Wind Integrated Compressed Air Energy Storage In Colorado

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I. Introduction and Motivation

The past few years have seen a rapid increase in the development of electricity generation from renewable resources, due to many factors including concerns over climate change and the passage of Renewable Portfolio Standards (RPS) in 25 states in the United States. Colorado passed an RPS in 2004 requiring 10% of electricity to come from renewable resources, with 4% coming from solar generation, by 2015. That standard will likely be met within the next year (seven years early), and in 2007 the target was increased to 20% by 2020. While wind development began in Colorado long before the 2004 RPS, this new law has rapidly increased the rate of development of wind generated electricity. Currently there are 366 MW of wind turbines online, with another 700 MW of wind turbines in the construction phase [1]. Solar development is increasing rapidly as well, with an 8 MW plant under development and a rebate program to encourage customers to install solar panels on their homes.

With the development of all of this new wind and solar generation, the intermittency issues that this type of electricity generation brings about must be addressed. As penetration levels increase, finding a balance between fluctuating renewable generation and fluctuating demand becomes more difficult and more expensive to manage. Xcel Energy's Wind Integration Study for Public Service Company of Colorado [2] demonstrates this by developing models of 10% and 15% wind penetration levels on their system. The cost per kWh of wind integration on the system increases at the 15% level from the 10% penetration level, and is expected to increase at a greater rate for the 20% penetration level.

One way to mitigate the intermittency of wind generation is utility-scale energy storage. There are many types of electricity storage, including (but not limited to) conventional batteries, flywheels, ultracapacitors, superconducting magnetic energy storage, flow batteries, pumped hydroelectric energy storage (PHES), and compressed air energy storage (CAES). Of these, PHES and CAES have been demonstrated as economically feasible solutions for utility-scale energy storage on the hours-to-days timescale. PHES is a mature technology with nearly 300 locations worldwide. CAES is also a technology that has been developed and implemented, though not nearly as common as PHES. There are currently only two CAES plants in the world (with more at various stages of development). Xcel Energy owns a PHES facility in Colorado (Cabin Creek Pump Storage facility), and their integration study notes a significant increase in generation costs and wind integration costs in models that remove Cabin Creek from the system [2]. This demonstrates the positive effect a storage facility can have on a utility system.

This study investigates the case for CAES in Colorado from an economic and feasibility standpoint, with an emphasis on its impacts for wind integration. While wind integration may or may not require storage, a large energy storage facility could have a significant economic impact on the utility system, and could significantly increase the commercial value of wind-generated electricity.

II. Compressed Air Energy Storage Background

Compressed Air Energy Storage (CAES) is a proven utility-scale energy storage technology that has existed for nearly 30 years. A CAES plant in Huntorf, Germany has operated since 1978, and a plant in McIntosh, Alabama has been in operation since 1991. CAES stores energy by using off-peak electricity to power a motor, which drives a compressor that compresses air into an underground reservoir. Energy is recaptured by expanding the compressed air through a high pressure air turbine (not a gas turbine), then mixing the exhaust from the high pressure turbine with natural gas, and finally firing the mixture in a low pressure natural gas turbine. Waste heat from the exit of the low pressure turbine is passed through a heat exchanger as the air comes out of the reservoir to preheat the compressed air and improve efficiency. The high pressure air turbine reduces technical risk by dropping the pressure of the air before mixing it with fuel, and without it the pressure in the cavern would have to be reduced to allow the low pressure gas turbine to operate reliably [3].

Since natural gas is required, CAES is considered a hybrid storage/generation system, but the natural gas input is much lower than with a conventional gas turbine. CAES requires approximately 0.7-0.8 kWh off-peak electricity and 4100-4500 Btu natural gas to produce one kWh of dispatchable electricity [3,4]. This compares with a heat rate of roughly 11,000 Btu/kWh for conventional natural gas turbines.

