Optimum Planning and Operation of Compressed Air Energy Storage with Wind Energy Integration

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Abstract—**The integration of increasingly available renewable energy sources, such as wind energy, into the power grid will have the potential to reduce dependence on fossil fuels and minimize greenhouse gas emission. However, due to the stochastic nature of renewable generation, balancing of generation and load becomes difficult. Energy storage is expected to play a major role in promoting the development of renewable energy by intermittent power source balancing, storing surplus generation, and providing electricity during high demands. One of the various emerging energy storage technologies is Compressed Air Energy Storage (CAES). In this paper, we model a wind generation-CAES system which can generate, store, and sell electricity to the grid. In addition, two optimization methodologies based on particle swarm optimization (PSO) are used to optimize the short-term operation and long-term planning of the wind generation-CAES system. The goal is to determine the optimum capacities of these resources as well as the optimum day-to-day operation strategy in order to maximize profit. The variables considered in this study include electricity market price, wind speed, gas price, etc., from a local electric utility. A number of sensitivity analyses are performed to evaluate the profitability of the wind generation-CAES system and the impact of different factors on the results.**

I. INTRODUCTION

The major technical impediment to using renewable energy systems (such as wind and solar power) is the intermittent nature of these sources and their inability to provide a continuous supply of power. Advanced storage systems can reduce the volatility of renewable deliveries from remote sites.

Indeed, energy storage is expected to play a major role in promoting the development of renewable energy, intermittent power source balancing, reducing carbon emissions, managing peak power, and reducing transmission congestion [1]. Large-scale storage technologies that can rapidly respond to variations in generation and load are vital. There are various emerging energy storage technologies, some with significant rates of maturity [2]. Energy storage technologies can be categorized as mechanical (i.e., Compressed Air Energy Storage (CAES), pumped hydro energy storage (PHES), flywheels), thermal (i.e., ice storage, molten salts, geothermal, hot water), electromechanical (i.e., batteries, fuel cells, hydrogen), and direct (i.e., capacitors, ultracapacitors, superconducting magnetic energy storage) [3]. Among these technologies, CAES, PHES, batteries, flywheels, and ultracapacitors can be used to support renewable energy integration into the grid [4].

There are currently two established large-scale energy storage technologies which have been developed and tested and can be used for wind power applications: PHES and CAES. Pumped hydro energy storage has been utilized for many years; and in the U.S., there are 40 PHES stations with a capacity of 20 GW [5]. However, in comparison, CAES has a smaller footprint, can be built in more places, has no requirement for obtaining water rights, and is cheaper [2, 6].

The first CAES power station, located in Germany, has been operational since 1978 [7]. This unit was designed to provide startup for nuclear power plants during a complete outage and to provide inexpensive peak power. The first large-scale CAES in the U.S. is located in Alabama and has been operational since 1991 [8]. This is a 110 MW plant which can provide full output power for 26 hours.

Recently, there have been a number of research studies on modeling and economic analysis of CAES [9-14]. The authors in [11], for example, provide a model for CAES considering the mass and energy balance inside the reservoir. Some of these studies include the intermittency of wind generation in their models as well [12-14]. In addition, many studies have been conducted on the efficient operation and optimization of CAES [15-17]. Lund et al. studied the optimal operation of CAES without considering renewable generation [15]. The study provided by [16] shows how the amount of energy dispatched and the profit may be improved by adding CAES to wind generation. The authors in [17] have incorporated CAES to enhance the operation of grid-integrated wind generation, considering the electricity market price.

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In this paper, we provide a co-optimization approach to determine the optimum operation and planning of a wind generation-CAES system using particle swarm optimization (PSO). In the first step, the goal is to determine the optimum operation strategy for a wind generation-CAES system in order to maximize the short-term profit; and in the second step, the goal is to calculate the optimum capacities of wind generation and CAES such that the long-term profit can be maximized. None of the previous research studies have addressed the optimization of both CAES operation and planning. The advantage of this co-optimization method is that the optimum capacities of wind generation and CAES are determined as best suited to their optimum operational scheme.

The model is developed using the MATLAB software, and different cases have been studied. In addition, different sensitivity analyses have been performed to determine the impact of power system parameters, such as electricity rates and power transmission limit, on the optimization results.

