Proceedings of ASME 2011 5th International Conference on Energy Sustainability & 9th Fuel Cell Science, Engineering and Technology Conference
ESFuelCell2011
August 7-10, 2011, Washington, DC, USA

ESFuelCell2011-54665

ENHANCING THE ECONOMICS OF WIND-BASED COMPRESSED AIR ENERGY STORAGE BY WASTE HEAT RECOVERY

Hossein Safaei Mohamadabadi
Department of Mechanical and Manufacturing Engineering, University of Calgary
Calgary, Alberta, Canada

Ronald J. Hugo
Department of Mechanical and Manufacturing Engineering, University of Calgary
Calgary, Alberta, Canada

David W. Keith
Canada Research Chair in Energy and the Environment, University of Calgary
Calgary, Alberta, Canada

ABSTRACT

Large scale penetration of the renewable energy sources such as wind and solar into the electric grid is complicated by their substantial hourly, daily, and seasonal fluctuations. Energy storage systems can mitigate these fluctuations by storing excess off-peak energy for use at peak-demand times. Compressed Air Energy Storage (CAES) is one of the most promising storage technologies due to the large amount of energy that can be stored at an economical cost. Although conventional CAES systems are operational, they do suffer from low overall efficiency due to the significant amount of energy lost during the air-compression process in the form of waste heat. The Adiabatic CAES design has been introduced to improve the economics of the conventional CAES systems by storing the heat of compression to heat the compressed air prior to the expansion process and electricity generation. However, this design is challenged by the technical complexity of the heat storage system due to the higher pressures and temperatures of the compressed air. We have analyzed the feasibility of improving the economics of a conventional CAES plant by strategically siting the plant to sell the heat of compression as a by-product. We have modeled a system composed of a variable electric and heat load, wind farm, CAES plant, and heat recovery system in Alberta, Canada at an hourly resolution and evaluated the economic gains of selling waste heat. The size of each component was optimized to minimize the cost of electricity generation and maximize revenues from heat sale. Furthermore, a sensitivity analysis on the price of natural gas, carbon tax, and geological constrains for underground storage of compressed air was performed.

INTRODUCTION

Among various energy storage technologies developed in the past few decades, Compressed Air Energy Storage (CAES) has been of special interest for large scale storage of wind energy. CAES systems are usually considered for storage requirements of 10s of MW of electric power and hours of discharge time [1]. Currently, two commercial CAES facilities are in operation and demonstrate the viability of this technology. The first facility located in Huntorf, Germany stores up to 310,000 m^3 of compressed air at a pressure range of 48-66 bar in two salt caverns and can produce 290 MW of electricity at full capacity for four hours. McIntosh plant, the second commercial CAES facility located in Alabama, generates 110 MW of electricity at full capacity for 26 hours. It stores up to 560,000 m^3 of compressed air at a pressure range of 45-74 bar in a salt cavern [2-3].

CAES uses inexpensive off-peak electricity to compress air into either underground or aboveground storage facilities. During peak hours of electricity demand, compressed air is heated (to prevent it from freezing during expansion) and expanded in modified gas turbines to generate electricity. As an example, the McIntosh plant uses 0.67 KWh of off-peak electricity and 4,220 KJ (LHV) of natural gas per KWh of peak electricity that it generates [4]. The necessity of burning fuels prior and/or during the expansion process limits the round trip efficiency of energy storage via CAES. Newer generations of

CAES systems have been proposed in the past few years to improve its efficiency. The "Adiabatic CAES" concept was originally introduced in 1980s which focuses on storing the otherwise wasted heat of compression in a heat storage facility. This heat source is then utilized to heat the compressed air prior to expansion and reduce, even eliminate the need for burning fuel during the expansion process. However, storing enough heat at high pressures and temperatures introduces technical difficulties with the design of the turbo machineries and the heat storage [5]. Isothermal CAES is another design in the R&D phase which focuses on improving the efficiency of CAES by close-to-isothermal compression and expansion processes [6-7]. Coupling conventional CAES facilities with simple cycle gas turbine plants in various configurations for enhanced heat recovery has also been proposed to improve the storage efficiency of CAES facilities [8-9]. Nevertheless, all these designs are still in the R&D phase and no commercial plant based on these designs exists.