Efficiency calculations for CAES are not a simple round-trip (energy out divided by energy in) calculation, because of the addition of natural gas to the process. Round trip efficiency could be calculated in two different ways, and in this example the midpoints of these ranges of electricity and natural gas input (0.75 kWh and 4300 Btu) are used. The first method is to assume that all energy inputs (electricity and natural gas) are the same. Under that assumption, 1 kWh of electricity requires 0.75 kWh of off-peak electricity plus 4300 Btu (1.26 kWh) of natural gas, or 2.01 kWh. This gives a total efficiency of 50%. This is a scientifically accurate way to calculate efficiency, however, counting the chemical potential energy of natural gas equally to electrical energy is a bit unfair, because natural gas (or any energy source used to produce electricity from a thermal cycle) will always have a very low (20-40%) conversion efficiency.

Another way to calculate the round trip efficiency of CAES is to assume that the natural gas would otherwise be used to produce electricity, and then determine how much electricity that natural gas would produce. This allows for comparison of electrical energy to electrical energy, which is more of an “apples to apples” comparison. Using the above heat rate of 11,000 Btu/kWh, the gas turbine would produce 0.39 kWh of electricity. Adding that to the 0.75 kWh of off-peak electricity, a theoretical total electricity input of 1.14 kWh is required to produce 1 kWh of dispatchable electricity. This yields an efficiency of 88%.

As stated above, CAES and PHES are currently the only two options for utility-scale quantities of power for hours to days, the time period needed for mitigation of intermittent renewable generation. In comparing the two, there are positives and negatives for each. In comparison to PHES, CAES has a lower capital cost, a smaller visible footprint, and CAES does not impact water rights in the way that PHES does. Additionally, finding a location to build a CAES plant is much easier, as PHES requires a location where two reservoirs can be built in close proximity with significant elevation difference. On the other hand, PHES has higher round trip efficiency and is truly a storage system as it does not require external inputs to recapture the electricity. PHES also has a lower operating cost due to the natural gas input required for CAES. It is not fair to say that one of these technologies is better than the other. Any choice between the two technologies would be based on factors including the specifics of the location, the needs of the utility system, and the legal aspects of the project.

III. Site Analysis

A CAES site has two requirements: it must be a location suitable to operate a gas turbine and it must have a reservoir for compressed air storage. The first requirement is generally available in most places, though the requirement for a gas line may increase the project cost if an adequate gas line is not already installed, and the environmental and noise considerations may pose problems in locating the turbine. The second consideration (locating a reservoir) poses a more difficult challenge, though there are many potential reservoir locations available. CAES reservoirs can be located in various geological formations, including salt domes, aquifers, and hard rock mines [5].

Solution-mined salt caverns have been used in the two CAES facilities that are currently operating. Salt caverns may be the easiest and most cost effective cavern option, because solution mining is relatively inexpensive and seals the cavern quite well. Another option is using an aquifer as the air storage reservoir. The Iowa Stored Energy Project [6] is a CAES facility currently under development in Iowa. This project uses an aquifer for compressed air storage. Additional study has been completed on using aquifers and depleted oil and gas wells for CAES reservoirs in Wyoming [7]. A third option for a CAES reservoir is a hard rock mine. While it would be possible to excavate a mine for this purpose, it is more likely that an abandoned mine would be used, due to the cost of excavating a new mine. A project has been under development in Norton, Ohio for a large CAES plant that would use an abandoned limestone mine as the storage reservoir [8]. While development on this project has not moved forward recently, much study has been completed on the mine and issues with sealing the mine for CAES pressures.

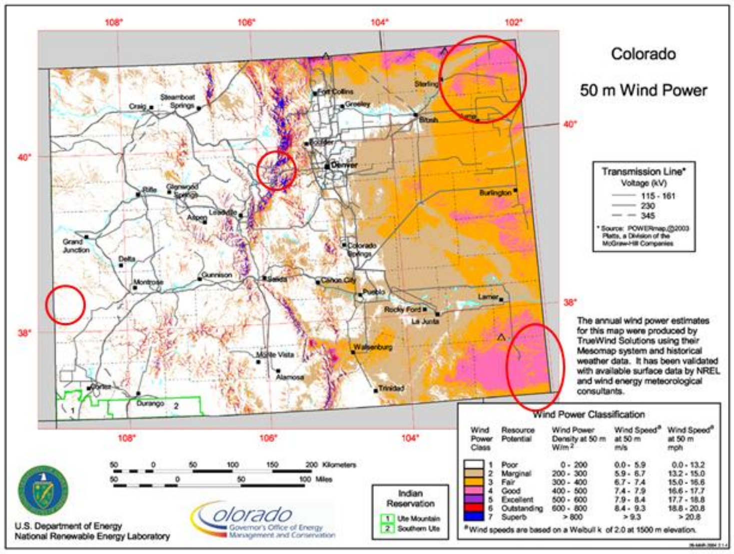

Figure 1: CAES site possibilities in Colorado [9]