II. WIND GENERATION-CAES MODEL

The general process for operation of wind generation-CAES can be explained as follows. When the electricity price is low, the power generated from wind turbines is used by electric-motor-driven compressors in order to trap the massive volume of high pressure air into an underground geologic formation during off-peak hours. Then, when electricity demand is high or the electricity price is expensive, the precompressed air can be used to drive special combustion turbines which, in turn, drive electrical generators to generate electricity. Natural gas or other fuels are still required to run the turbines, but the process is more efficient. This method uses up to 50% less natural gas than standard electricity production [18].

Based on the description of the process provided, the model of the wind generation-CAES system has been developed and is shown in Figure 1.

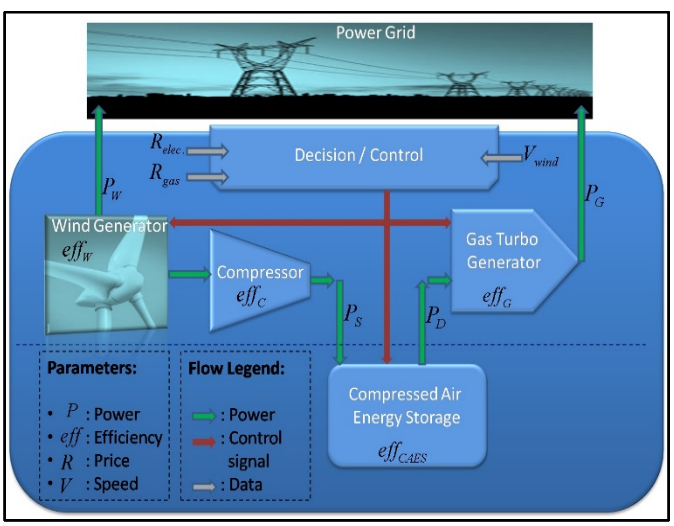

Figure 1. Model of wind generation-CAES system.

The main components of this model are a wind generator (which can also be a representative of a wind farm), compressor, CAES container, and a gas generator. The wind generation-CAES system is modeled from the perspective of a generation company which can sell the output power from its wind generators directly to the grid or can store it as compressed air to be used with a gas generator to generate electricity at a different time. The input variables of this system are wind speed, electricity rate, and gas rate, which are used at each time step by the control center to make operational decisions. The time step for this study is assumed to be one hour. A decision/control system in this model is in charge of the optimum operation of the system. Each hour, there are three decision options to choose from: 1) use the power generated to compress the air and store it in CAES; 2) sell the wind generation to the grid and keep the stored compressed air; or 3) sell electricity from both the wind generation and CAES to the grid. We denote the aforementioned decisions as *Decision 1*, *Decision 2*, and *Decision 3*, respectively.

The profit of the wind generation-CAES owner depends on the aforementioned input variables, and some system parameters, such as heat rate, energy ratio, power line capacity, wind generation, and CAES sizes, and their costs. Equation (1) is used to define this profit at each hour h.

$$\begin{aligned} Profit(h) = \big(P_W(h) + P_G(h)\big).R_{elec}(h) - C_W.P_W(h) \\ - C_C.P_S(h) - R_{gas}(h).HR.P_G(h) \\ - C_{CAES}.Cap_{CAES} - C_G.P_G(h) \end{aligned} \quad (1)$$

where $\frac{P_S(h)}{P_G(h)} = ER$; HR and ER are heat rate (amount of natural gas energy used to generate each kilowatt hour of electricity) and energy ratio (amount of electrical energy input per unit of electrical energy output), of the wind generation-CAES system, respectively. Cap_{CAES} represents the capacity of the CAES. C_C and C_G are the operation and maintenance costs of the air compressor and gas generation. In addition, the costs associated with wind generation (C_W) and CAES (C_{CAES}) are assumed to be the levelized costs per unit of wind power generation and CAES capacity, respectively.

The wind-generated power is calculated using a simple model representing a typical wind generator power curve [19].

$$P_W(\mathrm{h}) = \begin{cases} Cap_{\mathrm{W}}.\left(\dfrac{V_{wind}(\mathrm{h}) - V_{ci}}{V_r - V_{ci}}\right) & for\ \ V_{ci} \le V_{wind}(\mathrm{h}) \le V_r \\ Cap_{\mathrm{W}} & for\ \ V_r \le V_{wind}(\mathrm{h}) \le V_{co} \\ 0 & otherwise \end{cases} \quad (2)$$

where V_{ci}, V_{co}, and V_r are cut-in, cut-out, and the rated wind speed of the wind turbines; and Cap_{W} is the capacity of the wind generation .