This paper introduces and evaluates a novel idea to improve the efficiency of conventional CAES systems by using distributed air-compression stations within municipal regions, which is called Distributed CAES (D-CAES). A municipal-scale integrated compressed air pipeline network, supplied by distributed compressors located near high heat-load facilities (e.g. universities), uses off-peak electricity to compress air. This system would utilize or store the heat produced by air-compression for heating needs, and would lower the overall cost of the D-CAES system by negating the demand for heating fuel usage within these municipal regions. The compressed air from this system would be pipelined to favorable geological locations for underground storage. The expander of the D-CAES system located at the storage site would generate electricity via combustion and expansion of stored compressed air, similar to conventional CAES designs.

This novel idea focuses on improving the economics of CAES by the use of otherwise wasted heat of compression for space and water heating demands. Waste heat recovery from industrial compressors is a well mature technology and therefore introduces less technical complexity compared to the adiabatic and isothermal CAES designs. However, this design requires a pipeline between the compression site (municipal regions) and the storage site (e.g. cavern). The tradeoff between the increased capital cost (CapEx) of the system (due to the pipeline) and savings on fuel (used for heating purposes) can make the D-CAES system cheaper compared to the conventional CAES in certain situations. The intensity and the profile of the heat load, profile of the electric load, wind conditions, distance between the heat load and storage facility, and the construction costs are the major players in this tradeoff.

NOMENCLATURE

Symbol	Description	Unit
$CapEx_{Cavern}$	Annual capital cost of cavern	\$/MWh/Year
$CapEx_{Comp}$	Annual capital cost of compressor	\$/MW/Year
$CapEx_{Exp}$	Annual capital cost of expander	\$/MW/Year
$CapEx_{Furn}$	Annual capital cost of furnace	\$/MW thermal/Year
$CapEx_{HRU}$	Annual capital cost of HRU	\$/MW thermal/Year
$CapEx_{Pipe}$	Annual capital cost of air pipeline	\$/mm Diameter/Year
$CapEx_{Wind}$	Annual capital cost of wind farm	\$/MW/Year
CC	Carbon content of fuel	T Ceq/GJ
CCR	Capital Charge ratio	%
C_{tax}	Carbon tax	\$/t Ceq
D	Inside pipe diameter	mm
$Elec_{Exp}^{h}$	Electricity generated by expander at hour h	MWh
f	Friction factor	Dimensionless
G	Specific gravity of gas	Dimensionless
H	Number of hours simulated	hour
$Heat_{Furn}^{h}$	Heat generated by the furnace of DH	MWh
HR_{Exp}	Heat rate of expander	MJ(LHV)/MWh out
L	Length of pipeline	Km
P_1	Upstream pressure	KPa
P_2	Downstream pressure	KPa
P_b	Base pressure	KPa
P_{eff}	Effective natural gas price	\$/GJ
P_{market}	Market price of natural gas	\$/GJ
$Size_{Cavern}$	Optimal size of cavern	MWh
$Size_{Comp}$	Optimal size of compressor	MW
$Size_{Exp}$	Optimal size of expander	MW

$Size_{Furn}$	Optimal size of furnace	MW thermal
$Size_{HRU}$	Optimal size of HRU	MW thermal
$Size_{Pipe}$	Optimal diameter of air pipeline	mm
$Size_{Wind}$	Optimal size of wind farm	MW
T_b	Base temperature	K
T_f	Average temperature of gas	K
Z	Compressibility factor of gas	Dimensionless
η_{Furn}	Thermal efficiency of the furnace of DH	%

METHODOLOGY

A hypothetical scenario was developed in which a variable but concentrated heat load and a variable electric load were to be satisfied over a period of one full year. The heat load would be supplied via a District Heating (DH) facility while the electric load would be supplied by a combination of a wind farm and a compressed air energy storage facility in two different configurations; conventional CAES and D-CAES. The excess wind would be the only energy source used to charge the energy storage facility in both scenarios. The associated costs with the transmission line and the DH network were excluded since they both would exist in the two scenarios. These scenarios assumed that a compressed air storage facility was already justified by the market and either a conventional CAES or a D-CAES facility would be built.

