	
Volume	2,125,000.00	M^3	
	2,025.40	acre feet	
Surface Area	61.75	Acres	
Flow Rate Min	118.06	M^3/S	
Flow Rate Max	118.06	M^3/S	
Storage Time Min	5.00	hours	
Storage Time Max	5.00	hours	
Power Min	42.73	MW	
Power Max	42.73	MW	
Energy	213.67	MWh	** Assumes 15% of forebay volume is unused
Revenue			
Cycle Value	$13,113		
Annual Revenue	$4,091,399		
Avoided NG Cost	$2,999,984		
Avoided CO_2 Emissions	71,891.00	tons[metric] of CO2 avoided/year	
CO_2 value	$359,455.00	value per annual CO2 reduction	
Avoided SO_2 Emissions	16.03	tons[metric] of SO2 avoided/year	
SO_2 value	$9,616.11	Annual Traded Value	
Total	$7,460,453.78	Total Annual Value	
Total	$4,450,853.83	Counted Annual Value	

Cost				
Cost Breakdown by %	%			
land and land rights	2%	$2,189,283	yes	$2,189,283
Power Station structures and improvements	9%	$9,327,442	yes	$9,327,442
Reservoirs and Water Ways	22%	$23,660,681	yes	$23,660,681
Pumps Turbines Valves Governors	9%	$9,851,775	yes	$9,851,775
Generator Motors and Static Starting Equipment	6%	$6,841,511	yes	$6,841,511
Accessory Electrical Power plant Substation Equipment, Roads	10%	$10,866,143	yes	$10,866,143
Contingencies Engineering and Overhead	14%	$15,128,678	yes	$15,128,678
Allowance for funds during construction	27%	$28,971,517	yes	$28,971,517
Cost Estimate Based on Needed Facilities and other Costs	TOTAL	$106,837,031	itemized total	$106,837,031

Payback Period and Life Cycle		
overnight cost	$106,837,031	Cost based on Max Cost of shortest storage durration & itemized cost entries.
Does CO2 Have Market Value?	yes	yes or no CO2 valued at $359,455.00 at $5/ton
Annual Rev	$7,091,383	Revenue based on Min storage time and buying vs. selling delta
Payback Time	31	years

Interest Rate	4.90%	
O & M	$534,185	per year
Construction Time	5	years
Annual % increase i	1.00%	

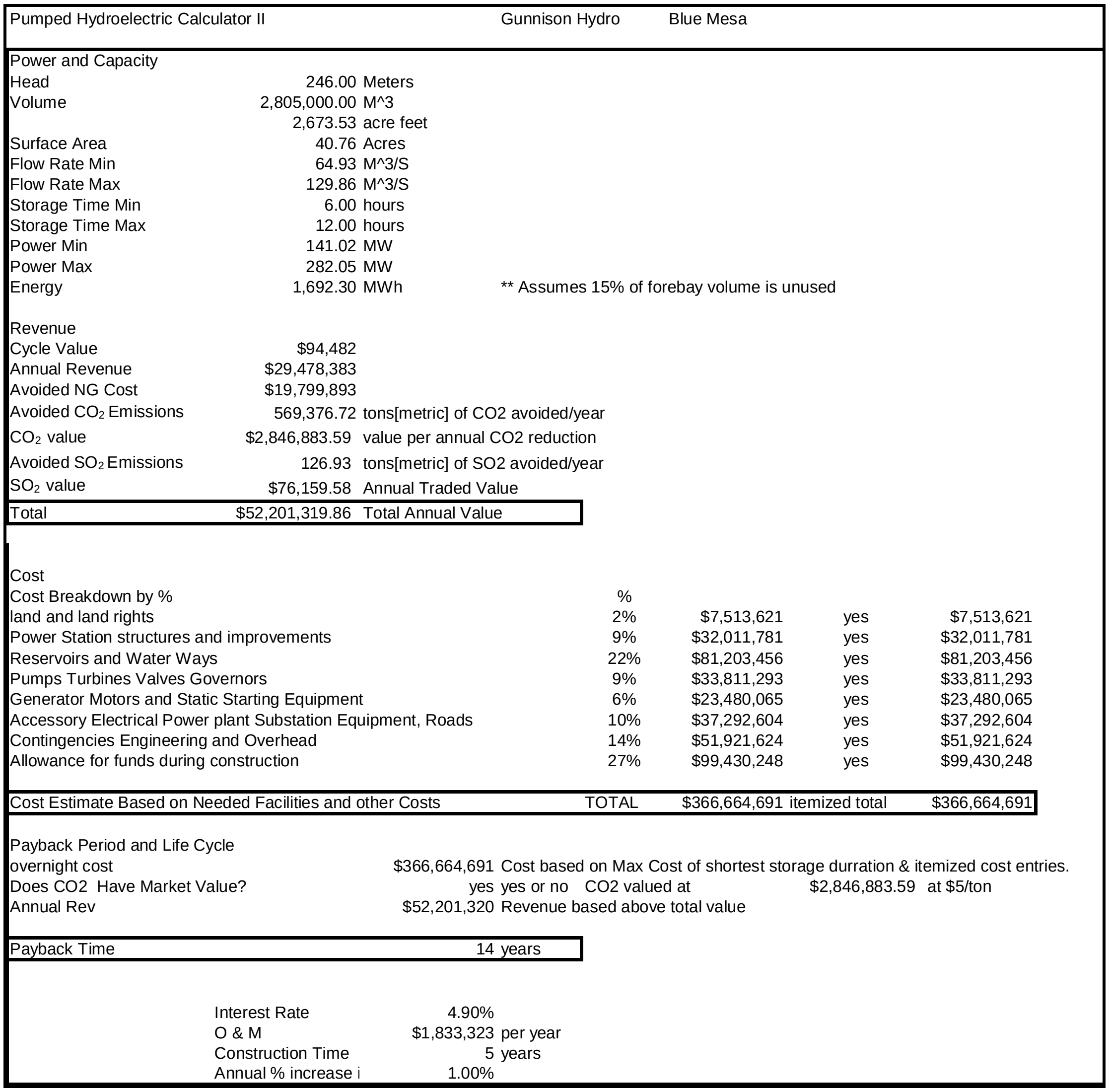
Figure 2-16: Peetz Bluffs technical and economic output

Gunnison/Blue Mesa

The Gunnison Blue Mesa site is located in Gunnison County just up steam from the Blue Mesa Dam. This location's forebay would be sited a top Pine Creek Mesa and the afterbay would be Blue Mesa Reservoir. This site has a potential hydraulic head of 246 meters with areas for development at the top for a reservoir. The bottom reservoir is in place.

With a surface area potential of about 40 acres for the upper reservoir, Gunnison Blue Mesa could have an energy storage capacity of 1,692 MWh deployable in 6 hours at 282 MW.

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 $29,487,383 plus an additional $19,799,893 in avoided natural gas and natural gas turbine operation costs. Also this plant could enable the avoidance of 569,376 tons of CO_2 for a value of $2,846,833 when valued at $5/ton. The above revenues and avoided costs set against the time valued capital cost yield a payback of 14 years.



Pumped Hydroelectric Calculator II			Gunnison Hydro	Blue Mesa
Power and Capacity				
Head	246.00	Meters		
Volume	2,805,000.00	M^3		
	2,673.53	acre feet		
Surface Area	40.76	Acres		
Flow Rate Min	64.93	M^3/S		
Flow Rate Max	129.86	M^3/S		
Storage Time Min	6.00	hours		
Storage Time Max	12.00	hours		
Power Min	141.02	MW		
Power Max	282.05	MW		
Energy	1,692.30	MWh	** Assumes 15% of forebay volume is unused	
Revenue				
Cycle Value	$94,482			
Annual Revenue	$29,478,383			
Avoided NG Cost	$19,799,893			
Avoided CO_2 Emissions	569,376.72	tons[metric] of CO2 avoided/year		
CO_2 value	$2,846,883.59	value per annual CO2 reduction		
Avoided SO_2 Emissions	126.93	tons[metric] of SO2 avoided/year		
SO_2 value	$76,159.58	Annual Traded Value		
Total	$52,201,319.86	Total Annual Value		

Cost				
Cost Breakdown by %	%			
land and land rights	2%	$7,513,621	yes	$7,513,621
Power Station structures and improvements	9%	$32,011,781	yes	$32,011,781
Reservoirs and Water Ways	22%	$81,203,456	yes	$81,203,456
Pumps Turbines Valves Governors	9%	$33,811,293	yes	$33,811,293
Generator Motors and Static Starting Equipment	6%	$23,480,065	yes	$23,480,065
Accessory Electrical Power plant Substation Equipment, Roads	10%	$37,292,604	yes	$37,292,604
Contingencies Engineering and Overhead	14%	$51,921,624	yes	$51,921,624
Allowance for funds during construction	27%	$99,430,248	yes	$99,430,248
Cost Estimate Based on Needed Facilities and other Costs	TOTAL	$366,664,691	itemized total	$366,664,691

Payback Period and Life Cycle					
overnight cost	$366,664,691	Cost based on Max Cost of shortest storage durration & itemized cost entries.			
Does CO2 Have Market Value?	yes	yes or no	CO2 valued at	$2,846,883.59	at $5/ton
Annual Rev	$52,201,320	Revenue based above total value			
Payback Time	14	years			

Interest Rate	4.90%	
O & M	$1,833,323	per year
Construction Time	5	years
Annual % increase i	1.00%	

Figure 2-17: Gunnison Hydro Blue Mesa technical and economic output

S1- White River

The S1- White River is located in Rio Blanco County to the West of the town of White River City, Colorado. This location's forebay is along a high ridge and the afterbay would be located in or near to gravel pits just North West of town. This site has a potential hydraulic head of 391 meters with areas for development at the top and bottom for reservoirs. The White River would serve as the water source and has substantial flow to supply the

PHES plant.[28] While the river would provide the water source the river would not need a dam. With a surface area potential of about 62 acres as the limiting reservoir this site could have an energy storage capacity of 4,075 MWh deployable in 10 hours at 407 MW.

Economic analysis of this system assumes an overnight capital cost of $1300 per installed kW, a construction time of 7 years, an interest rate of 6.5% and a CO_2 avoidance value of $5 per ton of CO_2. This yields estimated annual energy sales of $37,390,091 plus an additional $23,841,335 in avoided natural gas and natural gas turbine operation costs. Also this plant could enable the avoidance of 1,142,657 tons of CO_2 for a value of $5,713,288 when valued at $5/ton. The above revenues and avoided costs set against the time valued capital cost yield a payback of 35 years.

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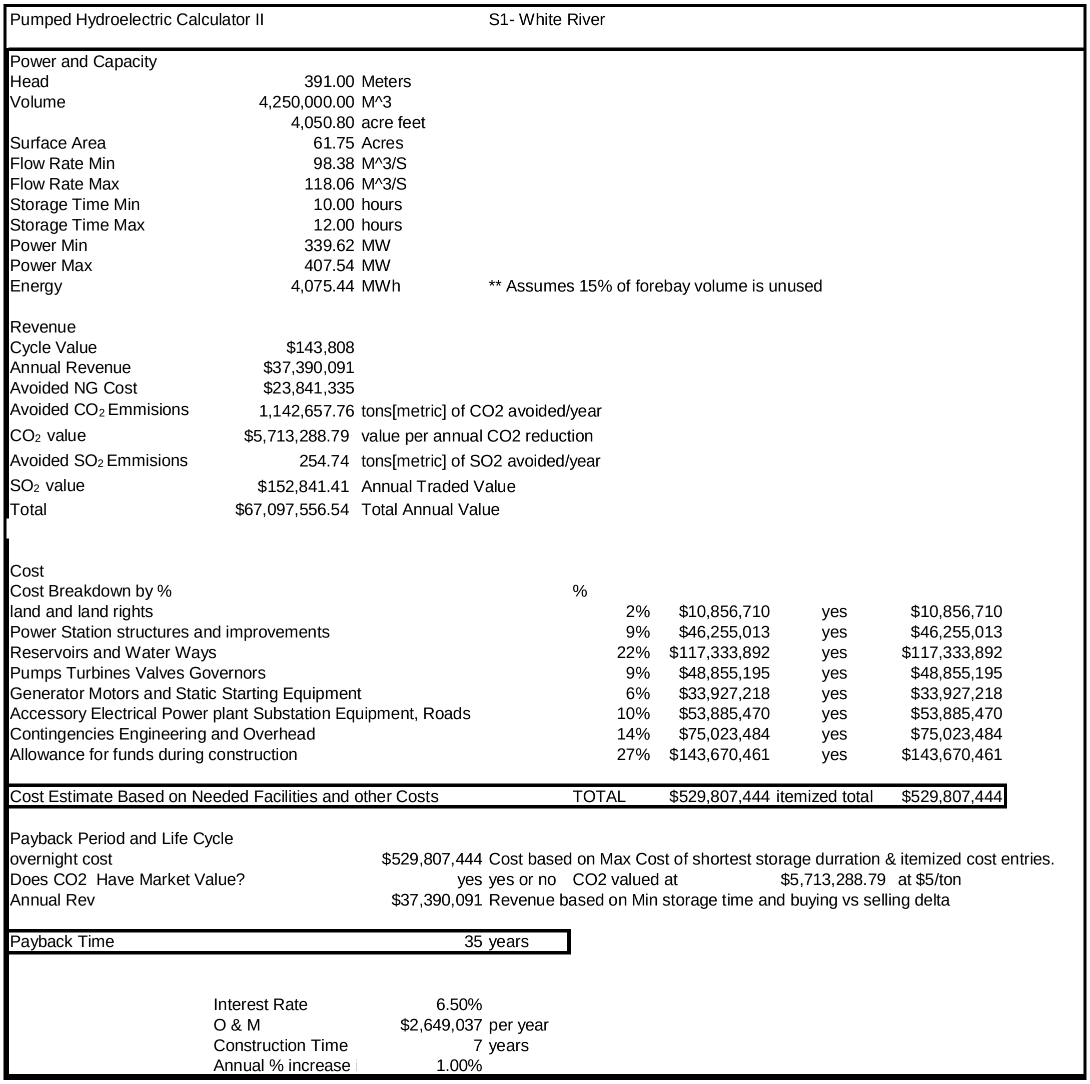
[28] Irving, D. Haines, B. Modde, T. (2003). *White River Base Flow Study, Colorado and Utah, 1995-1996.* Upper Colorado River Basin Recovery Implementation Program.*