In Colorado, all of these geological features exist. Salt domes are located in the western portion of the state, including a very large salt dome in the Paradox Basin [10]. Aquifers exist throughout the state, and could be an excellent resource for CAES, especially if a close proximity to Denver is desired. Abandoned hard rock mines are also abundant throughout the state. Figure 1 shows NREL's wind resource map for the state, with a few potential locations for CAES marked with circles. Salt domes in the Paradox Basin are marked, along with potential areas for salt exploration in the northeast and southeast portions of the state. The wind resource map is used to emphasize the point that storage may be most effective if located near the wind generation, as this would maximize the utilization of transmission lines. This increased utilization of transmission lines for wind generation could make a significant difference in the economics of wind generated electricity.

The location marked near the center of the state is the location of a wind generation project under development near Georgetown, Colorado. Clear Creek Power, LLC, is developing a wind turbine site in the mountains above the town. The site is on the north-south ridge just east of Georgetown, and sits at approximately 11,000 feet above sea level, with transmission lines nearby. There is an abandoned gold and silver mine sitting directly beneath the wind site, and the mine is owned by the wind developer. The mine is fairly large, with the main chamber having a volume of roughly 3.5 million cubic feet. This combination of factors (wind site, mine, and transmission lines), along with Clear Creek Power's interest in storing their wind power and selling it at peak rates, makes this an ideal site to study a potential integrated wind/CAES power plant using a hard rock mine as the storage reservoir. However, the heavily fractured nature of the rock in this area may make this mine unsuitable for holding air at pressures required for CAES. Significant geological study of the mine will be required, and pumping the mine full of air for an extended period may be the only way to determine the feasibility of using this mine as a CAES reservoir.

IV. CAES Modeling

In this report, two economic models are developed to examine the profitability of wind integrated CAES in Colorado. The first model is based on the Clear Creek Power site near Georgetown. In this scenario one wind site and one co-located CAES facility are modeled. The second model examines five wind sites on the eastern plains integrated with one large CAES facility, which should show a more system-wide view and also demonstrate the effect of spatial diversity on wind/CAES integration.

The underlying concept of these models is to determine the value of CAES to the utility system and the potential profitability of developing a CAES facility. The models are designed to develop an operational scenario for the integrated wind/CAES power plant that provides maximum profit. The main assumption is that if wind energy is not dispatchable, it will be sold for a flat rate, no matter what time of day it is. This flat rate is the type of power purchase agreement that many wind energy providers have, so it is a reasonable assumption. On the other hand, the wind/CAES plant is dispatchable (meaning that it can provide electricity on demand, with a short startup time), so the provider will receive market rate for that electricity, operating as a merchant plant. Given this, the models determine the times and prices that energy should be sold and the times and prices that energy should be stored in order to maximize profit.

One important assumption needed for modeling is an approximation of the cost of CAES. CAES has a fairly low capital cost compared to other energy storage technologies. The capital cost of CAES is similar to, but slightly more expensive than a conventional natural gas turbine. A gas turbine has the lowest capital cost of any electrical generator, often quoted in the $400 to $500/kW range [3,11]. A CAES turbine is essentially a natural gas turbine with the front-end compression part separated, operating with an electric air compressor. The equipment may be more expensive due to economies of scale, and the cost of the reservoir must be included, but most estimates for the capital cost of CAES are in the $600 to $700/kW range [3,11].