CAES system: The electric load would be satisfied by a combination of wind energy and conventional CAES. Both the compressor and the expander of the CAES facility would be located at the storage site. A natural gas-based boiler would provide the heating energy of the DH facility located close to the heat load (within the city).

D-CAES system: The compression facility of the D-CAES system would be located within the municipal region while the expander would be located at the storage site. The compressed air would be pipelined from the compression site to the storage site. A waste Heat Recovery Unit (HRU) would recover the otherwise wasted heat of compression. The heat load would be satisfied by a combination of a natural gas-based boiler and the HRU via a DH network. No heat storage facility was considered in this phase meaning that the heat of compression would be dumped to the surrounding if not immediately utilized for heating purposes.

A linear optimization code was developed in MATLAB to minimize the levelized cost (both capital and operating) associated with meeting the hourly electric and heat loads over one full year. Both the size of various components and the dispatch strategy of the wind farm, CAES, D-CAES, and DH facilities were optimized in order to minimize the levelized cost of meeting the hourly electricity and heat loads.

The objective function of the optimization is shown in Eq.1 which is to be minimized. This equation shows the total levelized cost (both capital and operating) to satisfy the annual electric and heat loads. The terms in the first set of curly brackets show the summation of the hourly cost of fuel which would be consumed by the combustor of the expander (to meet electric load) and by the furnace of DH system (to meet heat load). All other operating and maintenance costs were considered negligible. The second set of curly brackets include the levelized capital cost of all components of the system required to meet the hourly electric and heat loads in the CAES and D-CAES systems over the one full year of investigation. The capital cost of the DH network was ignored since it would exist in both CAES and D-CAES configurations.

$$\left\{\sum_{h=1}^{H} P_{eff} \times 10^{-3} \times \left(HR_{Exp} \times Elec_{Exp}^{h} + \frac{Heat_{Furn}^{h}}{\eta_{Furn}}\right)\right\} + \{CCR \times (CapEx_{Exp} \times Size_{Exp} + CapEx_{Wind} \times Size_{Wind} + CapEx_{Comp} \times Size_{Comp} + CapEx_{Cav} \times Size_{Cav} + CapEx_{Furn} \times Size_{Furn} + CapEx_{HRU} \times Size_{HRU} + CapEx_{Pipe} \times Size_{Pipe})\} \qquad \text{Eq. 1}$$

Heat Load: EE4[1] software was used the simulate hourly heating loads of a 20 floor tower (40x40 m plan) in Alberta over one full year [10]. Once the heat load profile was determined; it was scaled up to result in the same annual heat load as the main campus of the University of Calgary, Alberta in 2008. This profile was used to represent a concentrated municipal heat load that the DH system was to satisfy.

Electric Load: The minimum hourly electric load of the province of Alberta in 2008 was used to determine the hourly peak load profile of electricity over the year of study [11]. Then this profile was scaled down 10^5 times to form the "peak electric load" profile. This electric load profile was later used to develop various electric load scenarios.

Wind Power Capacity Factor: Hourly wind power generation data from Alberta in 2008 was used to calculate the

[1] EE4 is a computer software developed by Natural Resources Canada to simulate energy use of buildings characterized by the user.

hourly capacity factor of the wind farm over the entire year of the study [11].

Pipeline: Pressure drop in gas pipelines can be calculated from Eq. 2 [12].

$$Q = 1.1494 \times 10^{-3} \times \left(\frac{Tb}{Pb}\right) \times D^{2.5} \times \sqrt{\frac{(P_1{}^2 - P_2{}^2)}{G \times T_f \times L \times Z \times f}} \quad \text{Eq. 2}$$

The maximum allowable pressure drop along the compressed air pipeline was assumed 25 KPa/Km [13]. Then Eq. 2 was used to determine the smallest diameter of the air pipeline which satisfied the allowable pressure drop at each operating condition.

CAES and D-CAES: Table 1 shows the performance characteristics used for the conventional CAES configuration based on the McIntosh CAES plant. The D-CAES plant had the same minimum and maximum storage pressures; however, the discharge pressure of the compressor and the work ratio were modified for each operating condition based on the anticipated pressure drop along the compressed air pipeline. The thermal efficiency of HRU is defined as the ratio of the net heat provided to the heat consumers of the DH network per unit of electric energy consumed by the compressor to charge the cavern.