*This resource shows flow rates but does not state what rates can be utilized for what purposes



Pumped Hydroelectric Calculator II S1- White River

Power and Capacity			
Head	391.00	Meters	
Volume	4,250,000.00	M^3	
	4,050.80	acre feet	
Surface Area	61.75	Acres	
Flow Rate Min	98.38	M^3/S	
Flow Rate Max	118.06	M^3/S	
Storage Time Min	10.00	hours	
Storage Time Max	12.00	hours	
Power Min	339.62	MW	
Power Max	407.54	MW	
Energy	4,075.44	MWh	** Assumes 15% of forebay volume is unused

Revenue		
Cycle Value	$143,808	
Annual Revenue	$37,390,091	
Avoided NG Cost	$23,841,335	
Avoided CO_2 Emmisions	1,142,657.76	tons[metric] of CO2 avoided/year
CO_2 value	$5,713,288.79	value per annual CO2 reduction
Avoided SO_2 Emmisions	254.74	tons[metric] of SO2 avoided/year
SO_2 value	$152,841.41	Annual Traded Value
Total	$67,097,556.54	Total Annual Value

Cost				
Cost Breakdown by %	%			
land and land rights	2%	$10,856,710	yes	$10,856,710
Power Station structures and improvements	9%	$46,255,013	yes	$46,255,013
Reservoirs and Water Ways	22%	$117,333,892	yes	$117,333,892
Pumps Turbines Valves Governors	9%	$48,855,195	yes	$48,855,195
Generator Motors and Static Starting Equipment	6%	$33,927,218	yes	$33,927,218
Accessory Electrical Power plant Substation Equipment, Roads	10%	$53,885,470	yes	$53,885,470
Contingencies Engineering and Overhead	14%	$75,023,484	yes	$75,023,484
Allowance for funds during construction	27%	$143,670,461	yes	$143,670,461
Cost Estimate Based on Needed Facilities and other Costs	TOTAL	$529,807,444	itemized total	$529,807,444

Payback Period and Life Cycle		
overnight cost	$529,807,444	Cost based on Max Cost of shortest storage durration & itemized cost entries.
Does CO2 Have Market Value?	yes	yes or no CO2 valued at $5,713,288.79 at $5/ton
Annual Rev	$37,390,091	Revenue based on Min storage time and buying vs selling delta
Payback Time	35	years

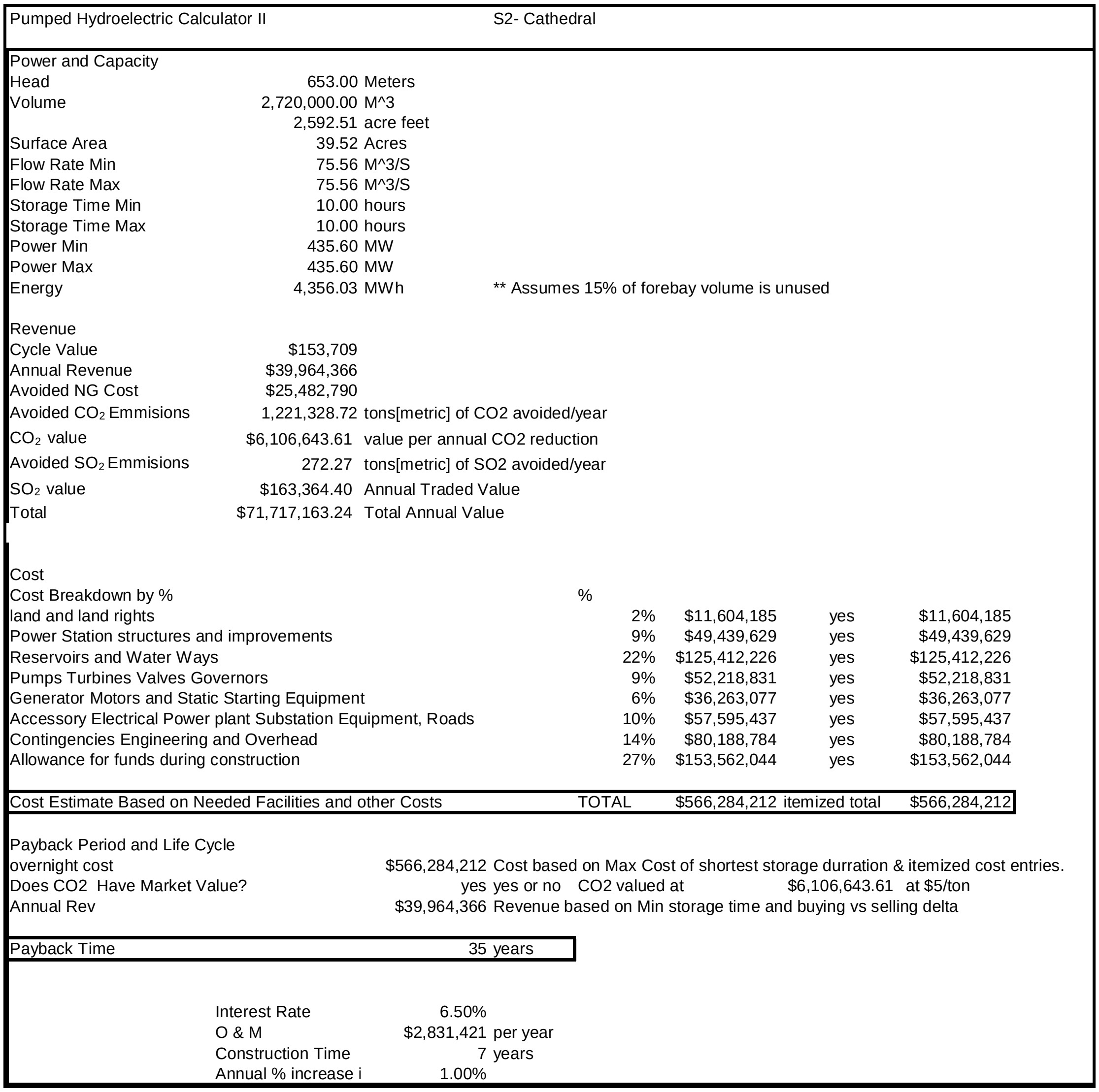
Interest Rate	6.50%	
O & M	$2,649,037	per year
Construction Time	7	years
Annual % increase i	1.00%	

Figure 2-18 White River technical and economic output

S2- Cathedral

The S2 Cathedral site is located in Rio Blanco County along Cathedral Creek utilizing Cathedral Bluffs as the elevation change. This site is in a remote location 10 Miles South West of a private business venture to extract oil from oil shale; questions from the company were the motivation behind this site location. This site has a potential hydraulic head of 653 meters with areas for development at the top and bottom for reservoirs. Cathedral Creek would serve as the water source but the annual flows are small relative to the water need of the plant, significant water rights would be required. With a surface area potential of 40 acres as the limiting reservoir S2 Cathedral has an energy storage capacity of 4,356 MWh deployable in 10 hours at 435 MW.

Economic analysis of this system assumes an overnight capital cost of $1300 per installed kW, a construction time of 7 years, an interest rate of 6.5%, and a CO_2 avoidance value of $5 per ton of CO_2. This yields estimated annual energy sales of $3,964,366 plus an additional $25,482,790 in avoided natural gas and natural gas turbine operation costs. Also this plant could enable the avoidance of 1,221,328 tons of CO_2 for a value of $6,106,643 when valued at $5/ton. The above revenues and avoided costs set against the time valued capital cost yield a payback of 35 years. This site was motivated by a private company, thus the interest rate and site development figures have been increased.



Pumped Hydroelectric Calculator II S2- Cathedral

Power and Capacity		
Head	653.00	Meters
Volume	2,720,000.00	M^3
	2,592.51	acre feet
Surface Area	39.52	Acres
Flow Rate Min	75.56	M^3/S
Flow Rate Max	75.56	M^3/S
Storage Time Min	10.00	hours
Storage Time Max	10.00	hours
Power Min	435.60	MW
Power Max	435.60	MW
Energy	4,356.03	MWh ** Assumes 15% of forebay volume is unused

Revenue		
Cycle Value	$153,709	
Annual Revenue	$39,964,366	
Avoided NG Cost	$25,482,790	
Avoided CO_2 Emmisions	1,221,328.72	tons[metric] of CO2 avoided/year
CO_2 value	$6,106,643.61	value per annual CO2 reduction
Avoided SO_2 Emmisions	272.27	tons[metric] of SO2 avoided/year
SO_2 value	$163,364.40	Annual Traded Value
Total	$71,717,163.24	Total Annual Value

Cost				
Cost Breakdown by %	%			
land and land rights	2%	$11,604,185	yes	$11,604,185
Power Station structures and improvements	9%	$49,439,629	yes	$49,439,629
Reservoirs and Water Ways	22%	$125,412,226	yes	$125,412,226
Pumps Turbines Valves Governors	9%	$52,218,831	yes	$52,218,831
Generator Motors and Static Starting Equipment	6%	$36,263,077	yes	$36,263,077
Accessory Electrical Power plant Substation Equipment, Roads	10%	$57,595,437	yes	$57,595,437
Contingencies Engineering and Overhead	14%	$80,188,784	yes	$80,188,784
Allowance for funds during construction	27%	$153,562,044	yes	$153,562,044
Cost Estimate Based on Needed Facilities and other Costs	TOTAL	$566,284,212	itemized total	$566,284,212

Payback Period and Life Cycle		
overnight cost	$566,284,212	Cost based on Max Cost of shortest storage durration & itemized cost entries.
Does CO2 Have Market Value?	yes	yes or no CO2 valued at $6,106,643.61 at $5/ton
Annual Rev	$39,964,366	Revenue based on Min storage time and buying vs selling delta
Payback Time	35	years

Interest Rate	6.50%	
O & M	$2,831,421	per year
Construction Time	7	years
Annual % increase i	1.00%	

Figure 2-19: S2 Cathedral technical and economic output

Figure 2-20: Overhead view of S2 Cathedral

2.4. Conclusions Next Steps

1. Bellyache Ridge
    a. Work should not continue on this example due to NIMBY concerns. This was determined on a site visit where significant high valued home construction was identified adjacent to the proposed site.
2. West Gypsum
    a. Contact should be made with the Bureau of Land Management field office responsible for the Gypsum area to explore the process that would be required to move forward on this project.
    b. Sarah Fisher an Eagle County Commissioner should be kept a breast of the situation as well as be consulted for advice on the way forward.
3. Horsetooth College Lake
    a. Reservoir draw-down in Horsetooth reservoir throughout the year decreases 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.

    b. 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.
    c. The waterway 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 waterways would have to be constructed for a project of this size or the waterway in place may need significant augmentation.
    d. Due to national security concerns as stated by the Bureau of Reclamation attaining drawings of the waterworks through solder dam are not readily available. CSU may be the appropriate entity to push this effort forward and they should start by attaining those drawings.
    e. Fort Collins and CSU individuals that will be pivotal in further development of this project will include: Dr. Frank Barnes; Dr. Richard Smart; Dr. Wade Troxell; and, Representative Randy Fischer. Those individuals will be valuable resources to tap while continuing this effort.