The first model, based on Clear Creek Power's Georgetown location, has one wind site and one co-located storage facility. The model assumes 55 MW of wind generation, a 50 MW maximum size for the CAES turbine, and 525 MWh of storage space in the mine. These parameters are based on the size of CCP's project and the size of the mine beneath their site. These and other parameters for the model are shown in table 1.

Table 1: Single wind site model parameters

Installed capacity of wind turbines	55 MW
Maximum capacity of storage reservoir	525 MWh
CAES energy out / energy in ratio	1.25
CAES natural gas heat rate	4300 Btu/kWh
Natural gas cost	$6.00/MMBtu
CO_2 production	0.000117 lbs/Btu natural gas

The model also requires an assumption for the daily variation in energy costs for a peaking merchant plant. While cost data is very difficult to pin down, and changes rapidly, an assumption is made. The data in table 2 is used in the model to show a general trend in price fluctuation. In the original model, this data included a random statistical variation, but the results of modeling with that variation were virtually identical to the version that did not include this variation, so the random variation was not used. Note that the flat rate at which non-dispatchable wind would be sold is also included in the cost data.

Table 2: Cost data for CAES models

Wind/CAES dispatchable merchant rates			
12:00 AM	$0.037	12:00 PM	$0.086
1:00	$0.034	1:00	$0.088
2:00	$0.033	2:00	$0.103
3:00	$0.032	3:00	$0.106
4:00	$0.043	4:00	$0.109
5:00	$0.043	5:00	$0.105
6:00	$0.054	6:00	$0.104
7:00	$0.061	7:00	$0.092
8:00	$0.068	8:00	$0.083
9:00	$0.071	9:00	$0.083
10:00	$0.077	10:00	$0.072
11:00	$0.082	11:00	$0.062
Wind flat rate			
All times		$0.035	

The inputs to the model include a year of wind data (obtained from Clear Creek Power), the cost data in table 2, and the parameters shown in table 1. Crystal Ball and OptQuest [12] are used for the optimization. Two parameters are optimized: the maximum price at which wind generated electricity will be stored, and the minimum price at which electricity will be sold from the storage reservoir. Note that if storage were 100% efficient, these numbers would be identical, but the inefficiencies of storage give a middle range where it is most profitable to sell whatever is generated, but not sell from the storage. The outputs of the model include the revenue generated from the wind/CAES system and a comparison to the revenue that would be generated from selling wind energy at the flat wind rate.

Results of this model are shown in table 3. The annual net revenue increase from selling dispatchable energy at merchant rates (over selling wind energy at the flat wind rate) is $6.85 million. Using the $700/kW installed cost of CAES, the capital cost is calculated at $35 million, giving a simple payback period (without interest) of 5.1 years.

Table 3: Single wind site model results

Maximum price to store electricity	$0.0823
Minimum price to sell from storage	$0.0880
CAES turbine size	50 MW
Annual wind/CAES revenue	$11,827,000
Annual wind only revenue	$4,977,000
Annual CAES value added	$6,850,000
CAES capital cost ($700/kW)	$35,000,000
Annual revenue / capital cost	0.1957
Simple payback period	~5.1 years

The second model looks at five separate wind sites integrated with one large CAES facility. The five wind sites are all on the eastern plains of Colorado, where nearly all of the wind development is happening in Colorado. The two main areas for wind development are the northeast portion of the state and the southeast portion of the state. Two sites are chosen for the model in each of these locations, and a fifth site is added in east-central Colorado, as there is a strong wind resource there as well. The wind sites chosen for the model are shown in figure 2, overlaid on the wind resource map to show the general wind characteristics for the state.