Economic analysis: Table 2 shows the capital cost values used for various component of the system. All costs were converted to 2008 USD according to the Chemical Engineering Plant Cost Index [14] and all operating and maintenance costs except the fuel charges were considered negligible.

Table 1: Performance characteristics of various components of the CAES and D-CAES systems

Parameter	Value	Unit	Reference
CAES, heat rate	4,200	MJ (LHV)/ MWh out	[4]
CAES, work ratio	0.67	MWh in/ MWh out	[4]
Min storage pressure	45	atm	[4]
Max storage pressure	74	atm	[4]
CAES and D-CAES, air consumption	5	Kg air/ KWh out	[4]
Boiler, thermal efficiency	80%	MJ thermal/ MJ LHV	
HRU, thermal efficiency	70%	MWh thermal/ MWh work	

Table 2: Economic parameters of the optimization

Parameter	Base value	Unit	Reference
Wind farm, capital cost	1,837	$/KW	[15]
Expander, capital cost	569	$/KW	[4, 16]
Compressor, capital cost	522	$/KW	[4, 16]
CAES storage, capital cost	1.5	$/KWh	[16]
Boiler, capital cost	418	$/KW thermal	[17]
HRU, capital cost[2]	0	$/KW thermal	
Capital charge rate	10	%	
Pipeline capital cost (*L*=30 km)	$984.05 \times D - 31{,}141$	$/Km	[18]
Pipeline capital cost (*L*= 50 km)	$824.34 \times D - 28{,}303$	$/Km	[18]

The same heat load profile was used in all scenarios to simulate a large scale, concentrated municipal heat load. However, various electric load profiles were considered by linearly scaling up the "peak electric load" profile. Since an hourly heat and electric load is to be supplied over one full year, the ratio and relative shape of these two profiles play an important role in the optimum size of the system. By keeping the heat load fixed at a reasonable size, the effect of the size of the electric load was studied in various scenarios. Moreover, a distance of 50 Km between the compression and storage sites for the D-CAES system was considered in the base case. The simulation repeated for a reduced distance of 30 Km to investigate the effect of distance on the optimal size of the system. The minimum effective natural gas price above which D-CAES became economic over conventional CAES was determined by running the simulation for various electric load profiles and pipeline lengths. Table 3 shows a list of various scenarios considered.

The effective fuel price was considered as the summation of the market price of the fuel and the associated carbon taxes and was calculated based on Eq. 3. The effective fuel price concept incorporates both the fluctuations in the market price of fuel and the associated carbon taxes due to the Greenhouse Gases (GHG) emissions from the combustion of the fuel. In other words, this price combines both the market price of the fuel and the associated carbon taxes.

$$P_{eff} = P_{market} + C_{tax} \times CC \quad \text{Eq. 3}$$

[2] No additional cost for HRU is considered since intercoolers and after-coolers already exist in compressors.

Table 3: Scenarios considered in the optimization of D-CAES and CAES configurations

Case	Electric load ratio	Peak electric load	Peak heat load	Pipeline length	D-CAES work ratio
	NA	MW electric	MW thermal	Km	KWh,in/ KWh,out
1	1	34	61	50	0.70
2	1.5	51	61	50	0.70
3	2	68	61	50	0.70
4	2.5	85	61	50	0.70
5	3	102	61	50	0.70
6	4	136	61	50	0.70
7	5	170	61	50	0.70
8	6	204	61	50	0.70
9	2	68	61	30	0.69
10	2.5	85	61	30	0.69
11	3	102	61	30	0.69
12	4	136	61	30	0.69

RESULTS

Effective natural gas price was increased at 0.1 $/GJ intervals to find the minimum price at which the D-CAES system resulted in a lower levelized cost compared to the CAES system in satisfying both the hourly electric and heat loads over the entire year. The electric load profile was scaled up at each scenario while the heat load kept fixed (see Table 3). Figure 1 shows the minimum effective natural gas price and the equivalent carbon tax at which D-CAES with a 50 Km pipeline was more economic compared to the conventional CAES system. The equivalent carbon tax was calculated based on a fixed market price of 5$/GJ for natural gas and a carbon intensity of 18.0 KgC eq/GJ, including the upstream GHG emissions [4].