The objective function to be maximized can be represented by (3).

$$F = \sum_{h=1}^{H} Profit(h) \quad (3)$$

subject to considering the components' capacities and a total power transfer limit $P_{sell,max}$ to the grid.

H is the total number of hours in the horizon of the study which is short-term for the operation optimization, and long-term for the planning optimization study.

III. Operation Optimization Method

The goal of this study is to determine the optimum operational decisions from the short-term predicted data. In this regard, three decision variables are defined which can determine which one of the decisions defined in the previous section is optimum at each hour. In particular, these decision variables are: low threshold rate (R_{l-th}), high threshold rate (R_{h-th}), and CAES discharge factor (f_D). The mapping between the decision variables and the decision options from which to choose are as follows:

$$\begin{cases} R_{elec} < R_{l-th} & \rightarrow \quad Decision\ 1 \\ R_{l-th} < R_{elec} < R_{h-th} & \rightarrow \quad Decision\ 2 \\ R_{elec} < R_{h-th} & \rightarrow \quad Decision\ 3 \end{cases} \qquad (4)$$

Discharge factor is a ratio by which the available stored energy in the CAES will be discharged when $Decision\ 3$ is selected, and it is variable between 0 and 1. The threshold rates defined are used to differentiate the decision options. Here, the operation optimization is intended for a duration of one day. Therefore, at the beginning of each day, the forecasted data for wind speed, electricity rates, and gas rates are acquired by the PSO program. This program searches for the optimum set of the decision variables such that the total profit suggested by (3) is maximized. The same process is repeated for the next day.

IV. Planning Optimization Method

Optimum planning requires a co-optimization of the short-term operational decisions and the long-term wind generation and CAES capacity calculation. The overall process is shown in Figure 2.

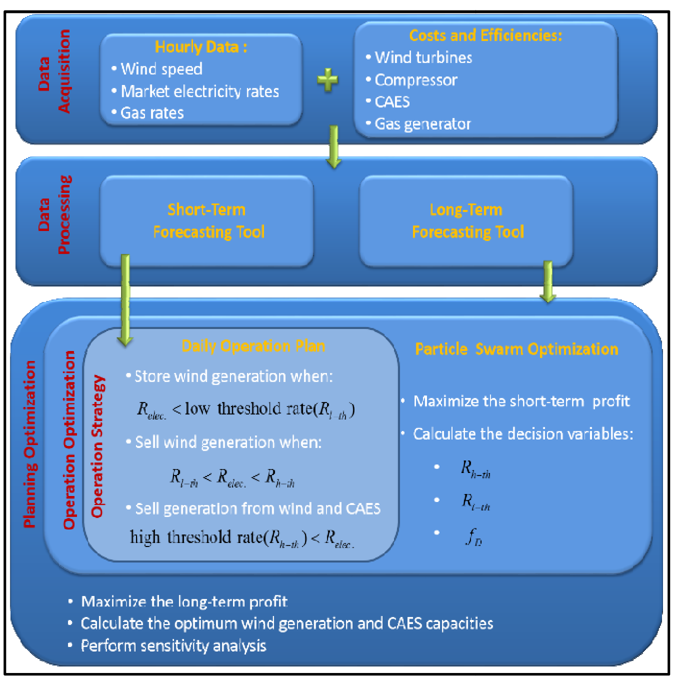

Figure 2. The process for co-optimization of wind generation-CAES operation and planning.

The first step is to obtain the hourly data and the parameters of the model components. In the second step, these data are used by short-term and long-term forecasting tools whose output will be used by operation and planning optimization programs, respectively. The third step has three layers of process. The first layer is the daily operation plan explained in Section III. The operation optimization program incorporates the daily plan to determine the daily profit and maximizes it using the PSO algorithm. On top of this layer, the planning optimization program is another PSO program which incorporates the previous layers.

In fact, the optimization program in this layer runs the following algorithm:

1- Start by populating the particles of the PSO with randomly selected wind generation and CAES capacities, within a defined range.
2- Run the wind generation-CAES model, managed by a day-to-day operation optimization strategy, for the intended duration of planning.
3- Calculate the profit for the duration of the planning using the equations provided in Section II.
4- Update the best capacities of wind generation and CAES for the particles and also update the global best solution which results in the maximum long-term profit.
5- If the maximum number of iterations or the minimum error has not been reached as yet, go to Step 2.
6- Report the global best capacities as the optimum capacities calculated.