4. Davis Pt and Schoolhouse Pt
    a. This set of sites will be challenged by transmission availability into and out of the western slope. Assessment of the transmission constraints where they stand today, as well as, what the transmission situation will be with the progress of current state transmission efforts.

    b. Transmission efforts in the state can be tracked via the Interwest Energy Alliance.[29]

5. Peetz Bluffs
    a. This example is low head and without much water availability.
    b. The location of this example may be useful to firm eastern wind resources and also maximize utilization of transmission resources although a CAES facility may be better suited to this area.
6. Gunnison Hydro
    a. This example will be challenged by its proximity to state outdoor recreation opportunity. In order to better understand how great that challenge will be a conversation should be had with an outdoor recreation stake holder group.
7. S1 and S2 Examples
    a. These example where developed for Shell Exploration and Production Co. The contact at Shell is Mr. Chet Sandberg P.E. Chief Heater System Engineer.[30]

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.

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[29] Interwest is available online at: http://www.interwest.org/transmission/index.html

[30] Mr. Chet Sandberg P.E. is available at chet.sandber@shell.com

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 locations of generation systems; and supports the development of appropriate virtual and traditional energy storage technology.

Moving forward from the this thesis, the author believes that a professional entity should take the findings and drill down into pumped hydro examples around Colorado to further pumped hydro development.

3. Spatial Diversity Optimization of Wind Capacity Development

3.1. Background

How can utilities incorporate intermittent renewable energy on a large scale? Integration of intermittent renewable power generation should be driven by geographic dispersion of wind resources on a large scale. The following analysis uses spatially distributed wind speed data from within the Midwest Reliability Organization (MRO), the Southwest Power Pool (SPP), and the Electric Reliability Council of Texas (ERCOT). This collection of wind data is used to assess the impacts of geographical dispersion on the variability of wind power generation.

The goal of this section will be to report results of the impacts of geographical dispersion of wind resources in the MRO, SPP, and ERCOT reliability regions. The photo below shows the spatial diversity mentioned here with pushpins for data location sites.

a. Literature Review

In 2004 Gilbert M Masters authored *Renewable and Efficient Electric Power Systems.*[31] Masters text has a chapter that covers the technical information required to calculate wind power production for current wind turbines.

In 1979 Kahn[32] published a paper addressing spatial distribution in wind generation for a region in California where he concludes that reliability increases as a function of

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[31] Masters, G. (2004). *Renewable and efficient electric power systems.* Chapter 6 *Wind Power Systems* Section 4 *Impact of tower height*, Equation 6.15. John Wiley and Sons Inc. Hoboken, New Jersey.

geographic dispersion of wind development. Kahn also points out that integration is a function not just the wind resources but also the rest of the system capacity.

From the late 1990's to the current time the National Renewable Energy Laboratory (NREL) along with co authors have published on this topic. Generally conclusions have said increased spatial diversity decreases intermittent power outputs. [33] [34]

A DOE funded program titled the Plains Organization for Wind Energy Resources (POWER) based out of the Energy and Environmental Research Center (EERC) used 28 locations between Minnesota, North Dakota, Kansas, and Iowa. This study[35] used in situ data to look at the correlation of wind speed between stations as a mean to address wind energy production. This study concluded that: "…geographically dispersed locations reduce the overall variability in energy production."

Archer and Jacobson based out of Stanford University have published a series of papers on this topic including: *U.S. winds and wind power at 80 m (2003)*[36]; *Evaluation of global wind power*(2005)[37]; and, *Supplying baseload power and reducing transmission requirements by interconnecting wind farms* (2007)[38]. The first two papers assess wind power

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[32] Kahn, Edward. (1979). *The Reliability of Distributed Wind Generators.* Electric Power Systems Research. Energy and Environmental Division, LBL, Berkley, CA

[33] Milligan, M. Artig, R. (1999). *Choosing Wind Power Plant Locations and Sizes Based on Electric Reliability Measures Using Multiple-Year Wind Speed Measurements.* National Renewable Energy Laboratory Report No. CP-500-26724

[34] Milligan, M. Artig, R. (1998). *Reliability Benefits of Dispersed Wind Resource Development.* National Renewable Energy Laboratory Report No. CP-500-24314

[35] Simonson, T. Bradley, S. (DATE). *Regional Wind Energy Analysis for the Central United States.* Available online: www.undeerc.org/wind

[36] Archer, C.L., and M.Z. Jacobson, Journal of Geophysical Research, Vol. 108, No. D9, 4289, doi:10.1029/2002JD002076, May 16, 2003

[37] Archer, C. M Jacobson. (2005). Evaluation of global wind power. Available online at: <http://www.stanford.edu/group/efmh/winds/aj07_jamc.pdf>

[38] Archer, C.L. M.Z. Jacobson. (2007). Supplying Baseload power and reducing transmission requirements by interconnecting wind farms. Journal of Applied Meteorology and Climate.

in the US and abroad respectively these papers introduce/utilize the method of least square extrapolation technique to obtain wind speeds at 80 M. The third paper looks at integrating multiple wind sites to decrease intermittence in a similar fashion as what is used in this analysis. This paper found that, “As more [wind] farms are interconnected in an array, wind speed correlation among sites decreases and so does the probability that all sites experience the same wind regime at the same time. Consequently, the array behaves more and more similarly to a single farm with steady wind speed and thus steady deliverable wind power…It was found that an average of 33% and a maximum of 47% of yearly-averaged wind power from interconnected farms can be used as reliable, baseload electric power. Equally significant, interconnecting multiple wind farms to a common point, then connecting that point to a far-away city can allow the long-distance portion of transmission capacity to be reduced, for example, by 20% with only a 1.6% loss of energy”…

A vast number of wind integration reports as well as generation assessments are available online from private companies as well as Utilities of all sizes. These reports are planning tools to bring wind online and deal with the challenges incurred on the electric system. One example of those reports was produced for ERCOT in 2007.[39] This report in particular has a methods section which clearly lays out the steps for the construction of a power production model. A power production model is a model that can take wind speeds into the model and show power out of the model. For a review of grid integration studies a 2007 study produced by a private public working group is available.[40]

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[39] Brower, M. (2007). *Electric Reliability Council of Texas: Wind Generation Assessment.* AWS Truewind. Albany, New York.

[40] Smith, C. Et Al. (2007). *Best Practices in Grid Integration of Variable Wind Power: Summary of Recent US Case Study Results and Mitigation Measures.* EWEC. Milan, Italy. Available online at: http://www.wapa.gov/UGP/PowerMarketing/WindHydro/EWEC07paper.pdf

Analysis of Wind Farm Energy Produced in the United States authored by Vick, Clark, and Carr[41] looks at wind energy produced in the US between 2002 and 2006 summarizing outputs via capacity factors.

In 2005, Ms. Lena Hansen authored *Can Wind Be a Firm Resource? A North Carolina Case Study.*[42] This study concluded, "Geographically dispersing wind farms and considering their output together rather than individually, significantly reduces the variability of the wind system." The methods from this study with regards to portfolio optimization have been expanded and reused in the work to follow.

3.2. Methods

a. Data Collection

The first step in an analysis of wind power production is collection of wind data. Due to the proprietary nature of wind data, attaining it is challenging. Organizations that facilitated this data search and attainment are listed below:

1. Plains Organization for Wind Energy Resources (POWER) part of the Energy and Environmental Research Center (EERC), based out of the University of North Dakota. Available online at: http://www.undeerc.org/programareas/renewableenergy/wind/default.asp
2. National Renewable Energy Laboratory (NREL). Available online at: http://www.nrel.gov/wind/

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[41] Vick, B. Et Al. (2006). *Analysis of Wind Farm Energy Produced in the United State*. USDA-Agricultural Research Service. WTAMU-Alternative Energy Institute.

[42] Hansen, L. (2005). *Can wind be a firm resource? A North Carolina case study*. Duke Environmental Law and Policy Forum. Vol.15:341

3. Alternative Energy Institute (AEI) based out of West Texas A & M University. Available online at: http://www.wtamu.edu/research/aei/
4. Renewable Energy Research Laboratory (RERL) based out of the Center for Energy Efficiency and Renewable Energy (CEERE) from the University of Massachusetts Amherst. Available online at: http://www.ceere.org/rerl/index.html
5. The Oklahoma Wind Power Initiative (OWPI) a collaborative effort between The University of Oklahoma and Oklahoma State University. Available online at: http://www.seic.okstate.edu/owpi/
6. Idaho National Laboratory (INL). Available online at: http://www.inl.gov/wind/idaho/
7. Utah Geological survey. Available online at: http://geology.utah.gov/sep/wind/anemometerdata/sitedata.htm#data
8. Energy Resources Research Laboratory based out of Oregon State University. Available online at: http://me.oregonstate.edu/ERRL/
9. Stanford University via Dr's Mark Jacobson and Cristina Archer.
10. Renewable Energy Advancement in Nevada and the Southwest program sponsored by U.S. Senator Harry Reid and is supported by NREL and in cooperation with Desert Research Institute and Western Regional Climate Center. Available online at: http://www.wrcc.dri.edu/nrel/

Total data acquired to this point in time totals 494 sites spread across the United States of America. Only data sets that overlap in time can be used for this analysis. So, while nearly 500 data sites are available the greatest overlap in time yields 95 sites. Of those 95 data sets many were not useable do to poor data quality -less then 85% good data points- or other technical or logistical problems.

3.2.1. Data Choice

The base of literature clearly states that wind generation power output has a decrease in intermittence with an increase in spatial diversity. But, what that decrease is has yet to be defined. The relationship between spatial diversity and power output is a function of the wind regime over which the system is connected. If an interconnected wind system has wind patterns that are non-correlated the power output of the system may be less intermittent due to the complimentary production of multiple wind farms throughout the system. In an attempt to find the greatest diversity in wind patterns the period of time chosen for analysis maximized: The total number of wind data sites; the total number of power pools; and the total number of states.

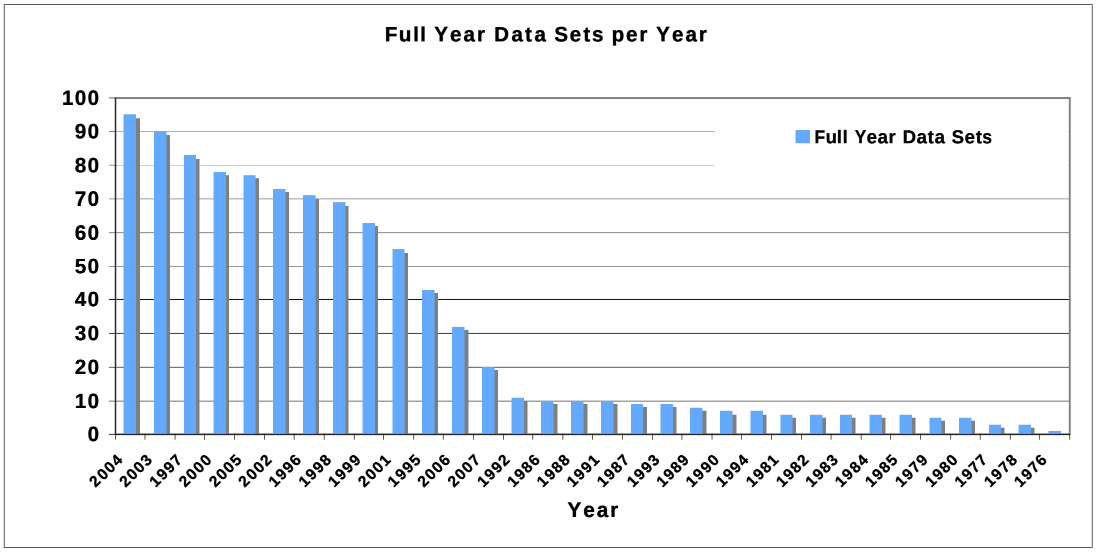

Figure 3-1: Available data sets refering to distinct data recording locations per year

Figure 3-1 shows year 2004 having the greatest number of data sites available with 95 locations.