According to Figure 1, the optimum size of the D-CAES system occurred at 2.5 times of the "peak electric load" profile (case 4) and the minimum required fuel price increased as the profile deviated from this optimum point. Table 4 and Table 5 show the capacity and performance of various components of the two systems in case 4, respectively. One should note that the D-CAES system had a slightly larger wind farm (96.0 MW) and cavern (242.3 hours of storage) compared to the conventional CAES configuration (95.0 MW and 198.5 hours of storage, respectively). On the other hand, the D-CAES system had a smaller compressor (32.9 MW) compared to the conventional system (37.5 MW). These observations lead to interpretation that although the compressor of the D-CAES system was smaller, it had a higher capacity factor. According to Table 5, 46.7% and 53.3% of the total electric load was satisfied by the wind farm and the expander of the storage facility, respectively in the conventional CAES configuration. These figures were 41.1% and 58.9% in the D-CAES configuration, respectively. A higher capacity factor for the compressor of the D-CAES system required a larger cavern (higher capital cost). However, it negated the fuel burning for heating purposes through recovery of the heat of compression; 52.9% of the total heat load was supplied by the HRU in the D-CAES configuration. Since the energy level of the cavern at the end of the year was forced to reach its value at the beginning of the year, a higher percentage of the electricity load (58.9%) was provided by the expander in the D-CAES system compared to the conventional CAES system (53.3%).

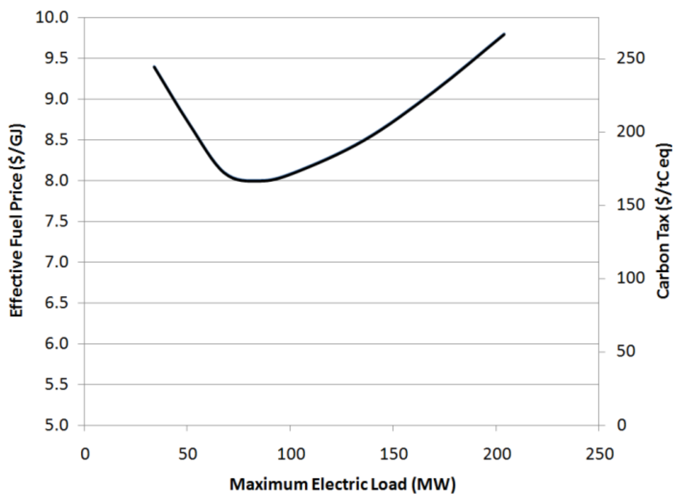

Figure 1: Minimum effective price of fuel for lower total levelized cost of D-CAES, pipeline length=50 Km and market price of natural gas=5 $/GJ

One should note that no upper limit for the size of the cavern was considered in this paper for the sake of simplicity. An upper and lower limit would be considered in the real world design based on the exact location of the project and the nature of the local electricity and heat markets.

Table 4: Capacity of various components of the conventional CAES and D-CAES systems in case 4

Component	Capacity	CAES	D-CAES
Wind farm	MW	95.0	96.0
Expander	MW	83.7	83.7
Compressor	MW	37.5	32.9
Cavern[3]	Hours	198.5	242.3
HRU	MW	0.0	23.0
Boiler	MW	61.1	52.3

[3] At full generation capacity of expander

Table 5: Performance of various components of the conventional CAES and D-CAES systems in case 4

		CAES	D-CAES
Wind Energy	Portion stored	41.5%	47.3%
	Portion sold	54.2%	47.3%
Electric load	Portion by wind	46.7%	41.1%
	Portion by expander	53.3%	58.9%
Heat load	Portion by boiler	100.0%	47.1%
	Portion by HRU	0.0%	52.9%

Figure 2 illustrates the dispatch profile of the wind farm in case 4 for conventional CAES and D-CAES systems. As shown, not only the D-CAES system had a larger wind farm, it tended to store more wind energy compared to the conventional CAES configuration. Since more wind energy was stored in the D-CAES configuration, the expander of this system regenerated more energy to satisfy the electric load as well (see Figure 3).