V. Case Study

The parameters of the model used for the base case study are given in Table I.

TABLE I. List of the Parameters for the Base Case Study

Item	*Parameters*	*Value*
Wind Generation-CAES Model	ER	0.85
	HR	3800 Btu/kWh
	$P_{sell,max}$	1.5 MW
	Cap_W	1 MW
	Cap_{CAES}	2.5 MWh
	C_W	2 Cents/kWh
	C_G	0.8 Cents/kWh
	C_C	0.2 Cents/kWh
	V_{ci}	4 m/s
	V_r	10 m/s
	V_{co}	20 m/s
PSO Method	*No. of Iterations*	60
	Dimention	3 (for operation) 2 (for planning)
	Population	20

The historical hourly data for electricity and gas rates were provided by a local electric utility and are provided in the next section. This paper does not aim to propose any forecasting methods; and, therefore, it is assumed that the data obtained has been calculated using forecasting tools. Explanations of the PSO method and its parameters can be found in [20].

VI. RESULTS AND DISCUSSIONS

This section provides the results for both operation and planning optimization methods as well as the sensitivity analysis.

A. Operation Optimization Results

As discussed before, this operation strategy optimizes day-to-day operations. Here, a ten-day period has been chosen to demonstrate the results. The wind speed, electricity rates, and gas rates for this period are shown in Figures 3 and 4, respectively.

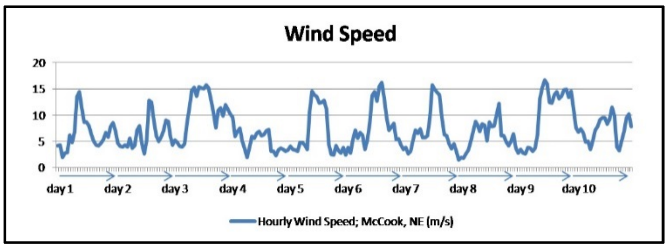

Figure 3. Ten-day wind speed data used for the operation optimization.

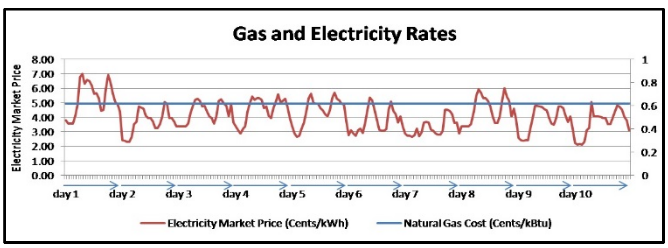

Figure 4. Ten-day gas and electricity rates used for the operation optimization.

While the wind speed and electricity rates are dynamically changing during this period, the gas rate is usually not volatile; and it is considered to be approximately constant throughout a month. As a result of the simulation, the following figures show the optimum decision variables. Figure 5 shows the optimum low and high threshold rates, and Figure 6 represents the optimum discharge factor for each day.

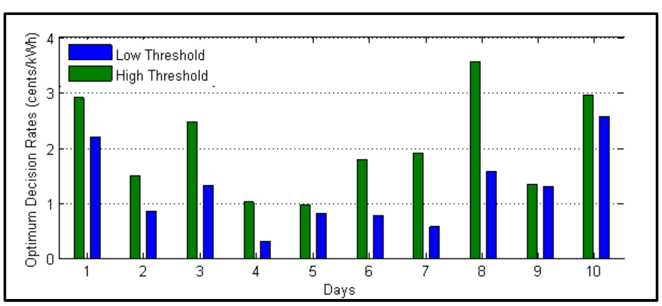

Figure 5. Optimum high and low threshold rates.

The standpoint of the hourly electricity rate within the thresholds of Figure 5 determines the willingness of the system to store or sell the electricity generated to the grid.

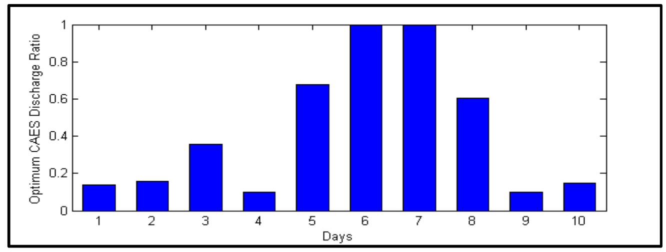

Figure 6. Optimum CAES discharge factor.

The profit calculated for all of the days is shown in Figure 7. In fact, this figure represents the objective function of the PSO maximized separately for each operation day. Figure 8 indicates the total amount of electricity sold daily to the grid.