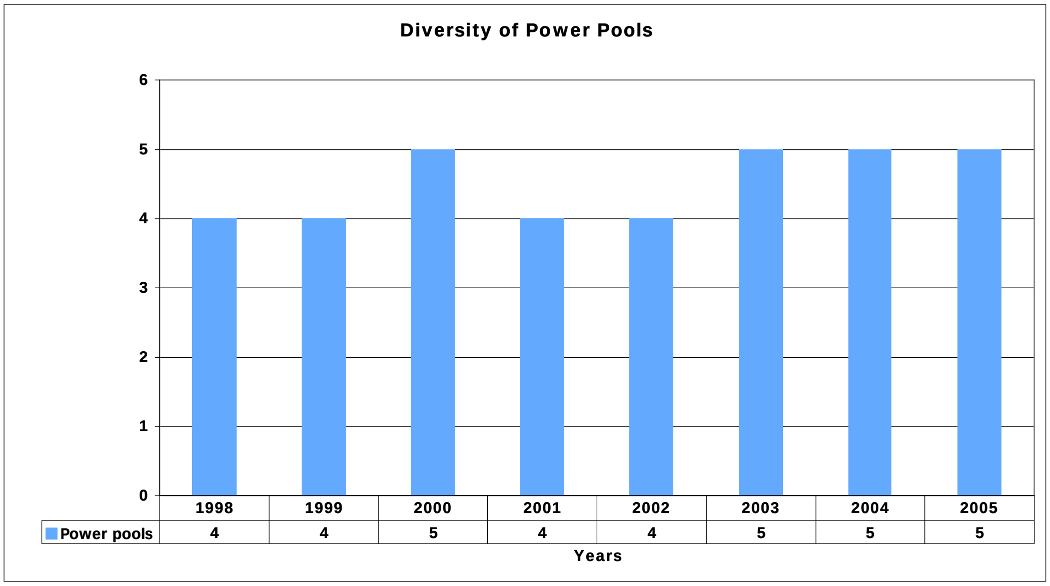

Figure 3-2: Diversity of data locations by power pool

Figure 3-2 shows years 2000, 2003, and 2004 having the greatest diversity of power pools within the data sets.

Table 3-1: Number of data sets in each of the power pools available by year

Power pools	1998	1999	2000	2001	2002	2003	2004	2005
NPCC	1	2	3	3	3	4	7	4
RFC	0	0	0	0	0	0	0	0
SERC	0	0	0	0	0	0	0	1
FRCC	0	0	0	0	0	0	0	0
ERCOT	14	8	11	7	8	9	11	11
SPP	0	0	15	0	0	2	7	0
MRO	49	50	43	42	55	51	54	40
WECC	5	3	6	3	7	24	16	21
Total sites	**69**	**63**	**78**	**55**	**73**	**90**	**95**	**77**

Table 3-1 breaks out the number of data sets in each power pool by year as well as the total number of sites. The year 2004 has the greatest number of sites as well as the greatest diversity of locations based on power pools.

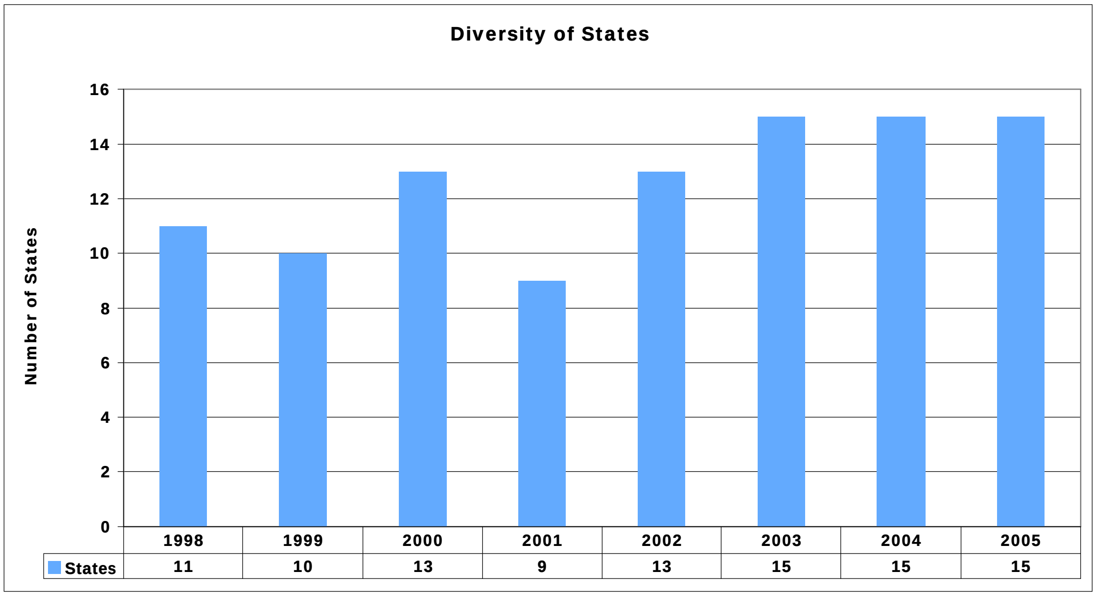

Figure 3-3: Diversity of data site locations by state

Figure 3-3 shows years 2003-2005 all having data sets from 15 states.

The year 2004 has the largest number of data sets from the largest diversity of locations. Thus, the year 2004 was chosen for power production analysis.

3.2.2. Power Production Model

In order to assess the power output of a wind system the data sets of wind speed have to be converted into power generation from wind turbines. This was accomplished through the following steps:

1. Attain wind speed data
2. Import wind speed data

3. Align the sampling period of the data sets
4. Adjust the wind speeds to the hub height of a utility scale wind turbine
5. Adjust power curve for elevation and air density
6. Pick a wind turbine
7. Power production calculation, via a 3rd order polynomial
8. Optimization

1. Attain wind speed data

See Methods Data Collection for resources related to this topic. Attaining wind speed data is difficult due to the proprietary nature of the data. All of the organizations and or persons listed under Methods Data Collection were pivotal in the ability to do this analysis. Over 1.5 years were spent searching for data sources. Working with both with University of Colorado contacts as well as contacts from the Rocky Mountain Institute (RMI) this data set was acquired through countless hours on the phone, Internet, and library. It is the intent of the author, the University, and RMI to make all data that can be shared from this set available to other researchers.

1. Import wind speed data

Once the data is located it was converted to a text file. From the text file the data was imported into MS Excel. Depending on the format of the original data set the import function had to be adjusted in order to capture the data in a useable format.

3. Adjust sampling period of data sets

Data was found that sampled wind speeds on a ten-minute period, a thirty-minute period, an hourly period, a daily period, and a monthly period. This analysis was conducted on an hourly period. All data sampled less frequently then an hourly period was not used. All data sampled more frequently then an hourly period had to be converted to an hourly period. The conversion from greater than hourly sampling, to hourly sampling, was done by taking the hourly mean average of the more frequent samples, and reporting the average at the beginning of each hour. This conversion was done in MS Excel with a mean average function and a V-Look-up and reporting function. In the case that data quality information was reported with wind speeds an average data quality figure needed to be preserved as well. Data quality figures were preserved by taking the mode of the data quality numbers reported in the hour data was averaged for.

3. Adjust the wind speeds to the hub height of a utility scale wind turbine

Modern utility scale wind turbines are installed with hub heights at 80 meters plus or minus 20 meters. This analysis took all measurements made below 80 meters and scaled the data up to 80 meters. All data collected at or above 80 meters was left as collected. The wind speeds were adjusted for height using the one-seventh-power rule. The one-seventh-power rule is expressed through the equation:[43]

$(V/V_o) = (H/H_o)^{\alpha}$

Where:

V = wind speed at height H

V_o = wind speed at height H_o

α = The friction coefficient which is a function of the terrain over which the wind is blowing alpha in this case is assumed to be 1/7th.

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[43] Masters, G. (2004). *Renewable and efficient electric power systems.* Chapter 6 *Wind Power Systems* Section 4 *Impact of tower height*, Equation 6.15. John Wiley and Sons Inc. Hoboken, New Jersey. PG 319-321

To increase the validity of this analysis all attempts were made to collect data sets that were taken at or above 80 meters.

4. Adjust power curve for elevation and air density

Due to the variety of locations data was taken from, adjustments had to be made to the energy production ability of a turbine at any given site. This adjustment is made based on the air density of the location from which the data was collected. Not all data sets had temperature readings along with wind speeds so a direct calculation of air density was not possible. Air density was estimated based on the elevation of the site. Assuming that a turbine manufacturer can adjust the power curve of a given turbine relative to the environmental characteristics it will be operating in. The power curve of our modeled turbine was adjusted to the air density based on the elevation of the data collection site.

Table 3-2: Assumed air density based on elevation

Altitude above Sea Level [m]	Density [kg/m3]
0.000	1.2014
152.400	1.1774
304.800	1.1533
457.200	1.1293
609.600	1.1053
762.000	1.0893
914.400	1.0732
1066.800	1.0568
1219.200	1.0404
1371.600	1.0208
1524.000	1.0012
1676.400	0.9811
1828.800	0.9611
1981.200	0.9439
2133.600	0.9267
2286.000	0.9103
2438.400	0.8938

2590.800	**0.8778**
2743.200	**0.8618**
2895.600	**0.8458**
3048.000	**0.8298**

Wind power production is dictated by the equation:[44]

$P_w = 1/2 CP \rho AV^3$

Where:
P_w = power in watts of the wind
CP= the coefficient of power, or the amount of energy extractable from the wind
ρ = air density in kg/m^3
A = swept area of the rotor in m^2
V = wind speed

For each data location an elevation was attained and the ρ value was adjusted to account for the air density change relative to elevation.

6. Pick a wind turbine

In order to drive out the power production equation one must chose a turbine so the swept area as well as the operating specifications can be attained. This analysis used the Vestas V80 2 MW wind turbine.[45] One may consider pushing this set of work forward by having a suite of turbines to choose from and depending on the average wind speeds of a particular site picking the turbine with the cut-in, cut-out, and nominal rating wind speeds that maximize production or value per time.

7. Power production

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[44] Master, G. (2004). Circular reference footnote 43. PG 325

[45] Technical specifications for this turbine can be found online at:
http://www.vestas.com/vestas/global/en/Products/Wind_turbines/V80_2_0.htm
The use of this turbine is not an endorsement of this product

Once all the above information is calculated the power production can be calculated in each hour for each data set. Each hour now has an adjusted ρ, A, and V; the air density, swept area, and the wind speed respectively.

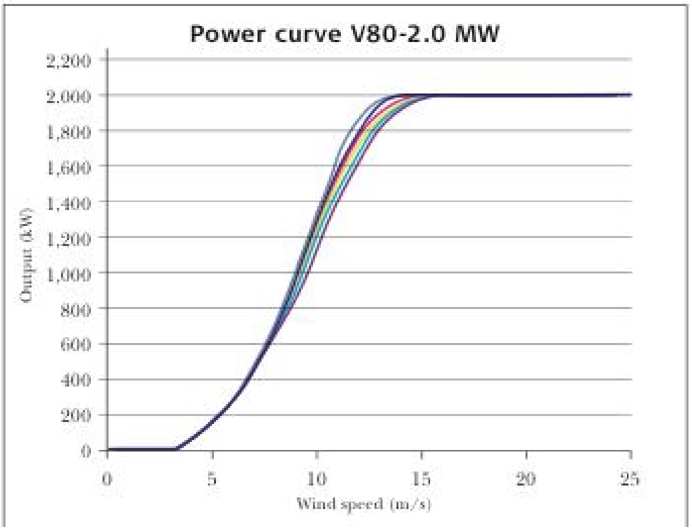

Figure 3-4: Power curve for a V80- 2.0 MW at 1.22kg/m^2 air density

The relationship between wind speed and power output is displayed in Figure 3-4. The power production calculation for each hour of each site is a numerical representation of the figure shown above. Where the turbine cuts in at 3.99 ms wind speed, gains power output with the cube of the wind speed through the 15 ms wind speed rated nominal, and the turbine cuts out or stops production of power above 25 ms wind speed. The equation to calculate this in the model is a 3rd order polynomial where if the wind speed is below the cut in speed no power is produced, if the wind speed is above 25 ms no power is produced, if the wind speed is between 15ms and 25 ms 2.0 MW of power are produced, and finally if the wind speed is between 3.99 ms and 15 ms the power output is a function of $P_w = 1/2CP\rho AV^3$.