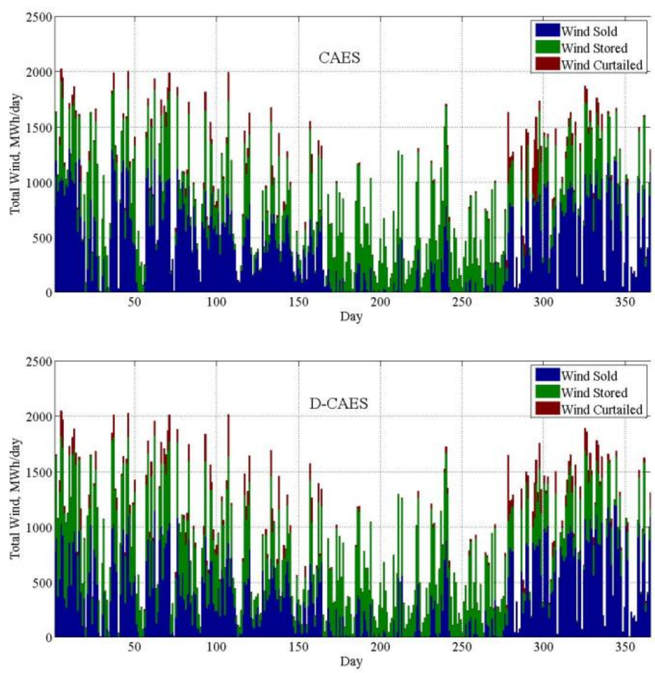

Figure 2: Utilization of wind energy in CAES (up) and D-CAES (down) configurations in case 4

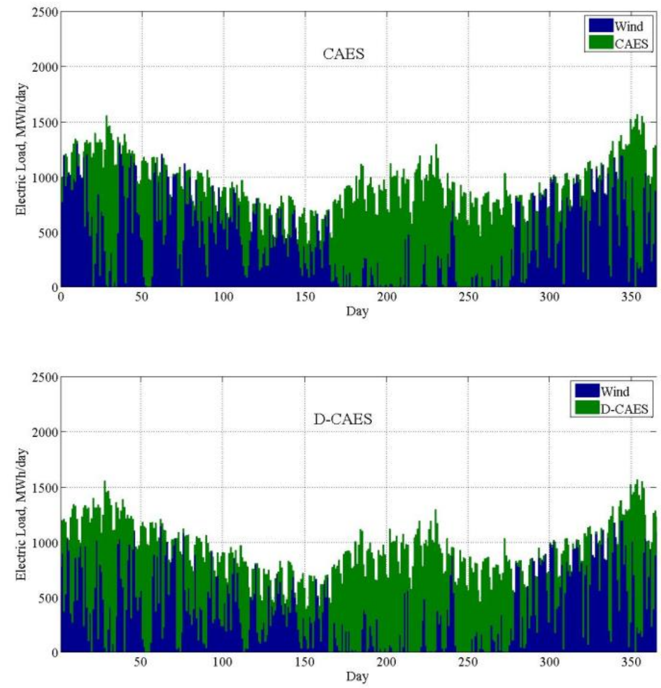

Figure 3: Share of electric load supply in CAES (up) and D-CAES (down) configurations in case 4

Table 6 shows the distribution of the levelized (both capital and fuel) cost of meeting hourly electric and heat loads over the studied one year period in case 4 for both CAES and D-CAES systems. The ratio of capital cost of the storage facility (expander, compressor, cavern, and compressed air pipeline) to the total levelized cost is 4.9% higher in the D-CAES configuration (28.0%) compared to the CAES configuration (23.1%). 4.1% of this difference is due to the existence of the compressed air pipeline in the D-CAES systems compared to the conventional CAES system. However, due to the opportunity of waste heat recovery in the D-CAES configuration, a smaller furnace would be required to meet the heat load in this system. The smaller size of furnace led to a 0.9% reduction in ratio of levelized capital cost of furnace to the total levelized cost in the D-CAES system (5.5%) compared to the CAES system (6.4%). The major financial saving of the D-CAES system is illustrated by a 4.4% (22.3% for D-CAES and 26.7% for CAES) reduction in the ratio of annual fuel cost to the total levelized cost of the system to meet the hourly electric and heat loads over the 1 year period of investigation.