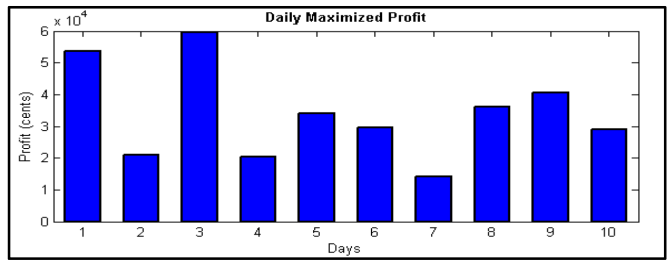

Figure 7. Daily maximized profit with operation optimization method.

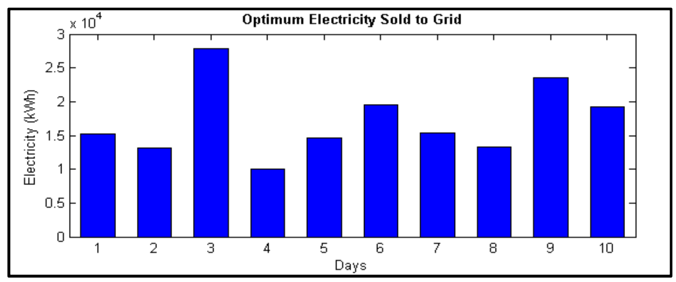

Figure 8. Daily electricity sold to grid with operation optimization method.

In general, the profit on the days with higher wind speeds and higher electricity rates is relatively higher than the other days. In addition, a comparison between Figures 8 and 3 shows a correlation between the wind speed and the amount of power sold to the grid on different days.

B. Planning Optimization Results

The goal is to determine the optimum wind generation and CAES capacities. Figures 9 and 10 show the wind speed, electricity rates, and gas rates for a duration of one year. A longer duration of study for planning purposes can be selected without loss of generality.

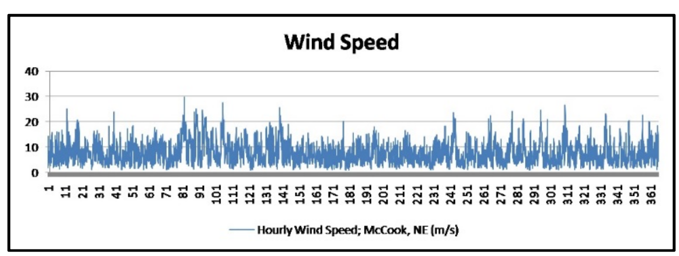

Figure 9. Wind speed data during a year.

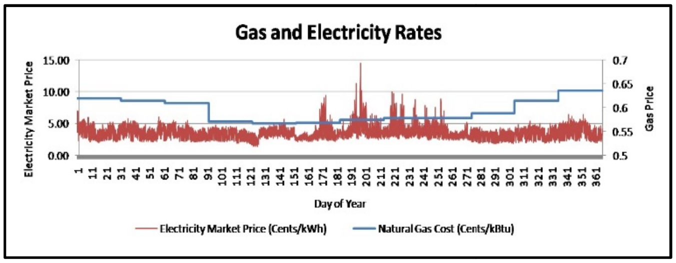

Figure 10. Gas and electricty rates during a year.

Based on the data in Figure 10, electricity rates reach peak values during the summer when the wind speed is not dominant (Figure 9). The results in this case are provided by (5), and they are different from the initial capacities chosen for the base case operation optimization study.

$$\begin{cases} Cap_{\mathrm{W}} = 1.1\ MW \\ Cap_{\mathrm{CAES}} = 6\ MWh \end{cases} \tag{5}$$

Figure 11 shows the maximum daily profit with the optimum capacities calculated. Since the costs associated with wind generation and CAES have also been included in the objective function, there are some days in Figure 11 when those costs are higher than the revenue; and the daily profit shows a negative value. Specifically, it can be observed that on some of those days, the wind speed is higher than 20 m/s which is the cut-out wind speed. Therefore, wind generation outage contributes to the negative profit on those days. It is also observed that as expected, the profit curve of Figure 11 has a good correlation with the electricity rates in Figure 10.