9. Optimization

The following optimization methods are taken from Hansen 2005.[46]

The first step in determining the value of geographical dispersion is to determine whether the sites of interest exhibit any covariance. Covariance matrices were generated for each site relative to the other sites in their state, power pool, and the system as a whole. Covariance matrices where driven out according to the formula:

$\mathrm{Cov}(x,y) = 1/n * \Sigma (x_i - \mu_x)(y_i - \mu_y)$

Where:
- x, y = data series
- n= number of data points
- μ = data point series average
- i = data point

When a site exhibits negative covariance relative to another site it indicates that large power output values at one site are associated with small power output values at another site. This negative covariance should have the effect of reducing the variability of the combined output of the system as a whole.

The value of this negative covariance in reducing the system variability was determined by running an optimization model to determine the amount of capacity as a percentage of the total generation that each site should have to yield the collective minimum variability. This optimization problem minimizes the portfolio variability by changing the amount of capacity development in each location, subject to several constraints, as follows:

- Minimize the covariance
- Change the amount of generation at each location
- Subject to: the development share at each site is greater than or equal to 0 and also less then or equal to 1
- The total of all shares does not exceed 100% of the development

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[46] Hansen 2005, circular reference 42

- The output of the total shares is greater then or equal to a minimum specified production number

3.3. Results & Discussion

a. Data Collection

The data collection to this point has turned up 494 data collection locations. The sites are spread out from across the USA with a concentration of data across the center swath of the country. To facilitate further work in this area a database of all sources and specific locations of the data is available on the Internet at:

http://www.colorado.edu/engineering/energystorage/

Graphical representation of the data sets is shown in the Methods Data Choice section.

b. Data Choice

The single year 2004 had the greatest amount of available data as well as greatest diversity of location. Thus, 2004 is the time period chosen for analysis. Assessment of multiple years of data in succession is of interest although the sample size of data drops precipitously when multiple consecutive years in the same location are required. A late development in data collection may make a multiple year BPA study possible. See Methods Data Choice for graphical representation of what data is available.

c. Power Production Model and Optimization

The power production model calculates the energy generated in each hour of the year wind speed data is available, for each location. An example of power production is shown for ERCOT, Texas, five data locations.

Table 3-3: Power production output for five Texas locations on a Vestas V80-2MW

	Amarillo	Corpus	Presidio	Sweetwater	Washburn
Date/Time	kW-hr	kW-hr	kW-hr	kW-hr	kW-hr
1/1/04 0:00	698.27	570.34	77.98	179.12	478.45
1/1/04 1:00	704.73	515.19	73.11	463.16	319.08
1/1/04 2:00	677.03	447.34	55.64	1518.92	330.75
1/1/04 3:00	621.83	447.34	63.98	710.99	763.19
1/1/04 4:00	503.15	400.57	88.36	730.98	1143.08
1/1/04 5:00	294.58	415.78	225.89	807.50	1226.01
1/1/04 6:00	440.41	292.01	370.30	622.49	1283.47
1/1/04 7:00	687.60	224.92	529.48	1099.33	702.97
1/1/04 8:00	662.42	214.86	584.84	1237.17	592.19
1/1/04 9:00	602.18	130.16	429.45	796.77	354.94
1/1/04 10:00	625.81	186.46	179.00	224.66	493.72
1/1/04 11:00	602.18	195.63	0.00	0.00	541.46
1/1/04 12:00	884.44	205.09	44.55	0.00	627.72
1/1/04 13:00	1027.18	343.44	0.00	0.00	702.97
1/1/04 14:00	876.92	317.03	63.98	0.00	1116.29
1/1/04 15:00	1035.53	246.00	44.55	51.34	1170.29
1/1/04 16:00	1230.89	246.00	88.36	245.17	525.22
1/1/04 17:00	698.27	168.99	99.63	302.74	609.78
1/1/04 18:00	773.82	130.16	73.11	714.30	1013.31
1/1/04 19:00	1052.37	214.86	105.61	908.49	893.76
1/1/04 20:00	1136.32	186.46	99.63	786.13	1038.43
1/1/04 21:00	1101.06	224.92	215.93	581.13	1116.29
1/1/04 22:00	1571.41	268.35	206.26	1280.66	1531.26
1/1/04 23:00	1827.44	257.01	246.73	1464.81	2000.00
Total kWh	20,335.86	6,848.90	3,966.37	14,725.84	20,574.63
Capacity Factor	42.4%	14.3%	8.3%	30.7%	42.9%

The twenty-four hour power production output show in

Table 3-3 is represented graphically Figure 3-5.

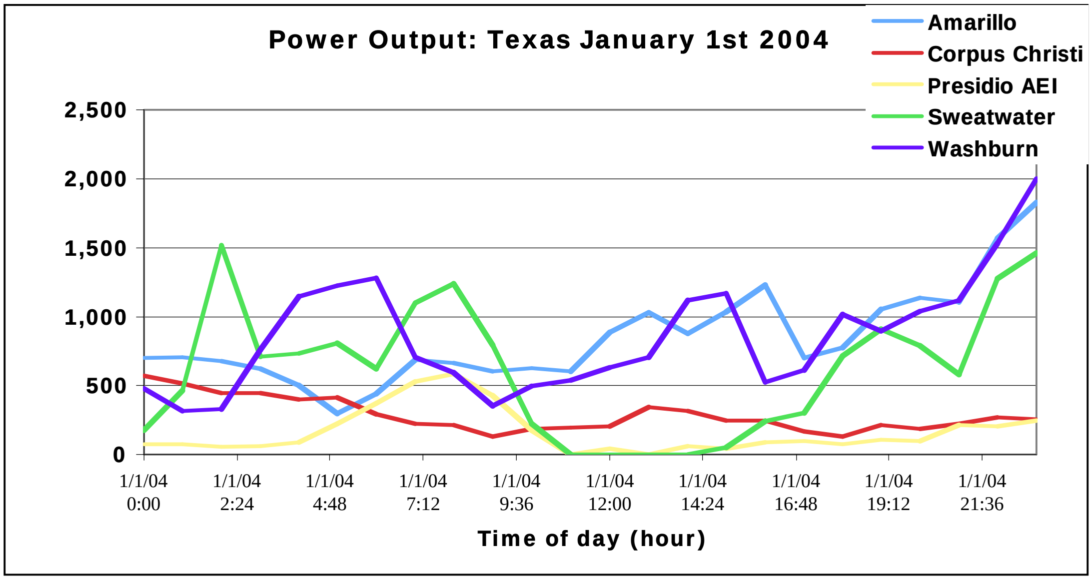

Figure 3-5: Power output of five locations in Texas, Jan 1st 2004

The above system if assessed one location at a time has outputs that vary from 0.00MW to 2.00MW. As a system the output varies from 1.34 MW to 5.80 MW. This 5-location system has a benefit of omitting the hours of zero production. Although this approach to looking at multiple wind farms assumes that each plant is developed with the same capacity at each site. When this Texas system goes through optimization the benefits of reduced time at zero production are retained and the cost to develop wind sites is optimized to reduce variability by placing capacity in locations that will balance power production if possible.

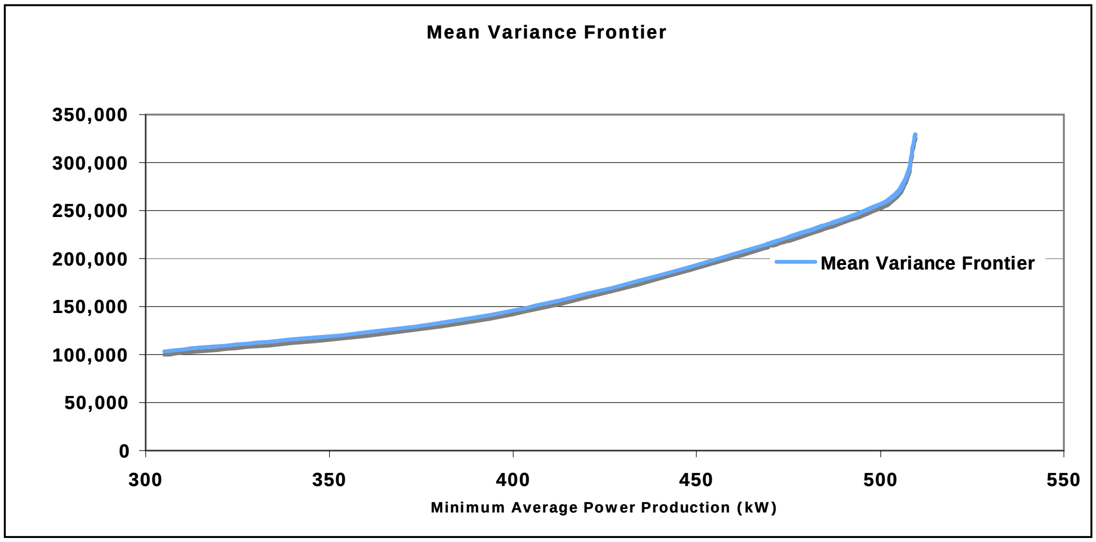

Figure 3-6: Texas system mean variance frontier

Figure 3-6 shows increasing portfolio variability with increasing minimum average power production. The goal of this work is to minimize intermittent power production thus decreasing the portfolio variability. The variability in the Texas system shown above increases minimally through the minimum output of 400kW where variability begins to increase at a steeper slope and at 500kW the variability becomes vertical. Developing this system with the intent of the highest minimum average power production with the lowest portfolio variability one specify optimization at 400 kW minimum average power production. Out of a 2MW machine 400kW is 20% firm. When the model runs this optimization the development is specified at:

- Amarillo = 0%
- Corpus Christi = 51%
- Presidio =0%
- Sweetwater = 9%
- Washburn = 40%

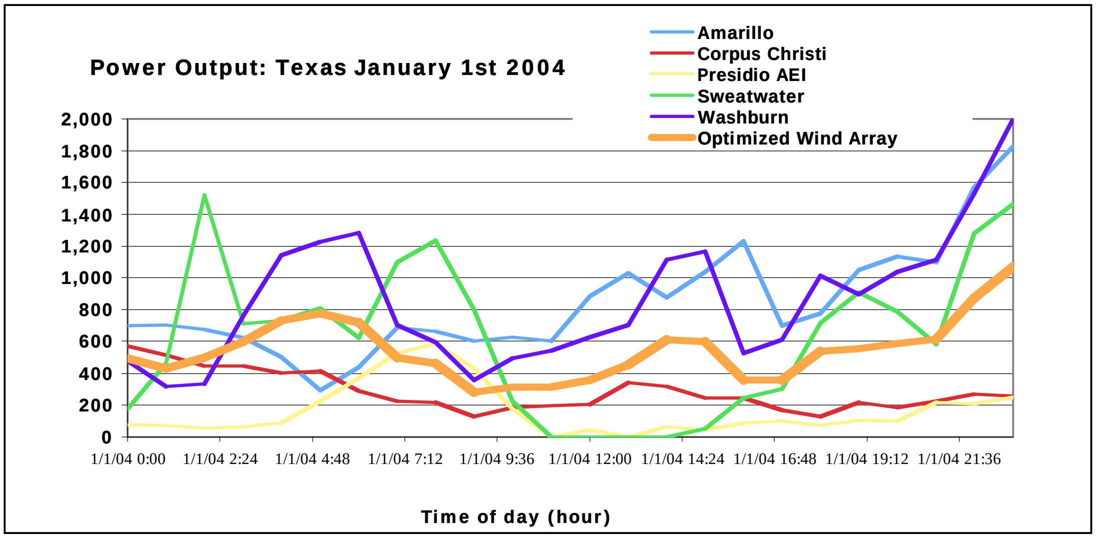

Figure 3-7: Optimized output of the Texas system on Jan 1st 2004

Figure 3-7 shows the output of the Texas system with the intent to minimize intermittence while maximizing output. This optimization is not the highest energy output possible, but it is the highest energy output attainable with a specified 20% firm power. The previous series of charts displayed one day out of 365 days of analysis. The full year of the Texas system is shown in a histogram format in Figure 3-8.