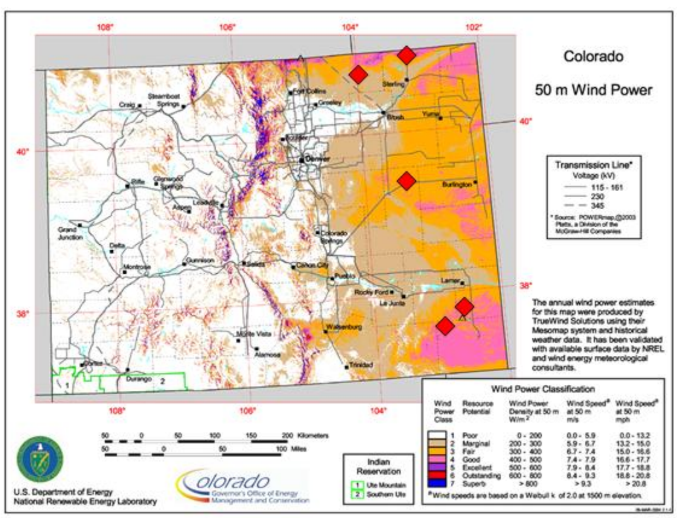

Figure 2: Location of wind sites for five-site model (locations marked with diamonds) [9]

This model uses five sets of time-correlated wind data obtained from the University of North Dakota Energy and Environmental Resource Center's wind database [13]. The model assumes 200 MW of wind turbines installed at each wind site, for a total of 1000 MW installed capacity. To compliment this, a 1000 MW CAES facility with 10,000 MWh of energy capacity was modeled. The location is assumed to be on the eastern plains in order to maximize transmission utilization, but a specific site was not selected. The remaining model parameters are shown in table 4.

Table 4: Five wind site model parameters

Installed capacity of wind turbines	1000 MW
Maximum capacity of storage reservoir	10,000 MWh
CAES energy out / energy in ratio	1.25
CAES natural gas heat rate	4300 Btu/kWh
Natural gas cost	$6.00/MMBtu
CO_2 production	0.000117 lbs/Btu natural gas

This model is developed in the same way as the single site model. Results are shown in table 5. The results are similar to the single site model, but the simple payback period is slightly shorter. This is not surprising, as spatial diversity should require the CAES facility to operate less frequently, which improves the efficiency of the overall system and reduces the amount of natural gas used.

Table 5: Five wind site model results

Maximum price to store electricity	$0.0831
Minimum price to sell from storage	$0.0906
CAES turbine size	1000 MW
Annual wind/CAES revenue	$260,360,000
Annual wind only revenue	$108,040,000
Annual CAES value added	$152,320,000
CAES capital cost ($700/kW)	$700,000,000
Annual revenue / capital cost	0.2176
Simple payback period	~4.6 years

V. Conclusions

The models show that CAES can be a financially viable method to deal with intermittency in renewable energy generation. While storage is not the only means to deal with intermittency issues, storage has the potential to increase the value of wind and solar energy. As Colorado approaches meeting the 20% RPS, wind integration costs will rise. A single large CAES facility in Colorado would significantly reduce these integration costs, and would be an important step in keeping the cost of renewable energy generation in line.

VI. References

[1] American Wind Energy Association. 2007. http://www.awea.org/projects/colorado.html
[2] EnerNex Corporation. Wind Integration Study for the Public Service Company of Colorado. May 2006.
[3] Ridge Energy Storage & Grid Services L.P. 2005. The Economic Impact of CAES on Wind in Texas, Oklahoma, and New Mexico.
[4] Denholm, P. 2006. Improving the Technical, Environmental, and Social Performance of Wind Energy Systems Using Biomass-Based Energy Storage. Science Direct Renewable Energy 31 (2006) 1355-1370.
[5] Cohn, A. et al. 1991. Applications of air saturation to integrated coal gasification/CAES power plants. ASME 91-JPGC-GT-2.
[6] Iowa Stored Energy Park. 2007. http://www.isepa.com/.
[7] Neumiller, J. 2006. Reservoir Simulation of Combined Wind Energy and Compressed Air Energy Storage in Different Geologic Settings. Master's Thesis, Colorado School of Mines.
[8] CAES Development Company, LLC. 2001. http://www.caes.net/nortpres.html.
[9] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. http://www.eere.energy.gov/windandhydro/windpoweringamerica/wind_maps.asp.
[10] Bureau of Reclamation. http://www.usbr.gov/dataweb/html/paradox.html.
[11] EPRI and U.S. Department of Energy. 2003. EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications. 1001834.
[12] Decisioneering, Inc. 2007. http://www.crystalball.com/.
[13] University of North Dakota Energy and Environmental Resource Center. http://www.undeerc.org/wind/winddb/COwindsites.asp