Table 6: Distribution of annual levelized cost of D-CAES and CAES, % of total annual levelized cost of each system

Cost Component	CAES	D-CAES	Difference (DCAES minus CAES)
CapEx, wind farm	43.8%	44.3%	0.5%
CapEx, expander	12.0%	12.0%	0.0%
CapEx, compressor	4.9%	4.3%	-0.6%
CapEx, cavern	6.3%	7.6%	1.4%
CapEx, pipeline	0.0%	4.1%	4.1%
CapEx, storage[4]	23.1%	28.0%	4.9%
CapEx, DH furnace	6.4%	5.5%	-0.9%
Total CapEx	73.3%	77.8%	4.4%
Total fuel cost	26.7%	22.3%	-4.4%
Total annual cost	100%	100%	

In order to evaluate the effect of pipeline length on the results, similar scenarios were developed but with a shortened pipeline length of 30 Km (case 9-12) instead of 50 Km (case 1-8) (see Table 3). The optimum size of the system occurred at 2.5 times of the "peak electric load" profile (case 10), similar to the 50 Km scenario (case 4). However, the pipeline length had a significant effect on the minimum required natural gas price to make the D-CAES system more economically desirable. The minimum effective fuel price was 5.1 $/GJ at a 30 Km pipeline length, corresponding to a carbon tax of 6 $/tCeq at a base natural gas price of 5 $/GJ (Figure 4). The minimum fuel price was 8.0 $/GJ (167 $/tCeq) at a 50 Km pipeline length (Figure 1). Similar to case 4, the D-CAES system had a larger cavern (244.6 hours) as compared to the conventional CAES configuration (198.9 hours). In addition, the D-CAES system stored more wind energy as compared to the conventional CAES system to get benefit from the heat of compression for heating purposes (see Table 7 and Table 8).

Table 7: Capacity of various components of the conventional CAES and D-CAES systems in case 10

Component	Capacity	CAES	D-CAES
Wind farm	MW	93.9	93.2
Expander	MW	83.7	83.7
Compressor	MW	39.9	35.0
Cavern[5]	Hours	198.9	244.6
HRU	MW	0.0	24.5
Boiler	MW	61.1	52.5

[4] Summation of capital cost of expander, compressor, cavern, and pipeline
[5] At full generation capacity of expander

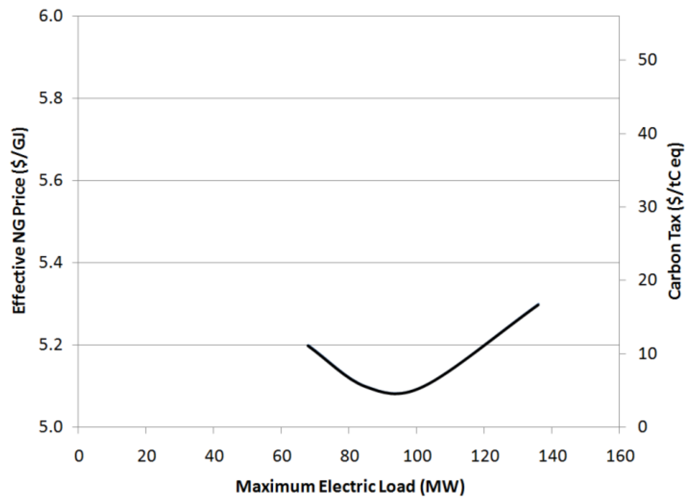

Figure 4: Minimum effective price of fuel for lower total levelized cost of D-CAES, pipeline length=30 Km and market price of natural gas=5 $/GJ

Table 8: Performance of various components of the conventional CAES and D-CAES systems in case 10

		CAES	D-CAES
Wind Energy	Portion stored	42.5%	49.5%
	Portion sold	54.0%	46.7%
Electric load	Portion by wind	46.0%	39.4%
	Portion by expander	54.0%	60.6%
Heat load	Portion by boiler	100.0%	46.6%
	Portion by HRU	0.0%	53.4%

CONCLUSION

A novel design for compressed air energy storage based on recovery of the compression heat was introduce and analyzed. This system would utilize the waste heat from the air compression for heating needs, and would lower the overall cost of the D-CAES system by negating the demand for heating fuel usage within the municipal regions. The compressed air then would be pipelined to suitable storage sites where it would be expanded during peak periods of electric load to regenerate electricity, similar to conventional CAES designs.