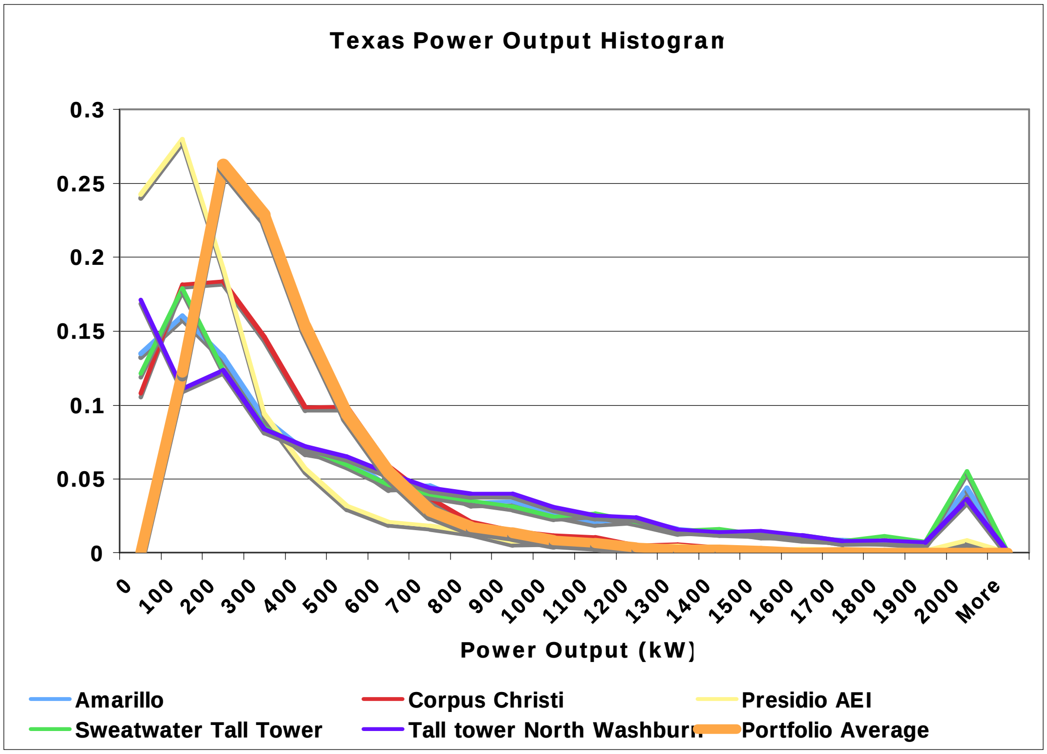

Figure 3-8: 2004 Texas system output histogram optimized to produce 400kW as a minimum portfolio output

The far left and right portions of the x-axis in Figure 3-8 should be of interest to those in the power industry. The left hand portion of the x-axis shows the optimized system with minimal probability of zero production. The right hand portion of the x-axis shows no spike in power production typical of individual wind farms. This optimization does not produce the most energy possible but does produce energy that is potentially easier to dispatch on to an electric grid. The histogram shown above is reproduced in Table 3-4 as a cumulative percent showing the reliability of the 2004 ERCOT data analyzed.

Table 3-4: System reliability percentage at x percent of capacity

	System Reliability %					
Capacity %	Optimized System	Amarillo	Corpus	Presidio	Sweetwater	Washburn
0%	0.03%	13.46%	10.82%	24.24%	12.14%	17.10%
5%	99.97%	86.54%	89.18%	75.76%	87.86%	82.90%
10%	87.77%	70.51%	71.02%	47.77%	69.98%	71.78%
15%	61.51%	57.30%	52.65%	28.54%	57.64%	59.43%
20%	38.64%	48.20%	38.08%	19.11%	49.17%	51.04%
25%	23.30%	41.29%	28.21%	13.43%	42.08%	43.82%
30%	13.87%	34.88%	18.33%	10.27%	36.11%	37.33%
35%	8.39%	30.43%	12.50%	8.20%	31.48%	31.96%
40%	5.58%	25.88%	8.82%	6.38%	27.53%	27.55%
45%	3.84%	22.50%	6.73%	4.96%	24.02%	23.57%
50%	2.49%	19.00%	5.25%	4.22%	20.87%	19.58%
55%	1.68%	16.36%	4.05%	3.44%	18.42%	16.51%
60%	1.02%	14.30%	3.02%	2.89%	15.79%	14.00%
65%	0.68%	12.02%	2.50%	2.48%	13.68%	11.60%
70%	0.46%	10.39%	1.94%	1.97%	12.19%	10.02%
75%	0.23%	9.01%	1.57%	1.70%	10.60%	8.63%
80%	0.10%	7.72%	1.30%	1.54%	9.37%	7.14%
85%	0.07%	6.71%	1.18%	1.26%	8.19%	5.94%
90%	0.01%	5.84%	0.99%	1.06%	7.40%	5.15%
95%	0.00%	5.04%	0.83%	0.97%	6.27%	4.34%
100%	0.00%	4.41%	0.72%	0.84%	5.53%	3.61%

Table 3-4 shows the numerical result of the histogram above. The optimized system significantly reduces both the time spent at zero production as well as the power spike traditionally found at 100% production or speeds over nominal. The 3% probability of zero production in the optimized system results in the equivalent of 11 days of zero production per year where as each of the systems individually would have the following days of zero production:

- Amarillo- 49 days of zero production
- Corpus- 40 days of zero production
- Presidio- 89 days of zero production
- Sweetwater- 44 days of zero production
- Washburn- 62 days of zero production

Each of the other systems analyzed had results with trends similar to that of the Texas system.

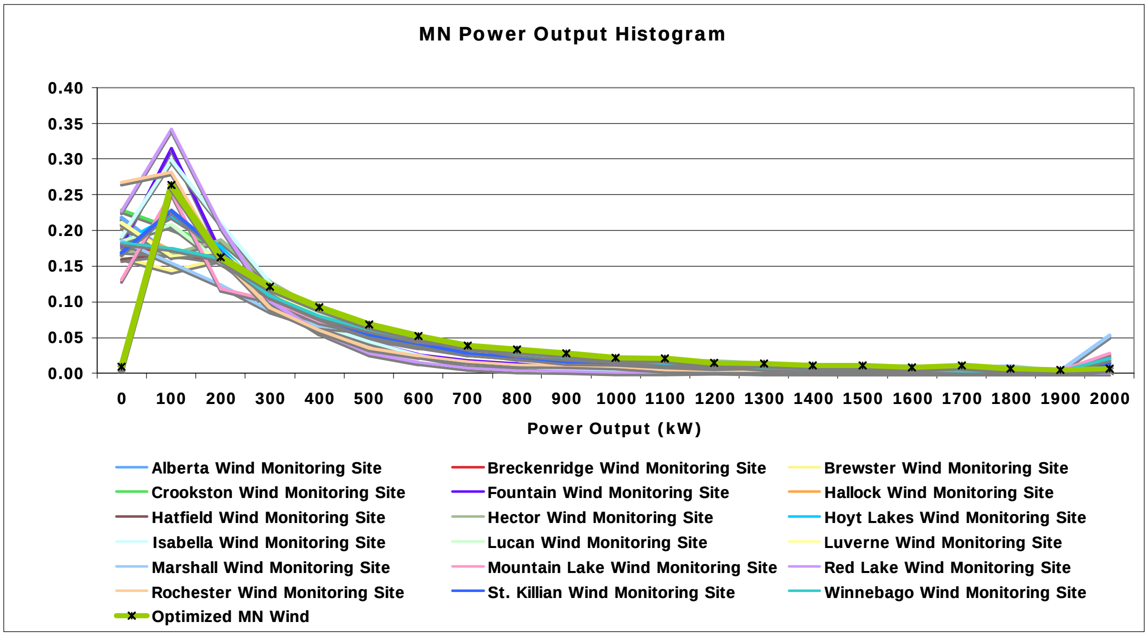

Figure 3-9: 2004 optimized Minnesota wind system

Table 3-5: Minnesota 2004 reliability percent as a percentage of total capacity when optimized

Capacity %	Optimized MN Wind System
0	0.91%
5	99.09%
10	72.77%
15	56.53%
20	44.42%
25	35.19%
30	28.34%
35	23.09%
40	19.23%
45	15.86%
50	13.05%
55	10.85%
60	8.75%
65	7.29%
70	5.91%
75	4.79%
80	3.72%
85	2.89%

90	1.81%
95	1.18%
100	0.69%

Figure 3-9 and Table 3-5 display the power output of the Minnesota wind system. When optimized 5% of the MN wind capacity is firm. Moreover, significant reductions are seen in time spent at zero power production as well as at full capacity potentially facilitating easier integration of wind power. The Minnesota system was built using 17 wind sites. When optimized 7 of the 17 locations where utilized for capacity development.

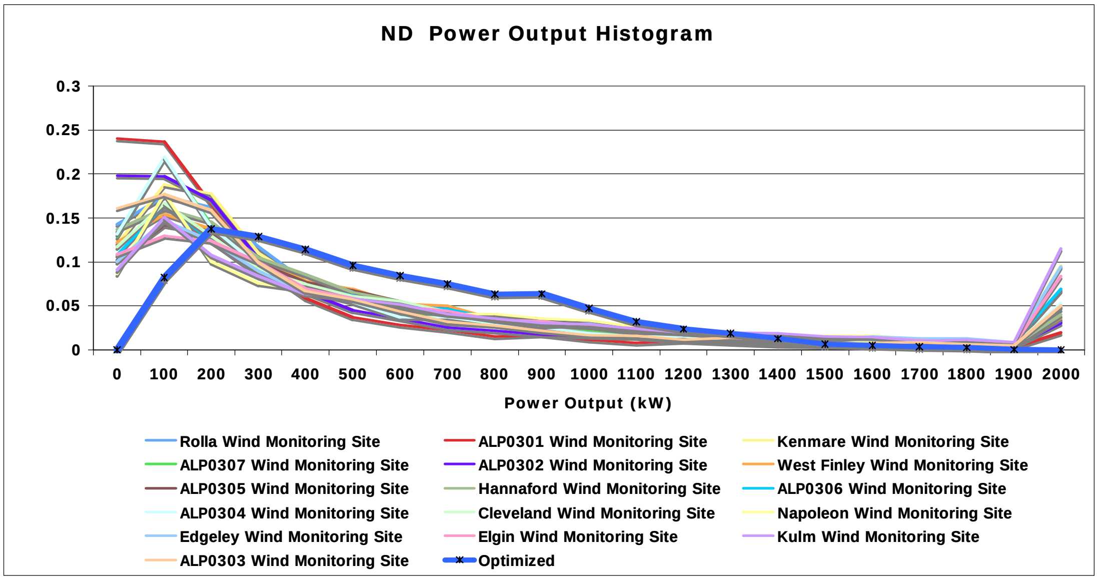

Figure 3-10: 2004 optimized North Dakota wind system

Table 3-6: North Dakota 2004 reliability percent as a percentage of total capacity when optimized

Capacity %	Optimized ND wind system
0	0.00
5	100.00%
10	91.75%
15	77.96%
20	65.04%
25	53.60%
30	43.97%
35	35.48%

40	27.97%
45	21.64%
50	15.24%
55	10.52%
60	7.31%
65	4.95%
70	3.05%
75	1.79%
80	1.16%
85	0.66%
90	0.30%
95	0.03%
100	0.01%

Figure 3-10 and Table 3-6 display the power output of the North Dakota wind system. When optimized 5% of the wind capacity is firm. Moreover, significant reductions are seen in time spent at zero power production as well as at full capacity potentially facilitating easier integration of wind power. The North Dakota system was built using 16 wind sites. When optimized 10 of the 16 locations where utilized for capacity development.