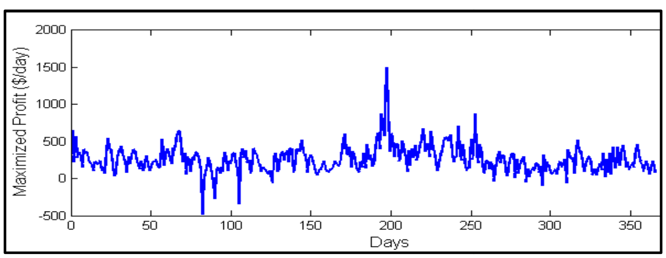

Figure 11. Daily maximized profit with optimum wind generation and CAES capacities.

C. *Sensitivity Analysis*

The first sensitivity analysis was conducted on varying the available capacity to transfer power to the grid, which could be perceived as a power transmission constraint. The power transfer limit increases from the base case (1.5 MW) up to 50 MW, and the results of the planning study show a considerable rise in profit (Figure 12).

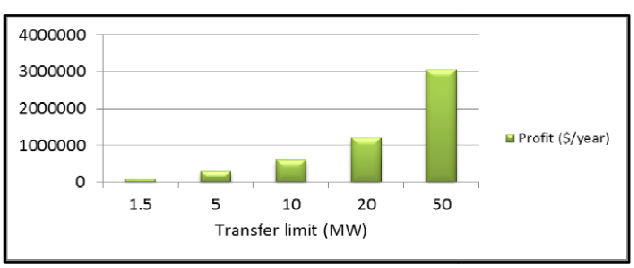

Figure 12. Sensitivity of the total profit to the power transfer limit.

The optimum capacities in this case are presented in Figure 13. It should be noted that, in this sensitivity analysis, the costs of transmission line upgrades have not been taken into account. More studies are required to determine whether the extra profit can cover the costs of higher transmission line capacity.

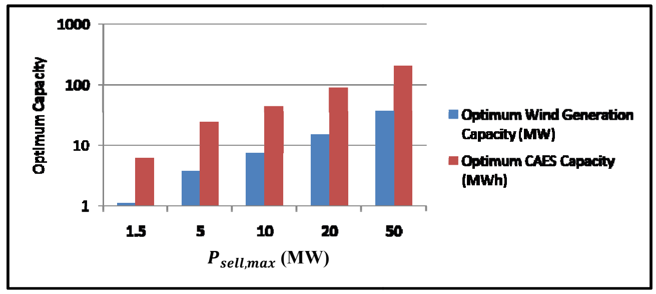

Figure 13. Optimum capacities of wind generation and CAES with higher power transfer limits.

Another sensitivity analysis was performed varying the average electricity rate and the heat rate of the base case study. In this study, the transfer limit was assumed to be 50MW; and the optimum capacities were selected from Figure 13, accordingly. As shown in Figure 14, the effect of the electricity rate on the profit is more than the heat rate. This means that high enough electricity rates can change a non-economically justifiable CAES project to be cost efficient.

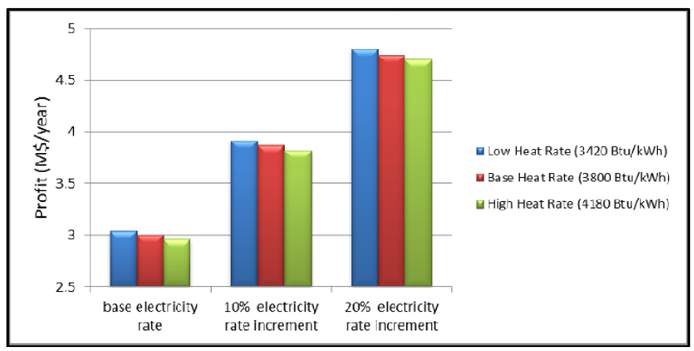

Figure 14. Sensitivity of the wind generation-CAES profit to electricity rate and heat rate.

VII. SUMMARY AND CONCLUSIONS

As the penetration of intermittent renewable energy sources is increasing, storage becomes a necessary asset to ensure reliability and efficient operation of power systems. Compressed air energy storage is a technology that is economical for large bulk storage and can provide cycling capability, regulation, and quick start for both peak and base load applications. We developed a model for integrating wind energy and CAES. Optimization techniques are utilized to determine the optimum day-to-day operation and capacities of the wind generation-CAES. The results of the case studies indicate that the cost-effectiveness of the wind generation-CAES plant depends on its efficiency and costs as well as the electricity rate and wind speed. Using the input variables from a local electric utility, the optimum CAES capacity calculated is five to six times the optimum capacity of wind generation.

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