The optimum size of the system depends of both on the shape and magnitude of the annual heat load, electric load, and availability of off-peak electricity. A minimum effective natural gas price of 8.0 $/GJ (corresponding to a carbon tax of 167 $/tCeq) would make the D-CAES system more economically favorable as compared to conventional CAES system (at a storage distance of 50 Km). This minimum fuel price significantly reduced to 5.1 $/GJ (a carbon tax of 6 $/tCeq) at a shortened storage distance of 30 Km. The major factors in determining the minimum fuel price are the capital cost of the pipeline and the heating fuel savings through the recovery of the waste heat of the compressor.

It is of note that this study did not address the transmission requirements of the CAES and D-CAES systems. No constrains on the transmission lines between the wind farm, storage facility, and electric load were considered. In addition, the optimum configuration of storage systems highly depends on the nature of the electric market investigated and the available wind resources. This paper provided insight into the potential economic savings of the D-CAES configuration over conventional CAES using a high-level approach.

ACKNOWLEDGEMENT

The authors thank Eduard Cubi Monyanya from the Thermal Energy and Building Performance Group at the Catalonia Institute for Energy Research (IREC) for his valuable comments and help with heat load simulation in EE4 software.

REFERENCE

[1] 2009, "Technical brief: compressed air energy storage state-of-science," Electrical Power Research Institute (EPRI), Palo Alto, CA.
[2] Succar, S., and Williams, R. H., 2008, "Compressed air energy storage, theory, resources, and applications for wind power," Princeton Environmental Institute, Carbon Mitigation Initiative, Princeton University.
[3] Knoke, S., 2002, "Compressed air energy storage (CAES)" Handbook of energy storage for transmission or distribution applications, S. Eckroad, ed., The Electric Power Research Institute (EPRI), Palo Alto, CA.
[4] Greenblatt, J. B., Succar, S., Denkenberger, D. C., Williams, R. H., and Socolow, R. H., 2007, "Baseload wind energy: modeling the competition between gas turbines and compressed air energy storage for supplemental generation," Energy Policy, 35(3), pp. 1474-1492.
[5] Bullough, C., Gatzen, C., Jakiel, C., Koller, M., Nowi, A., and Zunft, S., 2004, "Advanced adiabatic compressed air energy storage for the integration of wind energy," Proc. European Wind Energy Conference (EWEC 2004).
[6] SustainX Energy Storage Solutions, 2011, "Beyond Thermodynamics," http://www.sustainx.com/.
[7] General Compression Inc, 2011, "GCAES," http://www.generalcompression.com/gcaes.html.
[8] Nakhamkin, M., Chiruvolu, M., Patel, M., Byrd, S., Schainker, R. B., and Marean, J., 2009, "Second generation of CAES technology-performance, operations, economics, renewable load management, green energy," Proc. Power-Gen International.
[9] Nakhamkin, M., 2007, "Novel compressed air energy storage concepts," Energy Storage and Power Consultants LLC, Basking Ridge, NJ.
[10] CanmetENERGY, 2011, "Software tools: EE4," http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/eng/software_tools/ee4.html.
[11] Alberta Electric System Operator (AESO), 2011, "Wind power / AIL data," http://www.aeso.ca/.
[12] Menon, S., 2005, Gas pipeline hydraulics, Taylor and Francis Group, Boca Raton, FL.
[13] Sondergard, M., 2009, "2009 Annual plan," NOVA Gas Transmission Ltd, Calgary.
[14] 2011, "Chemical engineering plant cost index (CEPCI)," Chemical Engineering, 118(1), p. 60(61).
[15] 2010, "Annual energy outlook 2010," U. S. Energy Information Administration (EIA).
[16] Schainker, R., 2008, "Compressed air energy storage system cost analysis," Electric Power Research Institute (EPRI), Palo Alto, CA.
[17] Ghafghazi, S., Sowlati, T., Sokhansanj, S., and Melin, S., 2010, "Techno-economic analysis of renewable energy source options for a district heating project," International Journal of Energy Research, 34, pp. 1109-1120.
[18] McCoy, S., 2008, "The economics of CO_2 transport by pipeline and storage in saline aquifers and oil reservoirs," PhD, Carnegie Mellon University.