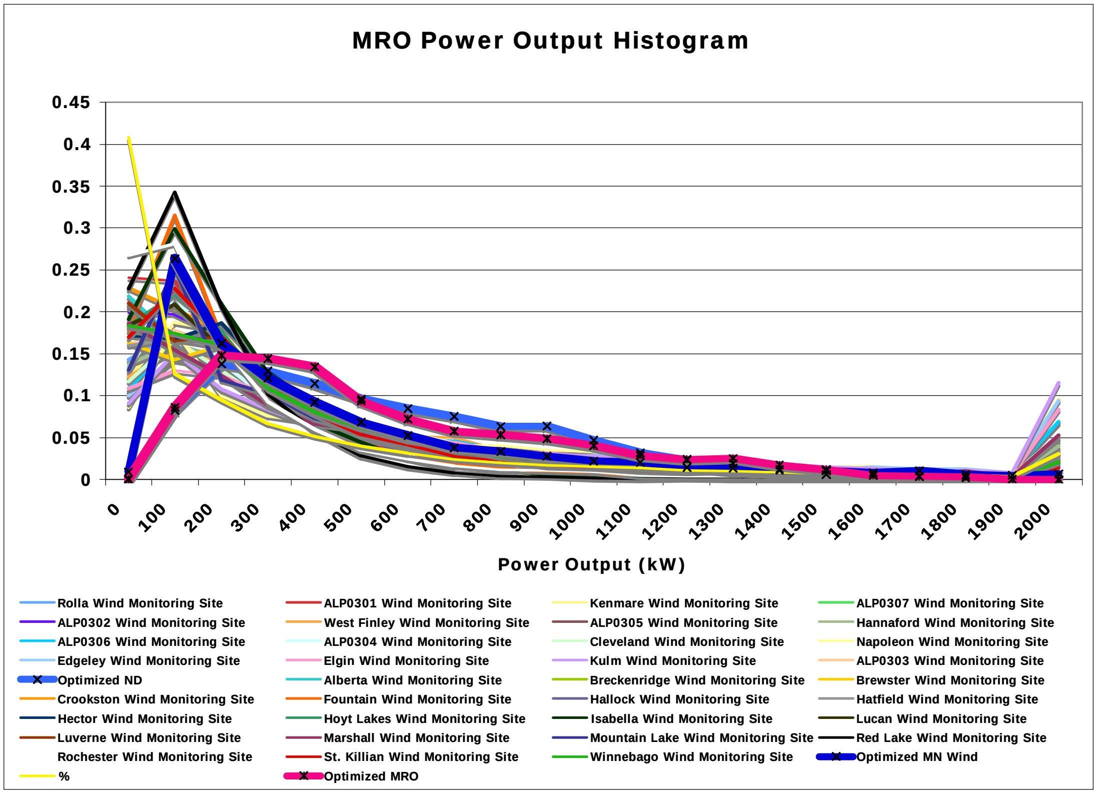

Figure 3-11: 2004 optimized MRO wind system, which includes both Minnesota and North Dakota

Table 3-7: Midwest reliability organization 2004 reliability percent as a percentage of total capacity when optimized

Capacity %	Optimized MRO wind system
0	0.07%
5	99.93%
10	91.30%
15	76.50%
20	62.06%
25	48.62%
30	39.26%
35	32.05%
40	26.29%
45	20.93%
50	16.04%
55	11.98%
60	9.08%
65	6.64%
70	4.11%

75	2.41%
80	1.22%
85	0.72%
90	0.35%
95	0.02%
100	0.00%

Figure 3-11 and Table 3-7 display the power output of the MRO wind system. When optimized 5% of the MRO system wind capacity is firm. Moreover, significant reductions are seen in time spent at zero power production as well as at full capacity potentially facilitating easier integration of wind power. The MRO system was built using 35 wind sites. When optimized 34 of the 35 locations where utilized for capacity development.

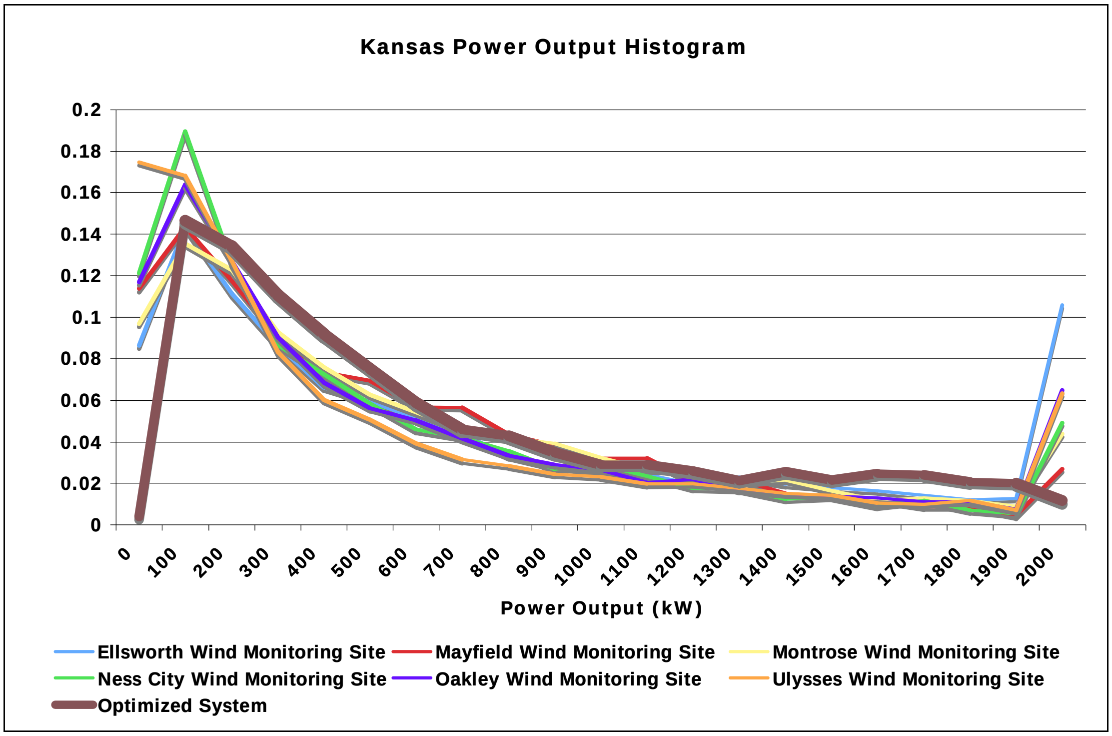

Figure 3-12: 2004 optimized Kansas wind system

Table 3-8: Kansas 2004 reliability percent as a percentage of total capacity when optimized

Capacity %	Optimized KS wind system
0	0.41%
5	99.59%

10	84.93%
15	71.51%
20	60.43%
25	51.24%
30	43.70%
35	37.82%
40	33.20%
45	28.92%
50	25.43%
55	22.52%
60	19.60%
65	17.02%
70	14.88%
75	12.31%
80	10.13%
85	7.65%
90	5.23%
95	3.16%
100	1.15%

Figure 3-12 and Table 3-8 display the power output of the Kansas wind system. When optimized 5% of the KS wind capacity is firm. Moreover, significant reductions are seen in time spent at zero power production as well as at full capacity potentially facilitating easier integration of wind power. The Kansas system was built using 6 wind sites. When optimized 5 of the 6 locations where utilized for capacity development.

3.4. Conclusions and Next Steps

To improve the quality of this assessment a number of steps can be taken. The quality of data can be improved by having data taken from hub height as opposed to ramping up wind speeds. There is a cost to collecting wind speed data but surely it is less costly to have multiple tall tower anemometer programs then it is to build a wind system that is less then optimal. While developers do take hub height data, they do this in specific location that they would like to develop. Data is not taken in multiple locations with the intent to optimize. As a youngster we learn think before you speak, to those in the wind industry one might suggest think and optimize before you build.

Turbine choice can be optimized for each location to maximize the production from each wind farm prior to optimizing the system as a whole. Wind speed data can be taken from functioning wind farms or significant wind resource areas. Many of the wind speed data locations used in this analysis where less then optimal. This analysis showed wind power can be firm at a low percentage of its total capacity when it is optimized. If the best wind locations with quality data attempted to optimize larger benefits may be found. Finally this optimization was conducted using Solver in MS Excel; while this tool is a good start to optimization stronger optimization methods should be used.

As an analogy to the challenges with this analysis; if one takes Lincoln logs and builds a geodesic structure to assess its structural soundness they would see a relatively strong Lincoln log structure. Although, that Lincoln log based improvement would be small due to the toy like nature of the Lincoln log. If one took viable building material and built a geodesic dome they would find significant structural improvements. The data used in this analysis can be seen as the Lincoln log version of wind speed data. Wind power developers, Public Utility Commissions, and others should facilitate the availability of quality data to truly assess potential improvements in the ability to firm wind power. That firming would be done first through optimization of spatial diversity and then other steps. Today wind developers see their wind data as a proprietary resource that should be kept private to ensure financial solvency. If sharing data would allow optimization of the wind system it would bring a higher value to the power purchase agreement (PPA) of those companies. Financial solvency maybe facilitated by sharing information as opposed to keeping it private.

This analysis shows wind is a firm resource when optimized at 5% of the total capacity developed. A larger percentage of wind power may be considered firm through improvement in data resources, optimization methods, or equipment utilization. Additionally looking beyond wind generation optimization firming may be achieved through other renewable resources, energy storage, demand response, and efficiency. All of the steps mentioned will surely yield a significantly firmer renewable resource then utility companies are dealing with today.

4. A spatially optimized and PHES integrated wind energy system

The firming benefits garnered from optimizing spatial distribution of wind capacity combined with the firming benefits of energy storage are two significant steps towards firming the energy output of a wind system. Keeping in mind that many other firming steps can be taken including; demand response, dispatchability of loads, efficiency of loads, power wheeling, and additional clean generation sources (to name a few other partial solutions) looking at spatial diversity and energy storage in tandem is a strong step forward.

Using the power output from five Texas wind plants for the year 2004 the following series of charts explores the benefits of combining optimized spatial distribution with PHES. This modeling stores and deploys wind energy without putting additional energy into the system from other generating sources. Due to the fact that no additional energy is put into the energy generation and storage system shown here it is impossible to have reliable power beyond the capacity factor of the wind energy system multiplied with the efficiency of the storage mechanism. Although the following analysis starts to look at these mitigation techniques combined, the modeling to yield these results is flawed. This modeling is flawed because there is not a limit on the amount of energy that can be stored. Meaning this calculation assumes an unlimited reservoir size. Additionally this model dispatches energy to minimize power output variability not to maximize economic value or to match load characteristics. Bringing in the above mentioned factors would be a strong addition to this work.

The following figures will show wind energy output without spatial distribution, followed by wind energy with spatial distribution, followed by wind energy with spatial distribution and increasing amounts of PHES capacity relative to the wind capacity. Where the term “% of Capacity” is used, it means the power output as a percent of the rated capacity of the installed generation.

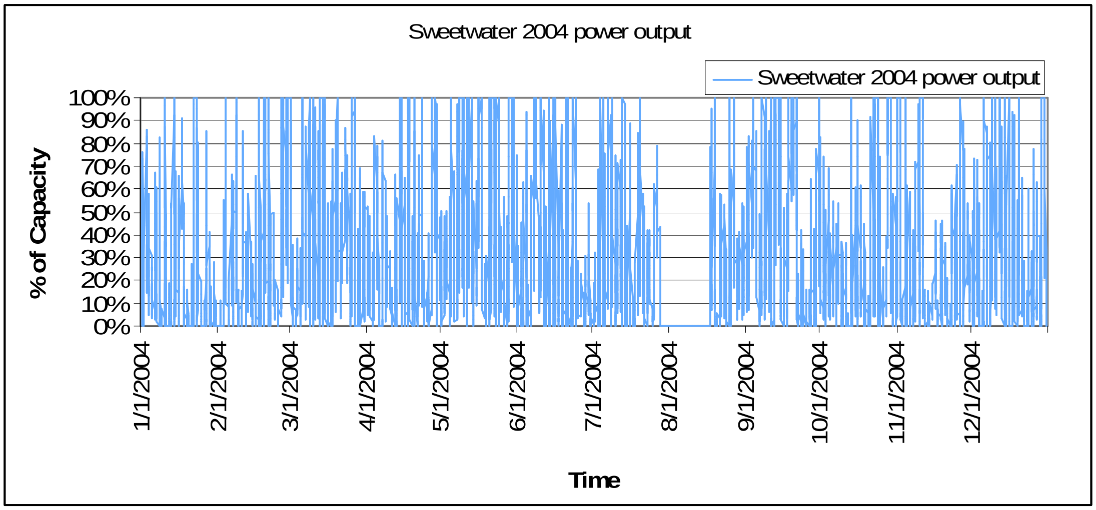

Figure 4-1: Sweetwater Texas 2004 power output

Figure 4-1 displays the power output of a wind farm as a percent of rated capacity in the year 2004. This output is from a single wind location with no energy storage. This single location, no storage, example of wind energy production displays the greatest amount of variability of any of the examples in this section. Wind energy produced in the year 2007 is seen by system operator on electric grid much like the output shown in Figure 4-1 and then backed up with fast responding generation.

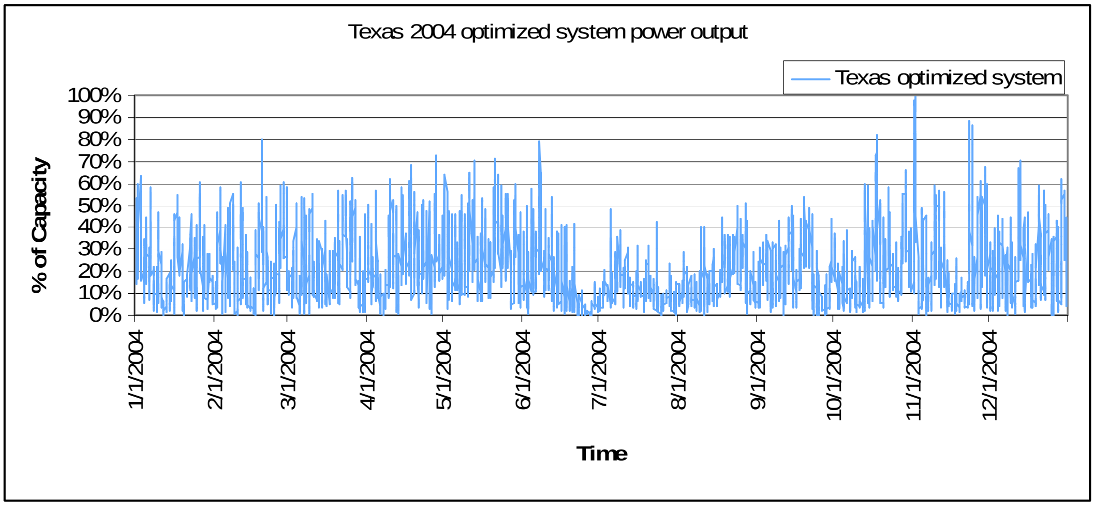

Figure 4-2: Texas wind system optimized to decrease variability utilizing spatial distribution

Figure 4-2 relative to Figure 4-1 displays significant improvement in ability to decrease variability. Figure 3-8 displays this output in a histogram format. The above output simply optimizes the spatial diversity of wind capacity development and significantly decreases time at 0% output and shows reliability of 5% capacity over 99% of the year.

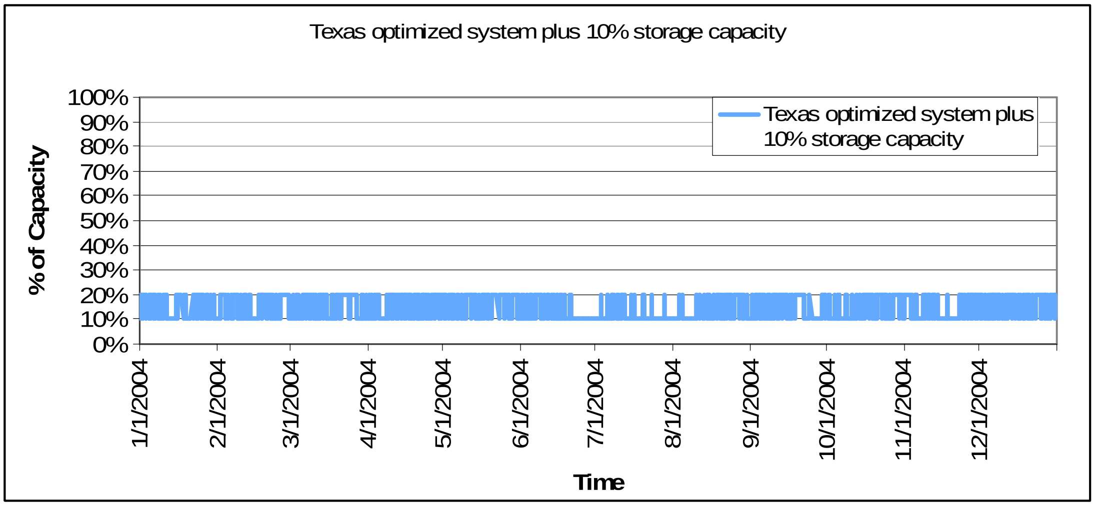

Figure 4-3: Texas wind system optimized to decrease variability utilizing spatial distribution and 10% capacity of PHES

Figure 4-3 displays the Texas optimized system with 10% of capacity backed up with PHES. This sizing of storage creates 100% reliability at 10% of capacity. At the end of the modeled year (2004) the storage reservoir had significant reserves of stored energy that were not deployed. Non-deployment would not happen in reality due to limited storage size, as well as the value of deployment and other factors. Never the less, with 10% of wind capacity backed up with storage, 10% of capacity becomes reliable 100% of the year.

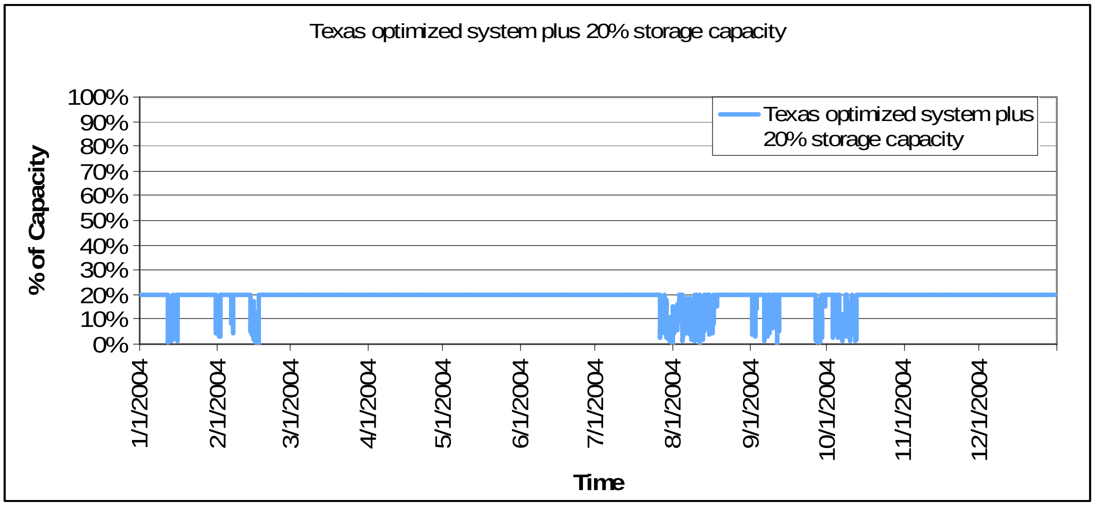

Figure 4-4: Texas wind system optimized to decrease variability utilizing spatial distribution and 20% capacity of PHES

Figure 4-4 displays the 2004 Texas optimized wind system with 20% of rated capacity backed up with PHES. This spatial optimization along with storage yields 20% of capacity reliable 87% of the year. Spatial optimization without PHES backup resulted in 20% of capacity reliable 39% of the year. Adding storage to the optimization yields an improvement in reliability at 20% capacity, of 48%. This sizing of storage is the same value as the mean average power output of the Texas optimized system. Aligning the mean average output of the optimized system and the capacity of the storage development tends to result in both a high reliability at the specified capacity, and a small amount of energy retained in the storage reservoir at the end of the modeled period. Aligning storage with the mean average output results in nicely sized development because sizing for the mean average allows the times of low generation to be compensated by the times of high generation (less the efficiency loss of the system). When looking at a real interconnected system as opposed to this modeled system one would see less variability because additional power generation would be added into the system when economically prudent.

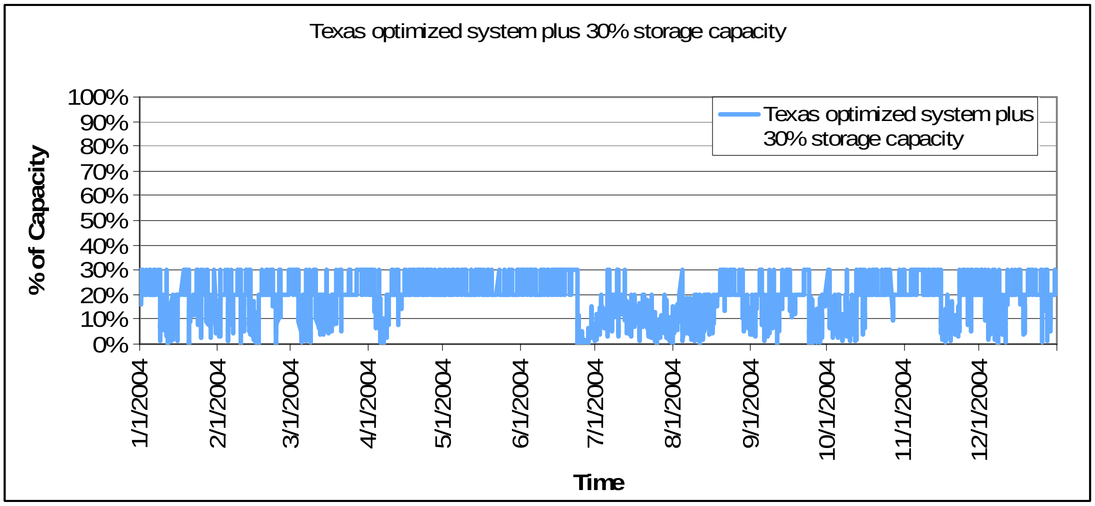

Figure 4-5: Texas wind system optimized to decrease variability utilizing spatial distribution and 30% capacity of PHES

Figure 4-5 displays the optimized 2004 Texas wind system with 30% of capacity backed up with PHES. This output show a significant amount of time where this energy system is not able to deploy, or is not reliable. Note that no energy is allowed to be used in this system that was not generated by the wind system analyzed. Thus, as the capacity of PHES reaches the capacity factor of the wind system multiplied by the efficiency loss of the storage without additional energy inputs, firming the output is not possible.

Although only two methods of integration are discussed above, the most effective solution to generation variability will be an integrated approach, which should include:

1. Diversifying the types and locations of renewable generation sources. This method should be an optimization of spatial diversity and renewable generation source that minimizes intermittence and cost while maximizing capacity to meet or exceed RPS targets while meeting loads.

2. Encouraging demand side management (DSM) to serve as a renewable source of energy as well as enabling the dispatchability of loads.
3. Developing adequate transmission infrastructure to facilitate diversified renewable plant locations. As well as imbedding intelligence into this system improving communications and management of resources on the grid.
4. Planning for additional energy storage on the electric grid that optimizes the utilization of transmission and generation resources minimizing costs and GHG emissions, allowing renewable energy to be dispatchable.
5. Formulate legislation that provides incentives for the first four points, smoothing intermittent generation as well as planning for storage to compensate times of excess and shortage.

None of the above points are silver bullets to facilitate 20% and greater penetration of renewable power sources. Moreover, if only one of the above strategies is pursued it will be less valuable than if a combination are pursued. Each point will increase the reliability of the electric grid and have synergistically positive effects on the other points.

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Glossary of Terms

Base Load- The minimum load over a given period of time, typically slow responding to changes in need. This resource generally has the lowest cost of energy in a traditional assessment.

Capacity- The maximum load that a machine, station, or system can carry under existing service conditions. Equivalent term: peak capability, peak generation, firm peak load, carrying capability. In transmission, the maximum load a transmission line is capable of carrying.

Capacity Factor- Capacity factor is connected with a power generator and is defined as the factor determined by dividing the energy delivered by generator during a given period by the energy that would have been delivered if the generator had been delivering energy at its maximum capacity every hour in that time period.

Energy- The capacity for performing work. The electrical energy term generally is kWh and represents power (kW) operation for some time period (h).

Energy, Electric- It is measured in terms of the work it is capable of doing; electric energy is usually measured in kWh. The heat equivalent of one kWh is equal to 3,412.97 Btu’s.

Energy, Off-Peak, Electricity- Energy supplied during period of relatively low system demands.

Energy, On-Peak, Electricity- Energy supplied during periods of relatively high system demands.

Head – The effective head is the upper elevation of a hydro site minus the lower elevation and yield the H or effective head of a site, this is expressed in meters (m).

Load- The amount of electric power or energy delivered or required at any specified point or points on a system. Load originates primarily at the energy consuming equipment of the customers.

Load Curve- A curve of power versus time sowing the value of a specific load for each unit of the period covered.

Loss of Load Probability (LOLP)- A measure of the probability that a system demand will exceed capacity during a given period, often expressed as the expected number of days per year over a long period, frequently taken as 10 consecutive years. An example of LOLP is one day in 10 years.

Pumped Storage- An arrangement whereby a reservoir is filled with water by pumping during off-pear periods when low cost energy is available or when water is being spilled at other hydro plants. This method of operating hydro plants stores water which can be used to meet peak loads.

Pumped Storage Plant (PHES)- A hydroelectric power plant, which generates electric energy on demand. Many times these plants function for peak-load use by utilizing water pumped into a storage reservoir during off-peak periods.

Renewable Penetration Percent, Penetration %- Total capacity of renewable generation/ Total system Capacity.

Spinning Reserve- Generating units operation at a no load or at partial load with excess capacity readily available to support additional load.